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# Characterization of Fault Roughness at Various Scales: Implications of Three-Dimensional High Resolution Topography Measurements

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► **To cite this version:**

Thibault Candela, François Renard, Michel Bouchon, Alexandre Brouste, David Marsan, et al.. Characterization of Fault Roughness at Various Scales: Implications of Three-Dimensional High Resolution Topography Measurements. 2008. hal-00326981

**HAL Id: hal-00326981**

**<https://hal.science/hal-00326981>**

Preprint submitted on 7 Oct 2008

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1 **Characterization of Fault Roughness at Various Scales:**  
2 **Implications of Three-Dimensional High Resolution Topography**  
3 **Measurements**

4

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20 Short title: Roughness of fault surfaces

21

22

23 **Abstract** – Accurate description of the topography of active faults surfaces represents an  
24 important geophysical issue because this topography is strongly related to the stress  
25 distribution along fault planes, and therefore to processes implicated in earthquake nucleation,  
26 propagation, and arrest.

27 Up to know, due to technical limitations, studies of natural fault roughness either performed  
28 using laboratory or field profilometers, were obtained mainly from 1D profiles. With the  
29 recent development of Light Detection And Ranging (LIDAR) apparatus, it is now possible to  
30 measure accurately the 3D topography of rough surfaces with a comparable resolution in all  
31 directions, both at field and laboratory scales. In the present study, we have investigated the  
32 scaling properties including possible anisotropy properties of several outcrops of two natural  
33 fault surfaces (Vuache strike-slip fault, France, and Magnola normal fault, Italy) in  
34 limestones. At the field scale, digital elevation models of the fault roughness were obtained  
35 over surfaces of  $0.25 \text{ m}^2$  to  $600 \text{ m}^2$  with a height resolution ranging from 0.5 mm to 20 mm.  
36 At the laboratory scale, the 3D geometry was measured on two slip planes, using a laser  
37 profilometer with a spatial resolution of  $20 \text{ }\mu\text{m}$  and a height resolution less than  $1 \text{ }\mu\text{m}$ .

38 Several signal processing tools exist for analyzing the statistical properties of rough surfaces  
39 with self-affine properties. Among them we used six signal processing techniques: (i) the  
40 root-mean-square correlation (RMS), (ii) the maximum-minimum height difference (MM),  
41 (iii) the correlation function (COR), (iv) the RMS correlation function (RMS-COR), (v) the  
42 Fourier power spectrum (FPS), and (vi) the wavelet power spectrum (WPS). To investigate  
43 quantitatively the reliability and accuracy of the different statistical methods, synthetic self-  
44 affine surfaces were generated with azimuthal variation of the scaling exponent, similar to  
45 what is observed for natural fault surfaces. The accuracy of the signal processing techniques is  
46 assessed in terms of the difference between the “input” self-affine exponent used for the  
47 synthetic construction and the “output” exponent recovered by those different methods. Two

48 kinds of biases have been identified: artifacts inherent to data acquisition and intrinsic errors  
49 of the methods themselves. In the latter case, the statistical results of our parametric study  
50 provide a quantitative estimate of the dependence of the accuracy with system size and  
51 directional morphological anisotropy.

52 Finally, we used the most reliable techniques (RMS-COR, FPS, WPS). For both field and  
53 laboratory data, the topography perpendicular to the slip direction displays a similar scaling  
54 exponent  $H_{\perp} = 0.8$ . However, our analysis indicates that for the Magnola fault surface the  
55 scaling roughness exponent parallel to the mechanical striation is identical at large and small  
56 scales  $H_{\parallel} = 0.6 - 0.7$  whereas for the Vuache fault surface it is characterized by two different  
57 self-affine regimes at small and large scales. We interpret this cross-over length scale as a  
58 witness of different mechanical processes responsible for the creation of fault topography at  
59 different spatial scales.

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67 **Key words:** fault, 3D laser scanner, fault-surface roughness, self-affine surface, roughness  
68 exponent.

69

## 1. Introduction

70  
71 Knowledge of the detailed fault geometry is essential to understand some major processes  
72 involved in faulting such as grain comminution or asperities abrasion during slip, geometrical  
73 heterogeneity of the stress field that controls earthquake nucleation (CAMPILLO *et al.*, 2001;  
74 VOISIN *et al.*, 2002a), rupture propagation, and arrest (VOISIN *et al.*, 2002b). Establishing  
75 correlations between geometrical properties of fault roughness (POWER *et al.*, 1987, 1988;  
76 POWER and TULLIS, 1991; SCHMITTBUHL *et al.*, 1993; LEE and BRUHN, 1996;  
77 POWER and DURHAM, 1997; RENARD *et al.*, 2006; SAGY *et al.*, 2007), seismic behavior  
78 of faults (OKUBO and AKI, 1987; PARSON, 2008), frictional strength and critical slip  
79 distance (SCHOLZ, 2002), wear processes during fault zone evolution (POWER *et al.*, 1988)  
80 represents a fundamental issue to understand seismic faulting.

81 At the laboratory scale, AMITRANO and SCHMITTBUHL (2002) highlight a complex  
82 coupling between fault gouge generation and fault roughness development. At larger scale,  
83 asperities control the slip distribution of earthquake (PEYRAT *et al.*, 2004). Indeed asperities  
84 on active fault planes concentrate the stress (MARSAN, 2006; SCHMITTBUHL *et al.*, 2006)  
85 and therefore may control earthquake nucleation (LAY *et al.*, 1982; SCHOLZ, 2002) and the  
86 propagation of the rupture to its ultimate arrest (AKI, 1984). High resolution relocations of  
87 earthquakes using the multiplet technique have shown streaks of earthquake along several  
88 faults in California (RUBIN *et al.*, 1999). This pattern has been interpreted as resulting from  
89 the presence of an organized large scale roughness (asperities) resisting slip (SCHAFF *et al.*,  
90 2002).

91 Despite recent progress in seismology, the imaging of fault planes over a large range of scales  
92 at depth is not yet available. A quasi-unique access to high resolution description of the fault  
93 plane comes from exhumed fault scarp observations. This requires, of course, that the main  
94 morphological patterns of faults mapped at the surface of the earth persist at least across the

95 seismogenic zone. Due to technical limitations, prior comparative studies of natural fault  
96 roughness were mainly based on 1D profilometry (POWER *et al.*, 1987, 1988; POWER and  
97 TULLIS, 1991; SCHMITTBUHL *et al.*, 1993; LEE and BRUHN, 1996; POWER and  
98 DURHAM, 1997). These 1D measurements have shown that fault roughness can be  
99 characterized by a scale invariance property described by a self-affine geometry (see section 2  
100 for the definition of self-affinity) with a roughness scaling exponent close to 0.8 for profiles  
101 oriented in a direction perpendicular to the striations observed on the fault plane. Such  
102 striations are aligned in the direction of slip. The value of 0.8 is similar to what was measured  
103 for tensile cracks (POWER *et al.*, 1987; SCHMITTBUHL *et al.*, 1995b; BOUCHAUD,  
104 1997). Moreover, the influence of slip was also quantified: the fault surfaces have smaller  
105 roughness amplitude along the slip direction than perpendicular to it (POWER *et al.*, 1988;  
106 POWER and TULLIS, 1991; LEE and BRUHN, 1996; POWER and DURHAM, 1997). The  
107 compiled fault roughness statistics of several studies (POWER and TULLIS, 1991; LEE and  
108 BRUHN, 1996; BEN-ZION and SAMMIS, 2003) suggest a change in scaling properties  
109 between large and short length scales. However, considering the noise in their data, these  
110 authors underlined that it was not possible to decipher whether this variation was related to  
111 small-scale surface weathering of the fault scarp or to the faulting process itself.

112 With the recent development of high resolution distancemeters, it is now possible to use  
113 accurate statistical approaches to quantify fault roughness. Indeed, portable 3D laser scanners  
114 (also called LiDAR, Light Detection And Ranging) allow mapping fault surface outcrops over  
115 scales of 0.5 mm to several tens of meters. The accuracy of the measurements enables a  
116 reliable quantification of the data. RENARD *et al.* (2006) and SAGY *et al.* (2007)  
117 demonstrated precisely the scaling invariance and anisotropy properties of fault topography  
118 using ground based LIDAR and laboratory profilometers. In these previous studies, statistical  
119 analysis of fault roughness was carried out with a single signal processing tool. However,

120 SCHMITTBUHL *et al.* (1995a, 1995b) recommend the simultaneous use of different methods  
121 in order to appreciate the confidence in the measured scaling invariance properties.

122 In the present study, we use new roughness data to extend the type of measurements made by  
123 RENARD *et al.* (2006) and SAGY *et al.* (2007) and propose a parametric study of the  
124 statistical results of fault topography, using multiple signal processing tools. In order to  
125 investigate the reliability and accuracy of the different signal processing methods, synthetic  
126 self-affine surfaces were generated with azimuthal variation of the scaling exponent. These  
127 synthetic rough surfaces are completely characterized by two different self-affine exponents  
128 prescribed in perpendicular directions. When comparing these synthetic surfaces to natural  
129 faults, one should keep in mind that any self-affine model can only describe a real surface to a  
130 finite degree of accuracy, and only within a finite range of scales. After this systematic study,  
131 we used the most reliable and accurate techniques to investigate the scaling properties and  
132 anisotropy of several outcrops of two natural fault surfaces that have been measured using 3D  
133 laser scanners in the field and a laser profilometer in the laboratory.

134 This paper is organized as follows. In Section 2, following a brief explanatory discussion of  
135 the self-affine notion, the generation process of synthetic self-affine surfaces with a  
136 directional morphological anisotropy is described. In Section 3, statistical methods to define  
137 the self-affine properties are reviewed. Section 4 is devoted to the systematic study of the  
138 accuracy of the methods. Section 5 is devoted to the acquisition of data on natural fault. In  
139 Section 6, analysis of the roughness, covering six orders of magnitude of length scales, is  
140 performed on several outcrops of two natural faults. Finally, in Section 7, we conclude by  
141 linking our findings on the statistical properties of natural fault topography to the results of  
142 earlier studies, with the ultimate goal of developing a more mutually consistent description of  
143 fault asperities geometry.

144

## 2. Generation of self-affine surfaces

### 2.1 Self-affinity in 1D and 2D

Surface roughness analysis provides a statistical characterization of a surface which is simpler and easier to use than a complete deterministic description. In geophysics, BROWN and SCHOLZ (1985) and POWER *et al.* (1987) demonstrated the self-similar property of natural fault surfaces at field scale. Coming from statistical physics, a more general scaling transformation has been proposed: self-affinity (MANDELBROT, 1985; MANDELBROT, 1986; VOSS, 1985) that was successfully used for the quantitative description of fault roughness (SCHMITTBUHL *et al.*, 1993, RENARD *et al.*, 2006).

A self-affine 1D profile remains unchanged under the scaling transformation  $\delta x \rightarrow \lambda \delta x$ ,  $\delta z \rightarrow \lambda^H \delta z$  for 1D profiles (Figure 1) extracted from a surface (MEAKIN, 1998). Here,  $\delta x$  is the coordinate along the profile and  $\delta z$  is the roughness amplitude. For a self-affine profile, the scaling exponent  $H$ , also called Hurst exponent, lies in the range  $0 \leq H \leq 1$ . Accordingly, self-affinity implies that a profile appears less rough as the scale increases. In other words, if a profile is self-affine, a magnified portion of it will appear statistically identical to the entire profile if different magnifications are used in the x and z-directions (Figure 1).

For 2D surfaces, this self-affinity property can be described for sets of 1D parallel profiles extracted from the surface. Moreover, if the surface is striated along some given orientation, anisotropic scaling behavior can emerge if  $H$  varies for different directions in the plane of the surface. An anisotropic self-affine surface  $Z(x, y)$  with coordinates  $(x, y)$  obeys the property:

$Z(\lambda^{1/H_{\parallel}} x, \lambda^{1/H_{\perp}} y) = \lambda Z(x, y)$ , where  $\lambda$  is a positive dilation factor,  $H_{\parallel}$  and  $H_{\perp}$  are the Hurst exponents, comprised between 0 and 1, in two perpendicular directions of the surface.  $H_{\parallel}$  is defined along a direction parallel to the main striations, and  $H_{\perp}$  is defined along a direction perpendicular to the striation (Figure 1b).



## 170 2.2 Synthetic anisotropic self-affine surfaces

171 To calculate synthetic fault surfaces (Figure 1b), we used a Fourier based method to simulate  
172 a fractional Brownian motion on a 2D grid (STEIN, 2002), where an anisotropy matrix

173  $E = \begin{pmatrix} 1/H_{//} & 0 \\ 0 & 1/H_{\perp} \end{pmatrix}$  was introduced when calculating the 2D Gaussian random field. The

174 eigenvalues of this matrix correspond to the inverse of the two roughness exponents  $H_{//}$ , and

175  $H_{\perp}$  that characterize the self-affine properties of the generated surface in two perpendicular

176 directions (BIERME *et al.* 2007, 2008). The code to generate an anisotropic 2D self-affine

177 surface, written in Matlab©, is given in the appendix A and can be run easily on a desktop

178 computer.

179 In the following sections, we decompose the signal processing analysis of rough surfaces in

180 two stages. Firstly, we present the six signal processing tools used to estimate the self-affine

181 property of an isotropic surface with a single Hurst exponent (Figure 1a), as observed for

182 example for fresh mode I brittle fractures in rocks (POWER *et al.*, 1987; SCHMITTBUHL *et*

183 *al.*, 1995b; BOUCHAUD, 1997). For this, we have synthesized several isotropic surfaces with

184 an exponent in the range [0.1 - 0.9] and grid sizes in geometrical series:  $129 \times 129$  points,  $513$

185  $\times 513$  points,  $2049 \times 2049$  points. Secondly, we analyse synthetic anisotropic surfaces (Figure

186 1b) with  $H_{//}$  in the range [0.7 - 0.9] and  $H_{\perp}$  in the range [0.4 - 0.9].

187

## 188 3. Statistical signal processing methods

189 We have used six different methods that characterize the amplitude of the roughness at

190 various spatial wavelengths. All these methods, presented in the following sub-sections, are

191 based on the analysis of 1D profiles (Figure 1c) that are extracted from the 2D Digital

192 Elevation Model (DEM) of 2D surfaces (Figure 1a, b). For each surface, a set of 1D parallel

193 profiles in a specific direction are extracted, detrended and then analyzed. Then, the properties

194 are averaged over all the 1D profiles to characterize the 2D surface in the chosen direction.  
 195 We have repeated such analyses for profiles extracted in several directions, following a 360°  
 196 rotation, allowing then to determine the azimuthal dependence of the statistical properties of  
 197 the surface (RENARD *et al.*, 2006) that could characterize a morphological anisotropy.  
 198 For the application to natural fault surfaces, we also tested how the noise in the data and the  
 199 presence of missing points could affect the estimation of fault surface. Indeed, the raw  
 200 scanner data consist of clouds of points, with x, y, and z coordinates, sampled more or less  
 201 regularly. Sometimes, data are missing (vegetation on the fault plane, low reflectivity of the  
 202 scanner light beam), and the surface is incomplete. An interpolation is then necessary, which  
 203 induce a bias in the estimation of scaling exponents that need to be estimated too.

### 204 *3.1 Root-mean-square correlation (RMS) and maximum-minimum height difference (MM)* 205 *methods*

206 Let consider a 1D profile  $L(x)$ . This profile is divided into windows of width  $\delta x$  and indexed  
 207 by the position of the first point  $x_0$  of the band. The standard deviation  $\sigma(\delta x)$  of the height  
 208  $L(x)$  and the height difference  $h(\delta x)$  between the maximum and minimum height are  
 209 computed for each band, and then averaged over all the possible bands of fixed width  $\delta x$   
 210 spanning the profile, by varying the origin  $x_0$ . We then obtain  $\langle \sigma(\delta x) \rangle$  and  $\langle h(\delta x) \rangle$ , where  
 211 both quantities follow a power law for a self-affine profile:  $\langle \sigma(\delta x) \rangle \propto \delta x^H$  and  
 212  $\langle h(\delta x) \rangle \propto \delta x^H$  (SCHMITTBUHL *et al.* 1995a).

213 Note that these techniques are useful when  $H$  is not too close from 0 or 1, where a significant  
 214 error can be measured (see [Figures 3a, b – 4a, b](#)). Usually, levelling off of  $\sigma(\delta x)$  at small  $\delta x$   
 215 values is due to the noise in the data (see [Figure 7c, d](#)), and leveling-off at large  $\delta x$  is due to  
 216 the finite size of the profile.

217

### 218 3.2 Height-height correlation function (COR) method

219 For a signal  $L(x)$ , we consider the height-height correlation function defined by

220  $C(\Delta x) = \left[ \langle (L(x) - L(x + \Delta x))^2 \rangle \right]^{1/2}$ , which estimates the average height-height difference

221 between two points of the profile separated by a distance  $\Delta x$ . For a self-affine profile, the

222 correlation function follows a power-law such that  $C(\Delta x) \propto \Delta x^H$  where  $H$  is the Hurst

223 exponent.

### 224 3.3 Standard deviation of the correlation function (RMS-COR) method

225 For a profile  $L(x)$  containing  $N$  points, the height difference  $\Delta L$  between each couple of

226 points separated by a distance  $\Delta x$  is calculated. The window size  $\Delta x$  is varied between the

227 sampling distance and the size of the system and, for a given  $\Delta x$ , the standard deviation of

228 the height difference  $\sigma(\Delta L_{\Delta x})$  is calculated. For a self-affine surface this measurement

229 follows a power-law such that  $\sigma(\Delta x) \propto \Delta x^H$ . This method was successfully applied to

230 characterize the self-affine properties of the Vuache fault plane (RENARD *et al.* 2006).

### 231 3.4 Fourier power spectrum (FPS) method

232 The Hurst exponent  $H$  can be estimated from the Fourier power spectrum which has a power

233 law form for a 1D self-affine profile (BARABASI and STANLEY, 1995; MEAKIN 1998).

234 For each parallel profile, the Fourier power spectrum  $P(k)$ , *i. e.* the square of the modulus of

235 the Fourier transform, is calculated as a function of the wave-number  $k$ . Then the spectrum of

236 the whole surface is calculated by stacking all the 1D Fourier transforms to reduce the noise

237 associated with individual profiles. For each profile of length  $L$  containing  $N$  increments,

238 the spatial frequencies range between  $1/L$  and the Nyquist frequency  $N/2L$  (*i.e.* the

239 reciprocal of the interval between data points). When plotting the power spectrum as a

240 function of  $k$  in log-log space, a self-affine function reveals a linear slope, which is itself a

241 function of the Hurst exponent  $H$  through  $P(k) \propto k^{-1-2H}$ .

242 *3.5 Average wavelet coefficient power spectrum (WPS) method*

243 The average wavelet coefficient method consists of decomposing the input signal into  
244 amplitudes that depend on position and scale. The wavelet transform of each 1D profile  $L(x)$

245 is defined as  $W_{a,b} = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} \psi\left(\frac{x-b}{a}\right) L(x) dx$  where  $\psi$  is the wavelet function. Then the

246 wavelet coefficients are averaged over the translation factor  $b$  for each length scale  $a$  :

247  $W_a = \langle W_{a,b} \rangle_b$ . If the profile is self-affine, the wavelet transform verifies statistically that, for

248 any positive dilatation factor  $\lambda$ ,  $W_{a,b}[L(\lambda x)] = \lambda^H W_{a,b}$ . Accordingly, the averaged wavelet

249 coefficients scale as  $W_a \propto a^{H+1/2}$ . A wide range of wavelet functions can be used. For a

250 simple and efficient implementation, we chose the Daubechies wavelet of order 12 as

251 suggested in SIMONSEN *et al.* (1998).

252

253 *4. Quantitative estimation of the accuracy of roughness analysis methods*

254 *4.1 Synthetic isotropic and anisotropic rough surfaces*

255 **Figures 1a and 1b** display the topography of synthetic rough surfaces where the data set  
256 includes  $2049 \times 2049$  points regularly spaced on a grid. **Figure 1a** shows an isotropic rough  
257 surface, whereas **Figure 1b** shows an anisotropic surface, with corrugations elongated parallel  
258 to the direction of smaller Hurst exponent (analogue to the direction of slip on a natural fault  
259 surface) and covering a wide range of scales.

260 The roughness amplitude of a profile parallel to the striation direction (green curve in **Figure**  
261 **1c**) is smaller than that of a perpendicular profile. The profile extracted along the direction  
262 with the smallest exponent (green curve) appears more jagged at small scales compared to a  
263 perpendicular profile, showing the different effects of the anisotropy of the surface on the  
264 waviness and amplitude of the profiles.

265 The outputs of the statistical methods described in section 2.3 are represented on [Figure 2](#)  
266 Each curve is calculated by averaging the outputs of all possible parallel 1D profiles extracted  
267 from the anisotropic surface of [Figure 1b](#). The results are represented in a log-log plot,  
268 allowing visualizing the linear portion of the curve that characterizes a power-law distribution  
269 ([Figure 2](#)). This linear portion is binned in a small number of increments, and a power-law fit  
270 is performed to extract the Hurst exponent that characterizes the self-affinity of the profile.  
271 The best fits are performed for each curve and a value of the "output" self-affine exponent is  
272 then calculated for all the six signal processing methods.

273 Using the RMS correlation function, we have also extracted sets of parallel profiles in several  
274 directions, at an angle  $\theta$  to the direction of the striations. For each set of profile, we have  
275 calculated the correlation function and estimated the value of  $H$ . The angular dependence of  
276  $H$  could be represented on a polar plot (inset in [Figure 2d](#)) (RENARD *et al.*, 2006). The  
277 anisotropy of such plot characterizes the anisotropy of the surface: an isotropic surface is  
278 represented as a circle of radius  $H$ , whereas an anisotropic one has a more complex elliptical  
279 shape.

#### 280 *4.2 Isotropic surfaces: effect of size and input exponent on the output estimation of the Hurst* 281 *exponent*

282 The comparison between the input Hurst exponent used to calculate an isotropic synthetic  
283 surface and the output Hurst exponent estimated using the six different methods is represented  
284 on [Figure 3](#), for different system sizes. The RMS, MM, COR and RMS-COR methods are all  
285 mainly sensitive to the value of the input self-affine exponent (the typical trend of the curve is  
286 not parallel to the diagonal). Small self-affine exponents are systematically overestimated  
287 whereas large exponents are underestimated. In contrast, the error for the WPS method is  
288 mainly function of the system size (the response is more or less parallel to the diagonal). The  
289 FPS method appears the most accurate technique, with only slight sensitivity to the input self-

290 affine exponent and size effects. This conclusion should however be interpreted cautiously as  
291 the algorithm used to generate the synthetic surface is based on a Fourier transform approach.  
292 The conclusion of this comparison tests is that the FPS, WPS, and RMS-COR methods are the  
293 most reliable because they have a small dependence on the value of the input Hurst exponent  
294 and a slight dependence on system size.

#### 295 *4.3 Anisotropic surfaces: Interaction between the two input roughness exponents*

296 For synthetic self-affine anisotropic surfaces, we have calculated the error on the estimation  
297 of the two Hurst exponents. For this, we have built surfaces (2049x2049 points, similar to  
298 [Figure 1b](#)) for which the Hurst exponents  $H_{input \parallel}$  and  $H_{input \perp}$  in two perpendicular directions  
299 were varied in the range [0.4 – 0.9]. We have then used the six signal processing techniques to  
300 estimate the values of these same exponents. The absolute error in the estimation of each  
301 Hurst exponent ([Figure 4](#)) depends on the input value of these parameters and also on the  
302 amplitude of their difference ( $H_{input \parallel} - H_{input \perp}$ ).

303 This error is particularly large for the RMS (up to 20%), MM (up to 25%), and COR (up to  
304 35%) methods. When the input anisotropy ( $H_{input \parallel} - H_{input \perp}$ ) increases, the absolute error on  
305 the two output exponents increases accordingly. The absolute error is smaller in the direction  
306 of the smallest exponent (analogue to the direction of striation on a natural fault surface) than  
307 perpendicular to it. Moreover, it is also noteworthy to mention that these three techniques  
308 show significant errors in the estimation for input exponents close to 0.8-0.9 even if the  
309 anisotropy is minimal, demonstrating the limited reliability of these methods to detect an  
310 exponent close to one.

311 The RMS-COR analysis is also sensitive to the input anisotropy ([Figure 4d](#)), however such an  
312 effect is not strongly pronounced (the absolute errors are smaller, up to 15%). For this  
313 method, the error does not depend on the values of the two input Hurst exponents. For  
314 example, with a synthetic surface defined by  $H_{input \parallel} = 0.8$  and  $H_{input \perp} = 0.6$ , the absolute error

315 in the estimation of each Hurst exponent is almost identical. As shown in [Figure 4d](#), when  
316 anisotropy is small, the errors do not increase significantly for input values close to 1 unlike  
317 the three previous methods.

318 The FPS and WPS analysis are only slightly sensitive to the “input” anisotropy and the  
319 estimated Hurst exponents do not depend on the input exponent values. Our analysis clearly  
320 shows that the FPS, the WPS and, to a lesser extent, the RMS-COR methods are the most  
321 reliable. More precisely, the RMS-COR and the WPS techniques slightly underestimate and  
322 overestimate, respectively, the roughness exponent compared to the FPS method.

323 We have also analyzed the azimuthal dependence of the Hurst exponent for synthetic  
324 anisotropic self-affine surfaces. Comparisons of the “output” anisotropy estimated using the  
325 RMS-COR method and the “input” anisotropy is represented on [Figure 5](#). We have used this  
326 technique because it does not require interpolation of the profiles, whereas the FPS and WPS  
327 methods would need regularly spaced data point. A significant directional morphological  
328 anisotropy of surfaces is visible on these polar plots of  $H$  even if a low “input” anisotropy is  
329 imposed, thus demonstrating the reliability of the RMS-COR method to detect a slight  
330 morphological anisotropy. Remarkably, following a  $360^\circ$  rotation, the azimuth variation of  $H$   
331 is not progressive. When departing a few degrees from the direction of the smallest “input”  
332 exponent, the “output” exponent is already very close to the largest “input” exponent. This  
333 property of anisotropic self-affine surface is not well understood yet.

334 A tentative way to calculate the error on the anisotropy that is made when estimating the  
335 anisotropy of the surface  $|H_{//} - H_{\perp}|$  is represented on [Figure 6](#). This plot indicates the error  
336 on the estimation of the anisotropy of the surface, and therefore provides some bounds on the  
337 accuracy of the determination of this property. Almost all methods underestimate the  
338 anisotropy, except the Fourier power spectrum which slightly overestimates it. For the RMS,  
339 MM, and COR methods, when the “input” anisotropy  $|H_{//} - H_{\perp}|$  increases, the absolute error

340 on the “output” anisotropy increases accordingly. Moreover, this absolute error is similar for  
341 all surfaces with the same “input” anisotropy, whatever the values of the two “input” self-  
342 affine exponents.

343 The determination of the “output” anisotropy with the RMS-COR, FPS, and WPS methods is  
344 less sensitive to the “input” anisotropy, except for the highest anisotropy, thus demonstrating  
345 the robustness of these three methods to determine the azimuth dependence of the statistical  
346 properties of an anisotropic self-affine surface. More precisely, estimates reported for the  
347 WPS method are somehow systematically lower than the two others techniques.

#### 348 *4.4 Effect of noise*

349 In all physical measurements, noise is present in the data because of the limited resolution of  
350 the measuring device. Such noise is usually described using Gaussian statistics with a zero  
351 mean and a constant variance. We have analyzed how the presence of noise in synthetic data  
352 could alter the estimation of the Hurst exponent. For this, we have calculated synthetic  
353 anisotropic surfaces and added a Gaussian noise with a standard deviation equal to 1/200 of  
354 the standard deviation of the rough surface (Figure 7a, b). This artificial alteration of the  
355 synthetic surface mimics measurements biases obtained on natural data, for example due to  
356 electronic noise in the measurement device or due to weathering of the fault surface. We have  
357 then estimated the Hurst exponents using the six signal processing methods and compared the  
358 results with the noise-free analysis. The results confirm that adding noise to the synthetic data  
359 induces a leveling-off of the curves at small length scales (RENARD *et al.*, 2006; SAGY *et*  
360 *al.*, 2007) and therefore a possible underestimation of the Hurst exponent, for all the six signal  
361 processing methods (Figure 7c-h).

362 Despite the fact that the Gaussian white noise added is isotropic, each plot (Figure 7c-h)  
363 indicates that the effect of noise is slightly dependent on the azimuth of the profile: the  
364 underestimation of the Hurst exponent is more pronounced along striations than



365 perpendicularly to them. Indeed, the addition of noise in the rough signal preferentially alters  
366 the roughness at small scales, and therefore has a stronger effect on the profiles parallel to the  
367 striations because they are characterized by a smaller amplitude at large length scales  
368 compared to the profiles perpendicular to the striations.

369 For the RMS, MM and RMS-COR methods, the noise does affect not only the small length  
370 scales but also the large length scales. Indeed, such an effect is strongly pronounced for these  
371 three methods and, slopes of the curves in [Figure 7c-f](#) lead to a significant underestimation of  
372 the actual value of the self-affine exponents. Notably, the polar plot of  $H$  from a surface with  
373 added noise obtained with the RMS-COR technique (see [Figure 7f](#)) shows errors of 10 % and  
374 20 % on the Hurst exponent measured in directions perpendicular and parallel to striations,  
375 respectively.

376 Conversely, the COR, FPS, and WPS techniques are less sensitive to the addition of noise. At  
377 large scale, the noise appears as a negligible correction, and even if the curves are affected at  
378 small scales, the estimation of the self-affine exponent is less affected.

#### 379 *4.5 Effect of missing data*

380 When considering natural fault measurements, local weathering and/or the presence of  
381 vegetation may form patches of missing data. To study their influence on estimation of fault  
382 surface properties, we generated incomplete data sets removing an increasing percentage of  
383 clusters of points from a synthetic surface that initially contained 513x513 points ([Figure 8](#)).

384 For the FPS and WPS methods, the incomplete cloud of points was interpolated across the  
385 gaps ([Figure 8b](#)), using a linear fit. However, for the RMS-COR method, the biased data can  
386 be used without interpolation of the holes ([Figure 8c](#)).

387 Typically, in our natural data sets 5 % of interpolated holes is the maximum percentage of  
388 spurious points removed from the raw scanner data. The results ([Figure 8d-f](#)) indicate that the  
389 RMS-COR, FPS and WPS analysis show an error of only 4 % on the Hurst exponent

390 estimated on a surface with 40 % holes compared to a complete surface. Therefore, 5% of  
391 missing points does not affect significantly the measurement of surface properties, whatever  
392 the technique employed.

393

## 394 *5. Acquisition of roughness data on natural faults at various scales*

### 395 *5.1 Acquisition of the data on the field and in the laboratory*

396 The roughness data of several fault samples were acquired at various scales using five  
397 different scanning devices (Table 1). At the laboratory scale, we used a home-made laser  
398 profilometer (MEHEUST, 2002), where a sample, set on a 2-axis moving table, is scanned by  
399 measuring the distance between the sample and a laser head. The horizontal scanning steps  
400 are either 20 or 24 micrometers and the vertical resolution is better than 1 micrometer.

401 On field outcrops, we measured several surfaces with four different LIDARs, where two main  
402 technologies were used. The S10 system (Table 1) contains a laser source and two cameras;  
403 the distance between the laser head and a surface point is measured by triangulation. The  
404 maximum shooting distance is around 15 m and the resolution in the distance measurement is  
405 close to 0.5 mm. Surfaces of several square meters can be measured with this system. The  
406 main drawback of this system is that it must be operated during night time otherwise the day  
407 light may blind the cameras.

408 The other three LIDAR systems (Table 1) are based on the same technology and were built by  
409 three different companies: a light pulse is sent from a laser head and the time of flight to the  
410 target point is measured, allowing calculating the distance, knowing light velocity. The whole  
411 target surface is scanned by rotating the laser head at constant angular velocity. The main  
412 advantages of this technology is that fast scanning rates can be achieved (up to 5000 points/s),  
413 the shooting distance can be as large as 1500 m and the system can be operated even under  
414 day light. However, compared to the S10 system, the measurement accuracy is lower,

415 between 1 and 2 cm. Note also that if the laser wavelength is in the infra-red range, absorption  
416 by water present on the target surface might also alter the quality of the data.

417 We have used these scanning measurement devices on two faults in limestones, where  
418 outcrop fault planes were scanned at various scales. Hand samples of slip surfaces were also  
419 collected and measured with the laboratory profilometer.

## 420 *5.2. The Magnola normal fault*

421 The Magnola fault outcrop, in the Fuccino area, is part of the extensive fault system in Central  
422 Apennines (Italy). This 15-km long normal fault shows microseismic activity and offsets  
423 limestone beds with a vertical displacement larger than 500 meters and a slight shear  
424 component witnessed by mechanical striations dipping at a 85° angle on the fault plane. This  
425 fault is characterized by recent exhumation (PALUMBO *et al.* 2004, CARCAILLET *et al.*  
426 2008) and the last earthquakes have risen to the surface a ~10-m thick band of fresh limestone  
427 (Figure 9a) where mechanical striations and grooves at all scales are still visible and less  
428 altered by weathering than older exhumed portions of the fault. We have scanned several sub-  
429 surfaces of the fault wall (Table 2, Figure 9b) and collected one hand sample from the roof of  
430 the fault for laboratory measurements (Table 2, Figure 9c). This sample, that shows  
431 mechanical striations, was dig from below the ground surface, to get a slip surface preserved  
432 from climatic weathering. The larger outcrop surfaces show evidence of erosion and some  
433 karstic water outlets provided holes for vegetation. Small bushes and grass outcrops had to be  
434 removed either directly from the fault plane, or from the LIDAR data. The result was  
435 incomplete data sets of the fault surface, with missing points in the records. Nevertheless,  
436 elongated bumps and depressions at large scales (Figure 9a), and grooves and ridges at small  
437 scales (Figure 9b) aligned parallel to slip can be observed.

438

439

### 440 *5.3. The Vuache strike-slip fault*

441 The Vuache fault is an active strike-slip fault system in the western part of the French Alps  
442 (THOUVENOT *et al.* 1998). The fault outcrop we analyzed lies on a short segment that  
443 connects to the main Vuache fault and that is not active anymore. This fault was analyzed in  
444 RENARD *et al.* (2006) and we present here new data of large and small scale slip surfaces  
445 (Figure 10).

446 This fault has a mainly strike-slip component, witnessed by large elongated bumps and  
447 depressions associated with linear striations of smaller size observed at all scales up to the  
448 resolution of the scanners LIDAR (Figure 10c, d). Conversely, the laboratory data show that  
449 the surface below the centimeter scale appears more polished and only smooth decimeter  
450 ridges persist (Figure 10f).

451 The fault offsets meter-scale beds of limestones and the fault plane was exhumed ten years  
452 ago by the activity of a quarry. As a consequence, the LIDAR measurements could be  
453 performed on fresh surfaces, where weathering was minimum and no vegetation had  
454 developed on the fault plane. For these surfaces, the data recovery was excellent, greater than  
455 99.5%. We therefore obtained the topography of the surfaces without holes in the data,  
456 making the signal processing results reliable.

457

## 458 *6. Roughness results and interpretation*

### 459 *6.1 Magnola Fault*

460 The roughness analysis results of the Magnola fault outcrop and hand sample are shown on  
461 Figure 11. On each plot (Figure 11a-d) both Lidar data (upper curve), acquired with the  
462 Optech scanner (Table 2), and laboratory profilometer data (lower curve) are represented,  
463 showing a scaling behavior over 5.5 orders of magnitude of length scales (50  $\mu\text{m}$  to  
464 approximately 20 m). Each curve represents an average over a large set of parallel 1D profiles

465 extracted from the DEM of the fault surface shown on [Figure 9](#). The level of noise for the  
466 field LIDAR scanner ([Table 1](#)) is estimated as the height of the flat part of the spectrum at  
467 small length scales and is indicated by the black arrows ([Figure 11](#)). The flattening of the  
468 scaling behavior at large scales is related to a finite size effect.

469 The FPS and WPS techniques performed along and perpendicular to the slip direction ([Figure](#)  
470 [11a-d](#)) indicate that the power laws can easily be connected for the field and laboratory data,  
471 demonstrating the robustness of the scaling behavior. Moreover, our results highlight a  
472 significant directional morphological anisotropy over a wide range of scales: the profiles  
473 parallel to the slip direction are rougher than perpendicular ones (POWER *et al.*, 1988;  
474 POWER and TULLIS, 1991; LEE and BRUHN, 1996; POWER and DURHAM, 1997;  
475 RENARD *et al.*, 2006; SAGY *et al.*, 2007). These two methods estimate a similar Hurst  
476 exponent perpendicular to the slip orientation ( $H_{\perp} = 0.8$ ) across the whole range of scales  
477 investigated in this study, a property similar to fresh mode I fracture surfaces (POWER *et al.*,  
478 1987; SCHMITTBUHL *et al.*, 1995b, BOUCHAUD, 1997). However, the FPS technique  
479 indicates a greater anisotropy,  $|H_{\parallel} - H_{\perp}| = 0.2$ , where  $H_{\parallel}$  represents the Hurst exponent in  
480 the direction of slip, than quantified by the WPS method ( $|H_{\parallel} - H_{\perp}| = 0.1$ ). Moreover, the  
481 WPS method overestimates the self-affine exponent along the slip direction ( $H_{\parallel} = 0.7$ )  
482 compared to the FPS method ( $H_{\parallel} = 0.6$ ). An attempted explanation of these last two  
483 differences is given by our parametric study of synthetic rough surfaces: the WPS method  
484 slightly overestimates the roughness exponents when measuring couples of Hurst exponents  
485 in perpendicular directions with range of values similar to those of natural fault surface (0.6 to  
486 0.9). Notably, the exponents accuracy with anisotropic surface of 2049 x 2049 points and for  
487 two Hurst exponents in perpendicular direction of 0.8 and 0.6 is numerically estimated as -  
488 0.01 and -0.06 for the wavelet method, respectively ([Figure 4f](#)). For example, an amount of -  
489 0.06 should be added to the measured minimal exponent with the WPS analysis to obtain the

490 actual one. Accordingly, on natural fault surface with two perpendicular exponents of 0.8 and  
491 0.6 calculated by the FPS, the estimated Hurst exponent in direction parallel to slip is  
492 systematically lower than with the WPS method (Figures 11-12). Moreover, since the error on  
493 the output Hurst exponent is greater in direction of slip than perpendicularly to it,  
494 consequently the output anisotropy decreases, as observed on natural fault surface (Figure 11-  
495 12).

496 Our estimations obtained on the hand sample with the RMS-COR function (see Figure 11e)  
497 show that the minimum Hurst exponent ( $H = 0.6$ ) is at  $85^\circ$ , in the direction of slip, and the  
498 maximum Hurst exponent ( $H = 0.8$ ) is almost in the perpendicular direction. These two  
499 extremes values of the self-affine exponent correspond also to those determined at all scales  
500 by the FPS and WPS methods. At the field scale (see Figure 11e), the minimum ( $H = 0.4$ )  
501 and maximum ( $H = 0.7$ ) Hurst exponents are observed in directions similar to that for the  
502 hand sample. However, the results obtained with the RMS-COR method suggest that the  
503 roughness exponent of the Magnola fault surface is smaller at the field scale compared to the  
504 laboratory scale, regardless of the azimuth. We ascribe this variation to natural weathering  
505 (pitting) of the exposed fault surface at short wavelengths, as POWER and TULLIS (1991).

506 Indeed, the section of the Magnola fault surface (Figure 9a) shows an increase of the  
507 roughness amplitude at short wavelengths created by weathering. Other sections of the  
508 Magnola fault surface, that are not presented in this study, display evidence of strong  
509 alteration at short length scales leading to a significant reduction of the Hurst exponent,  
510 regardless of azimuth. Conversely, the clean hand sample (Figure 9b), that shows mechanical  
511 striations, should represent the actual topography of the fault surface at short length scales,  
512 related to the faulting process before the action of climatic weathering. This hypothesis is  
513 supported by the fact that the fresh slip plane, scanned in laboratory, displays the same self-  
514 affine RMS-COR regimes in the directions parallel and perpendicular to slip than those

515 estimated using the FPS and WPS methods. The increase of roughness at short wavelengths  
516 on the field surface due to the erosion appears to be similar to the effect of an additional noise  
517 tested on “ideal” synthetic surfaces (Figure 7). In both cases, the Hurst exponent decreases in  
518 all directions. Our statistical study led on synthetic surfaces shows that the noise effect is  
519 more pronounced when using the RMS-COR technique. To summarize, the roughness scaling  
520 estimated using the RMS-COR calculated on the weathered field surface exhibits a decrease  
521 of the Hurst exponent in all directions, which is not observed with the FPS and WPS  
522 techniques.

523 On the polar plot of  $H$  obtained at the laboratory scale (see Figure 11e), when departing a few  
524 degrees from the direction of slip, the Hurst exponent is close to the value of the maximum  
525 Hurst exponent measured in the direction perpendicular to mechanical striations. Such  
526 behavior is also visible on “ideal” synthetic surfaces (Figure 5). In other words, the azimuth of  
527 the maximum Hurst exponent is not well-defined (gray shadows on Figure 11e), while the  
528 minimum exponent corresponds to a specific orientation. Note that this property is less visible  
529 on the polar plot of the altered field fault section (see Figure 11e) where the angular variation  
530 of  $H$  is more progressive.

### 531 6.2 *Vuache Fault*

532 The FPS and WPS techniques highlight a significant directional morphological anisotropy  
533 over six orders of spatial scales (Figure 12a-d). Profiles parallel to slip have a smaller Hurst  
534 exponent than perpendicular ones (POWER *et al.*, 1988; POWER and TULLIS, 1991; LEE  
535 and BRUHN, 1996; POWER and DURHAM, 1997; RENARD *et al.*, 2006; SAGY *et al.*,  
536 2007). These two methods, applied to series of profiles perpendicular to the direction of slip,  
537 indicate that the power laws of individual surfaces can easily be connected across the wide  
538 range of scales investigated (Figure 12b, d), and the value of  $H_{\perp} = 0.8$  is similar to what was  
539 measured on the Magnola normal fault surface. However, in the slip parallel direction there is

540 a slight change in the magnitude of  $H_{//}$  located in the length scale range between 5 mm and 2  
541 cm (gray shadows on [Figure 12a, c](#)).  $H_{//} = 0.75$  is larger below this length scale range than at  
542 larger length scales, where  $H_{//} = 0.65$  and  $H_{//} = 0.7$  for the FPS and WPS methods,  
543 respectively. The smoother aspect of the Vuache fault surface in the direction of slip  
544 compared to the perpendicular direction is an obvious and expected consequence of striations,  
545 but the smallest directional morphological anisotropy at the laboratory scale compared to the  
546 field scale is novel in this study. At the field scale, the morphology of the elongated bumps  
547 and depressions along the slip direction is different from the grooves and striations observed  
548 at the laboratory scale ([Figure 10](#)). As the fault Vuache outcrop is quite fresh, and was  
549 preserved from the climatic erosion, we propose that this cross-over in the slope at length  
550 scale of several millimeters is significant. We interpret this cross-over length scale as a  
551 witness of different mechanical processes responsible for the creation of fault topography at  
552 different spatial scales.

553 Our results obtained at the field and intermediate scales with the RMS-COR function (see left  
554 and center plots on [Figure 12e](#)) show that the minimum Hurst exponent ( $H_{//} \in [0.55 - 0.6]$ ) is  
555 oriented at  $20^\circ$  with respect to the horizontal, indicating the fault had a normal component and  
556 not only a strike-slip one. The maximum value  $H = 0.75$  is located for an almost  
557 perpendicular direction. These two extremes values of the self-affine exponent are slightly  
558 lower when estimated using the RMS-COR function than when using the FPS or the WPS  
559 methods. This slight underestimation with the RMS-COR technique is consistent with our  
560 results on synthetic surfaces for the accuracy in this range of parameters ([Figure 4](#)). Indeed,  
561 our parametric study led on anisotropic synthetic surfaces shows that the estimation of  $H$   
562 calculated with the RMS-COR technique slightly underestimates its actual value ([Figure 4d](#)).

563 At the laboratory scale (see right plot on [Figure 12e](#)),  $H_{//} = 0.8$  and  $H_{\perp} = 0.9$  are located in  
564 orientations similar to that for the three larger surfaces measured on the field. However, the



565 polar plot of  $H$  calculated using the RMS-COR function suggests an increase of the scaling  
566 exponents in all directions, while the estimation using the FPS or WPS techniques underlined  
567 that the exponent increased only along the slip direction. In addition, the two exponents  $H_{//}$   
568 and  $H_{\perp}$  for the hand sample are overestimated when calculated with the RMS-COR method  
569 compared to the FPS and WPS techniques. The latter observation cannot be explained by the  
570 results of our parametric study on synthetic surfaces. As a consequence of the extremely  
571 smooth aspect of the hand sample at small scales (Figure 10f), the RMS-COR method could  
572 lose its robustness. However, a new reliable result is that the directional morphological  
573 anisotropy calculated by the RMS-COR function significantly decreases at the laboratory  
574 scale, as observed with the FPS and WPS techniques.

575 As already observed on the polar plot of  $H$  calculated on the Magnola fault surface (Figure  
576 11e), the azimuth of the maximum Hurst exponent is less constrained (gray shadows on  
577 Figure 12e) than the single specific orientation of the striations. Remarkably, despite the weak  
578 anisotropy of the hand sample topography, the slip direction is always significant,  
579 demonstrating the accuracy and reliability of the RMS-COR method.

580

581

## 7. Discussion & Conclusion

582 The six statistical tools used in this study have different response under the effect of two kinds  
583 of biases, the intrinsic errors of the methods (Figures 3, 4, 5, 6) and the artifacts inherent in  
584 data acquisition (Figures 7, 8). Using a parametric approach, where we varied the size of the  
585 surface and its anisotropy, we selected the three most reliable and accurate methods (RMS-  
586 COR, FPS, WPS) for roughness analysis of natural fault topography (Figures 11, 12). The  
587 Hurst exponent estimation at various scales for the natural slip surfaces displays the same  
588 trends and provides a consistent and robust characterization of their scaling regimes. We

589 emphasize that the slight variations in the results given by each one of these methods fall  
590 within the range of error estimated by our parametric study (see Section 4).

591 One of the most robust results of our scaling analysis is that the FPS and the WPS methods  
592 estimate a same Hurst exponent equal to 0.8 in the direction perpendicular to slip, over  
593 approximately 6 orders of magnitude of length scales for two different fault surfaces (Figures  
594 11b, d and 12b, d). However, in the slip direction two different scaling behaviors are  
595 highlighted: the Magnola fault surface shows an identical scaling regime at large and small  
596 scales (Figure 11a, c). Conversely, the scaling property of the Vuache fault roughness exhibits  
597 a cross-over in the slope at length scale of several millimeters (Figure 12a, c). In other words,  
598 the scaling property of this fault surfaces is similar at large scales but changes at small scales.

599 The statistical analyses (Figure 12) and the scan of the Vuache fault surface (Figure 10)  
600 clearly show a smoothing of the roughness below a length scale of several millimeters.

601 The scaling regime of 0.8 measured in the direction perpendicular to slip is a classical result  
602 already observed for tensile cracks (POWER *et al.*, 1987; SCHMITTBUHL *et al.*, 1995b,  
603 BOUCHAUD, 1997), indicating that the topography of the fault surface in the direction  
604 perpendicular to slip has not registered the effect of shear. Along slip, the general  
605 interpretation is that mechanical wear processes, such as frictional ploughing, cause striations  
606 that reduce the amplitude of the large scale roughness (POWER *et al.*, 1987, 1988; POWER  
607 and TULLIS, 1991; POWER and DURHAM, 1997; SAGY *et al.*, 2007) and accordingly the  
608 Hurst exponent. Nevertheless, our scaling analysis seems to indicate different mechanical  
609 processes responsible for the creation of fault topography at different spatial scales.

610 Prior comparative studies of natural fault roughness based on 1D profilometry (POWER and  
611 TULLIS, 1991; LEE and BRUHN, 1996) suggest a change in scaling properties between large  
612 and short length scales. However, due to technical limitations, their measures were not

613 sufficiently accurate to decipher if this variation was related either to small-scale surface  
614 weathering of the fault scarp or to the faulting process itself.

615 From laboratory experiments CHEN and SPETZLER (1993) suggest that the break in slope at  
616 length scales of several millimeters is caused by a change in the dominant mode of  
617 deformation from small-scale intergranular cracking to intragranular cracking at a larger  
618 scale. We think this interpretation does not apply to the Magnola and Vuache faults because  
619 the grain scale of these limestones is very small ( $< 0.1\text{mm}$ ), well below the observed cross-  
620 over length scale.

621 Recently, SAGY *et al.* (2007) observed that faults with large cumulated slip display surfaces  
622 with elongate, quasi elliptical bumps at field scale and are polished at small scales.  
623 Conversely, fault with a small cumulative slip are rough on all scales. SAGY and BRODSKY  
624 (2008) proposed that the waviness of the large slip fault surface reflects variations of  
625 thickness of the cohesive layer under the slip surface formed as boudinage structures  
626 (JOHNSON and FLETCHER, 1994; SMITH, 1977; TWISS and MOORES, 1992,  
627 GOSCOMBE *et al.*, 2004). Therefore, they evoke two different deformation mechanisms  
628 between large and small scales: abrasion caused by frictional sliding at the origin of the  
629 smoothing at small scales, and “boudinage” creating elongated bumps and depression at large  
630 scales.

631 From our study of natural fault roughness, we observe large elongated bumps and depressions  
632 in slip direction on two different fault planes (Figures 9b, 10a-d). There is no evidence that  
633 the small segment, polished at small scale (Figure 10f), that connects to the main Vuache fault  
634 has accumulated more slip than the Magnola fault surface that is rough at all scales (Figure  
635 9b, c). Therefore, we propose that large elongated bumps and depressions of several meters in  
636 length with maximum amplitude of around 2 m may reflect the processes of lateral growth  
637 and branching that links together several fault surfaces, during all the stages of the evolution

638 of the fault zone, as suggested by LEE and BRUHN (1996) and LIBICKI and BEN-ZION  
639 (2005).

640 At small scales, two different kinds of scaling regime are observed on the two fault surfaces,  
641 (Figures 11, 12), both being linked to mechanical wear process. Frictional sliding is expressed  
642 through ploughing of small asperities and is responsible for the small scale abrasional  
643 striations on the Magnola fault surface (Figure 9c). This mechanism is also responsible for the  
644 polishing of the Vuache fault surface below the centimeter scale (Figure 10f). One should  
645 keep in mind that only one hand sample was measured for each surface and therefore it is  
646 possible that differences of the scaling behavior between the two fault planes reflect spatial  
647 heterogeneity of core fault at small scales. Notably, on the Vuache fault, although the surface  
648 appears polished at the laboratory scale on the whole surface, zones with striations due to  
649 ploughing elements could be present. A more extensive study of fault roughness in several  
650 different faults should therefore bring more information on the mechanisms at work during  
651 faulting.

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814

815 Table 1: Characteristics of the field and laboratory scanner devices.

<b>3D scanner device</b>	S10	GS100	LMS Z420i	Iiris-3D	Lab. Profilometer
<b>Company</b>	Trimble	Trimble	Riegl	Optech	Univ. Strasbourg
<b>Resolution (dx)</b>	0.5 mm	10 or 20 mm	20 mm	20 mm	20 or 24 $\mu\text{m}$
<b>Noise on the data</b>	0.9 mm	4.5 mm	10.2 mm	20 mm	< 1 $\mu\text{m}$
<b>Acquisition speed</b>	70 pts/s	5000 pts/s	5000 pts/s	2500 pts/s	60 pts/s

816

817 Table 2: Fault surfaces analyzed in this study.

Fault	Surface area, dx	Scanner
Vuache, SURF1	17 x 10 m, 20 mm	GS100
Vuache, SURF7	24 x 11 m, 30 mm	GS100
Vuache, SURF6	45 x 9 m, 20 mm	LMS Z420i
Vuache, SMALL	10 x 9 cm, 24 $\mu\text{m}$	Lab. Profilometer
Vuache, SURF-JPG	0.5 x 0.5 m, 1 mm	S10
Magnola, A32	35 x 15 m, 20 mm	Optech
Magnola, M2	7.2 x 4.5 cm, 20 $\mu\text{m}$	Lab. Profilometer

818

```

820 function RoughSurf = Synthetic2DFault(N,H1,H2)
821
822 % This Matlab(c) function creates a self-affine 2D surface,
823 % with a directional anisotropy (courtesy of Hermine Bierme,
824 % Univ. Paris V, France), when H1 is different from H2.
825 % Input parameters:
826 % N = size of the surface: (2^(N+1)+1) x (2^(N+1)+1)
827 % Typically N must be between 8 and 11 when running on a
828 desktop computer.
829 % H1, H2: Hurst exponents in two perpendicular directions
830 % must be positive, smaller than 1.
831 % Output result:
832 % RoughSurf: rough surface of size (2^(N+1)+1) x (2^(N+1)+1),
833 % with two perpendicular directions of self-affinity
834 % characterized by Hurst exponents H1 and H2, l1 = 1/H1 and
835 % l2 = 1/H2 represent the eigen values of the anisotropy
836 % diagonal matrix
837 l1 = 1/H1;
838 l2 = 1/H2;
839 X = (-2*2^N:2:2*2^N)/(2^(N+1));
840 X(2^N+1) = 1/2^N;
841 Y = (-2*2^N:2:2*2^N)/(2^(N+1));
842 Y(2^N+1) = 1/2^N;
843 XX = X(ones(1,2*2^N+1),:);
844 YY = Y(ones(1,2*2^N+1),:)' ;
845 clear X Y
846
847 % rho is the pseudo-norm associated to the eigen values l1 and
848 l2
849 % rho(x,y)=(abs(x)^(2/l1) + abs(y)^(2/l2) )^(1/2)
850 rho = sqrt(abs(XX).^(2/l1)+abs(YY).^(2/l2));
851 clear XX YY
852
853 %phi is the spectral density of the field built from rho
854 phi = rho.^(1 + (l1+l2)/2);
855 clear rho
856
857 % W = Fourier transform of the anisotropic Gaussian field
858 Z = randn(2*2^N+1,2*2^N+1);
859 W = fftshift(fft2(Z))./phi;
860 clear Z
861 T = real(ifft2(ifftshift(W)));
862 RoughSurf = T-T(2^N+1,2^N+1);
863
864 % Plot the 2D rough surface
865 imagesc(RoughSurf);
866 axis equal
867 axis tight
868
869

```

870

871

872 **Figure 1.** Digital Elevation Models (DEM) of 2D synthetic self-affine surfaces (up) and 1D  
 873 profiles (down) generated using the algorithm of the appendix. (a) Surface with an isotropic  
 874 self-affine property characterized by a Hurst exponent of 0.8. (b) Anisotropic self-affine  
 875 surface with two Hurst exponents ( $H_{//} = 0.6$  and  $H_{\perp} = 0.8$ ) in perpendicular directions. (c)  
 876 Representative 1D profiles extracted in two perpendicular directions of surface (b). Inset:  
 877 magnified portion of a profile along the  $H_{//}$  direction (parallel to the striations), which has a  
 878 statistically similar appearance to the entire profile when using a rescaling  $\delta x \rightarrow \lambda \delta x$ ,  $\delta z \rightarrow$   
 879  $\lambda^H \delta z$ .

880

881 **Figure 2.** Outputs of the six signal processing techniques applied on the data of the  
 882 anisotropic self-affine surface shown in Figure 1b. (a) Root-mean-square correlation (RMS),  
 883 (b) maximum-minimum height difference (MM), (c) correlation function (COR), (d) RMS  
 884 correlation function (RMS-COR), (e) Fourier power spectrum (FPS), (f) Wavelet power  
 885 spectrum (WPS). The inset in (d) displays a polar plot of  $H$  obtained by the RMS-COR  
 886 method and allowing then to determine the azimuth dependence of  $H$ . The black points  
 887 correspond to the Hurst exponents for the two profiles shown on this plot.

888

889 **Figure 3.** Comparisons between the “input” Hurst exponents introduced in the construction of  
 890 isotropic fractional Brownian surfaces and the “output” exponent measured on these surfaces  
 891 using the six independent signal processing techniques. The effect of system size is also  
 892 studied. (a) Root-mean-square correlation (RMS), (b) maximum-minimum height difference  
 893 (MM), (c) correlation function (COR), (d) RMS correlation function (RMS-COR), (e) Fourier

894 power spectrum (FPS), (f) Wavelet power spectrum (WPS). The gray line in (a), (b), and (c)  
895 indicate for which input exponent the error in the estimation is closest to zero.

896

897 **Figure 4.** Intrinsic errors in the estimation of the Hurst exponents for anisotropic synthetic  
898 surfaces characterized by two Hurst exponents  $H_{input \parallel}$  and  $H_{input \perp}$  in perpendicular directions  
899 (2049x2049 points, similar to [Figure 1b](#)). For each signal processing method, histogram plots  
900 are represented where the horizontal axis contains the Hurst exponents  $H_{input \parallel}$  and  $H_{input \perp}$   
901 used as inputs to generate the synthetic surface. The vertical axis represents the difference  
902 between the input exponent and the estimated output Hurst exponent, using the six different  
903 methods. For each method, two histogram plots are represented: the upper one shows the  
904 difference ( $H_{input \parallel} - H_{output \parallel}$ ) and the lower one the difference ( $H_{input \perp} - H_{output \perp}$ ). The black  
905 top surfaces on the histogram bars indicate a negative difference (overestimation of the output  
906 exponent) and the color ones a positive difference (underestimation of the output exponent).  
907 (a) Root-mean-square correlation (RMS), (b) maximum-minimum height difference (MM),  
908 (c) correlation function (COR), (d) RMS correlation function (RMS-COR), (e) Fourier power  
909 spectrum (FPS), (f) Wavelet power spectrum (WPS).

910

911 **Figure 5.** Polar plots of the angular dependence of the two Hurst exponents  $H_{\parallel}$  and  $H_{\perp}$  for  
912 synthetic anisotropic surfaces with principal directions oriented at angles  $\theta_{\parallel} = 0^{\circ}$  and  
913  $\theta_{\perp} = 90^{\circ}$ . The Hurst exponents  $H_{\parallel, \perp}(\theta)$ , as defined by the slope  $\beta = H$  in [Figure 2d](#), were  
914 calculated on series of 1D profiles extracted at an angle  $\theta$  on 2049x2049 points surfaces.  
915 Three series of simulations are represented here for three values of  $H_{\parallel}$  in the range [0.7 –  
916 0.9]. For each polar plot, the different curves corresponds to successive values of  $H_{\perp}$ . The

917 dashed lines correspond to the values of the output Hurst exponent measured with the RMS  
918 correlation method (center dashed circle:  $H = 0.2$ , outer dashed circle:  $H = 1$ ).

919

920 **Figure 6.** Quantification of the intrinsic errors on the estimation of the anisotropy of the  
921 surface ( $H_{//} - H_{\perp}$ ). The difference between the “input” anisotropy (difference between the  
922 two “input” Hurst exponents) introduced in synthetic surfaces (2049x2049 points, similar to  
923 [Figure 1b](#)), minus the “output” anisotropy is represented for the six signal processing  
924 methods: (a) Root-mean-square correlation (RMS), (b) maximum-minimum height difference  
925 (MM), (c) correlation function (COR), (d) RMS correlation function (RMS-COR), (e) Fourier  
926 power spectrum (FPS), (f) Wavelet power spectrum (WPS). Bars with black top surface  
927 indicate an overestimation (“input” anisotropy - “ouput” anisotropy < 0) and colored top  
928 surfaces indicate an underestimation (“input” anisotropy - “ouput” anisotropy > 0). Gray bars  
929 indicate isotropic surfaces ( $H_{//} = H_{\perp}$ ), thus without errors.

930

931 **Figure 7.** Influence of an additional noise on the self-affinity property of an anisotropic  
932 synthetic surface (513x513 points) characterized by two Hurst exponents ( $H_{//} = 0.6$  and  
933  $H_{\perp} = 0.8$ ) in perpendicular directions. The Gaussian white noise is characterized by a  
934 standard deviation two hundred times smaller than the roughness amplitude of the synthetic  
935 surface. (a) Example of 1D profiles extracted in two perpendicular directions of an “ideal”  
936 surface. (b) The same profiles but with an additional noise. Note that altered profiles appear  
937 more jagged or rougher at small scale compared the noise-free profiles. Analyses of those  
938 altered surfaces are performed with the six independent self-affine methods: (c) Root-mean-  
939 square correlation (RMS), (d) maximum-minimum height difference (MM), (e) correlation  
940 function (COR), (f) RMS correlation function (RMS-COR), (g) Fourier power spectrum  
941 (FPS), (h) Wavelet power spectrum (WPS). For each method, except the RMS-COR function,



942 two plots are represented: the upper plot shows the difference between the noise-free surface  
943 and the altered surfaces in the direction of the largest exponent and the lower one in direction  
944 of the smallest exponent. For the RMS-COR technique, the upper plot represents the  
945 difference between the noise-free and the altered surface in both directions: perpendicular and  
946 parallel to striations. The lower subplot displays two polar plot of  $H$  obtained with the noise-  
947 free and the biased surfaces. Note that the flattening of the scaling behavior at large scales is  
948 related to a finite size effect.

949

950 **Figure 8.** Influence of the interpolation of missing data on the estimation of the Hurst  
951 exponent. (a) Synthetic surface (513x513points) with  $H = 0.8$ . (b) Same surface with 5% of  
952 holes (white dashed lines) that have been interpolated. (c) 3D view of the surface in a) with the  
953 holes. (d) RMS correlation function (RMS-COR), (e) Fourier power spectrum (FPS), (f)  
954 Wavelet power spectrum (WPS). The different curves on each plot present the result of the  
955 analysis for five different percentages of missing points (5%, 10%, 20%, 40%).

956

957 **Figure 9.** 3D scanner data of the Magnola fault slip surface at different scales. (a) Photograph  
958 of the fault surface, showing significant weathering and covering by vegetation. The black  
959 polygon corresponds to the surface shown below. (b) Digital Elevation Model (DEM) of the  
960 surface A32 (Table 2). The LIDAR data contain 799,830 points, sampled on a roughly regular  
961 grid of  $\sim 40 \times \sim 40$  mm. The measurements were performed on a  $\sim 20 \times \sim 20$  mm grid and then  
962 averaged on a coarser grid. The resolution of the elevation is 20 mm. The fault surface shows  
963 elongated bumps (red) and depressions (blue), dipping at approximately  $85^\circ$ , and indicating a  
964 main normal slip motion. The corrugation, with maximum amplitude of around 2.2 m, can be  
965 observed at all scales down to the measurement resolution. (c) DEM of hand sample M2  
966 (Table 2) that contains  $3999 \times 3120$  points on a regular mesh of  $20 \times 20 \mu\text{m}^2$ . The surface

967 contains grooves (blue) and ridges (red) aligned parallel to slip and with maximum amplitude  
968 of around 1.2 mm.

969

970 **Figure 10.** 3D data of the Vuache fault slip surface at all scales. (a) Photograph of the  
971 outcrop, where the white boxes correspond to the surfaces shown in (c) and (d). (b) Lateral  
972 photograph of the slip plane that highlights its remarkable waviness. (c-d) Fault surface  
973 topography of SURF1 and SURF6 (Table 2). Each surface contains approximately 450,000  
974 points sampled on a constant grid of 20 x 20 mm. The resolution of the elevation is 10.2 mm  
975 for (c) and 4.5 mm for (d), respectively. The surfaces show large elongated bumps (red) and  
976 depressions (blue) with maximum amplitude of around 2 m associated with linear striations of  
977 smaller size (grooves and ridges). Both geometrical patterns dipping at 15-25° indicate a  
978 strike-slip motion with a small normal component. (e) DEM of the bumpy zone SURF-JPG  
979 (Table 2) that contains 107,606 points sampled on a regular grid of 1 x 1 mm. Note the  
980 vertical exaggeration. The resolution of the elevation is 0.9 mm. (f) DEM of the hand sample  
981 SMALL (Table 2) that contains 4099 x 3333 points on constant grid of 24 x 24  $\mu\text{m}^2$ . The  
982 resolution of the elevation is less than one micrometer. The scans clearly show a smoothing of  
983 the roughness from large to small scales. Large fault surface measured on the field have  
984 asperities over the entire range of observed scales down to the measurement resolution.  
985 Conversely, the laboratory data show that the surface below the centimeter scale appears more  
986 polished and only smooth decimeter ridges persist.

987

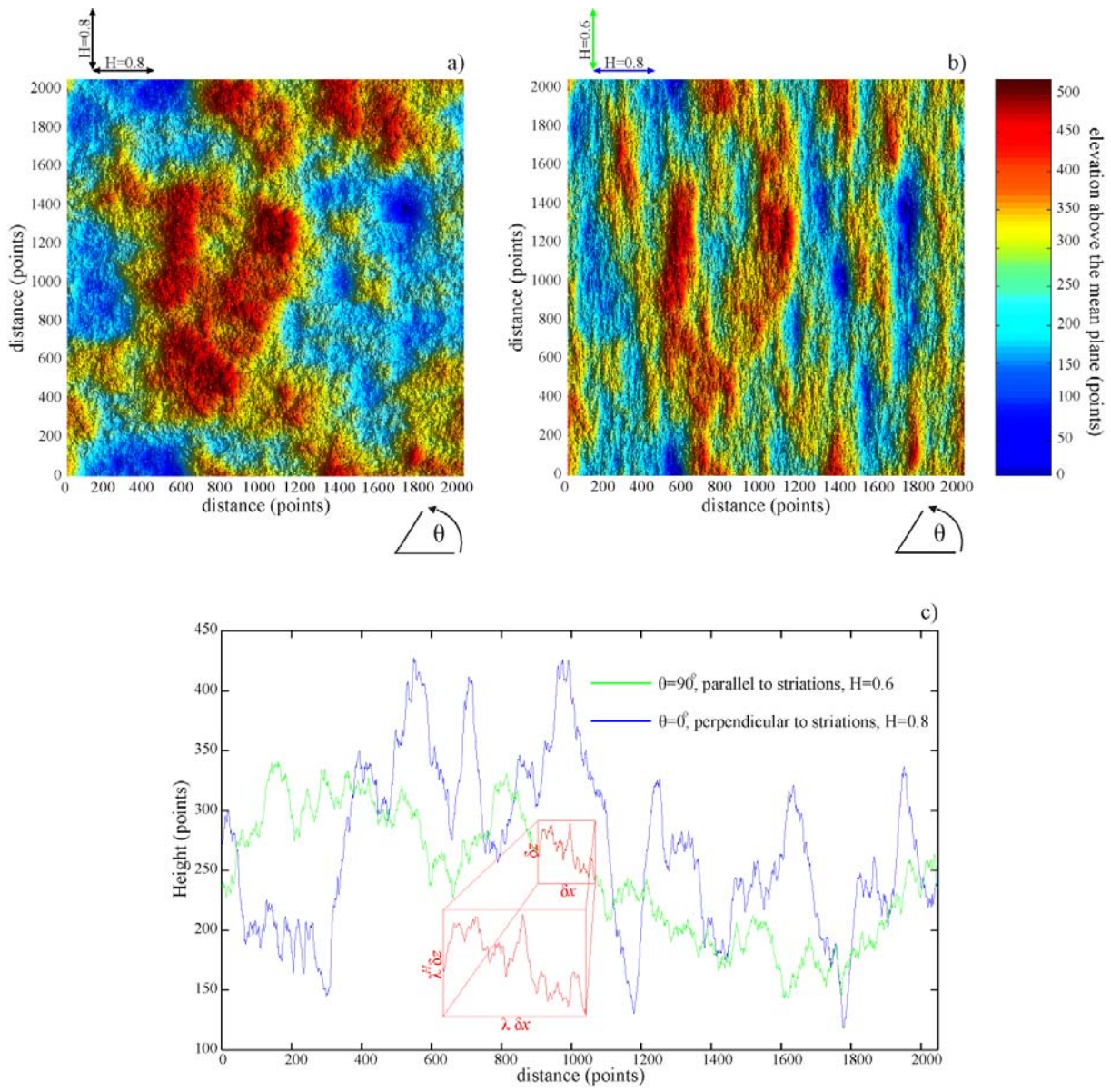
988 **Figure 11.** Roughness scaling analysis from the best preserved outcrops of the Magnola fault  
989 plane, scanned using ground based LIDAR (surface A32, Figure 9b), or using the laboratory  
990 profilometer (hand sample M2, Figure 9c). (a-b) Fourier Power Spectrum (FPS), and (c-d)  
991 Wavelet power spectrum (WPS) along two directions, parallel and perpendicular to the

992 direction of slip, are represented in log-log plots. Power-law fits (black dotted line) are  
993 performed for each curve and the corresponding slopes ( $\beta$ ) and roughness exponents ( $H$ ) are  
994 indicated above the spectra. The inset displays an example of the amplitude ( $Z$ ) and the  
995 wavelength ( $\lambda$ ) of a rough profile. Contours (red lines) of constant amplitude ( $Z$ ) to  
996 wavelength ( $\lambda$ ) ratio, reflecting a self-similar behavior, are provided to allow easier  
997 interpretation of the spectra. Black arrows indicate the level of noise of the LIDAR. (e)  
998 Surface anisotropy revealed by the angular variation of the Hurst exponent determined by the  
999 RMS correlation function method. The polar plot of  $H$  on the left and the right sides  
1000 correspond to data of the field surface and hand sample shown on [Figure 9](#), respectively.

1001  
1002 **Figure 12.** Roughness scaling analysis from five surfaces ([Figure 10](#), [Table 2](#)) of the Vuache  
1003 fault, covering 6 orders of magnitude of frequencies or wavelengths (40  $\mu\text{m}$  to approximately  
1004 40 m). The data collected contain four surfaces (blue and green curves) that have been  
1005 scanned using LIDAR and one hand sample (magenta curve) measured by laboratory  
1006 profilometer. (a-b) Fourier power spectrum (FPS) and (c-d) Wavelet power spectrum (WPS)  
1007 along two directions, parallel and perpendicular to the direction of slip, are represented in log-  
1008 log plots. Power law fits (black dotted line) are shown for each curve and the corresponding  
1009 slopes ( $\beta$ ) and roughness exponents ( $H$ ) are indicated next to the spectra. Each curve is an  
1010 average over a series of parallel profiles extracted from the DEM shown on [Figure 10](#). The  
1011 level of noise for the Lidar scanners is estimated as the height of the flat part of the spectrum  
1012 at small length scales and is indicated by the black arrows. The flattening of the scaling  
1013 behavior at large scales is related to a finite size effect. Contours (red lines) of constant  
1014 amplitude ( $Z$ ) to wavelength ( $\lambda$ ) ratio, reflecting a self similar surface, are also indicated a  
1015 guide for the eye. The inset displays an example of the amplitude ( $Z$ ) and the wavelength  
1016 ( $\lambda$ ) of a rough profile. (e) Roughness anisotropy revealed by the angular variation of the

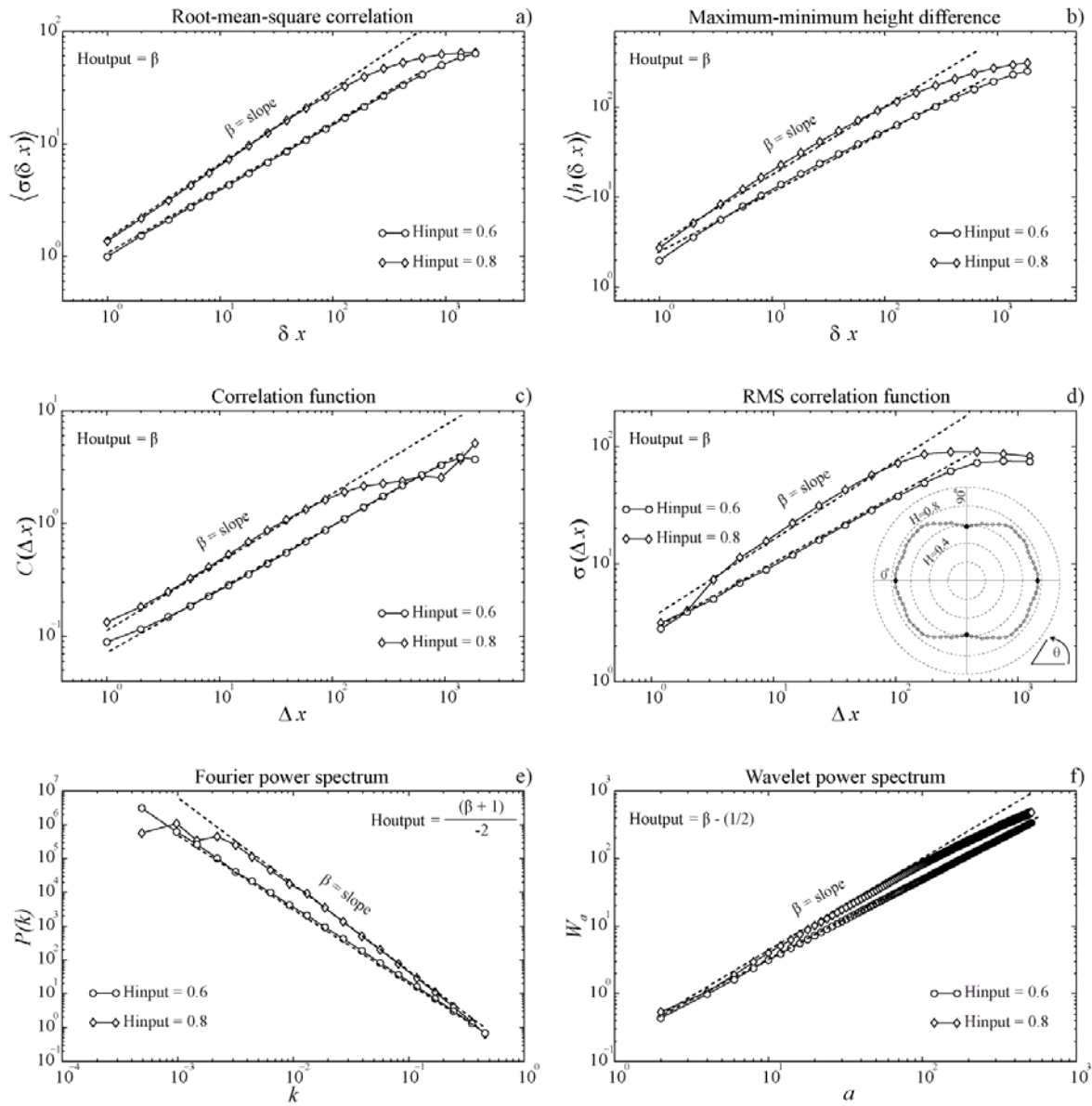
1017 Hurst exponent determined by the RMS-COR method. The polar plots of  $H$  on the left, in the  
1018 center and on the right correspond to data of the field surface, the intermediate scale section  
1019 and hand sample, respectively (see [Figure 10](#)).

1020



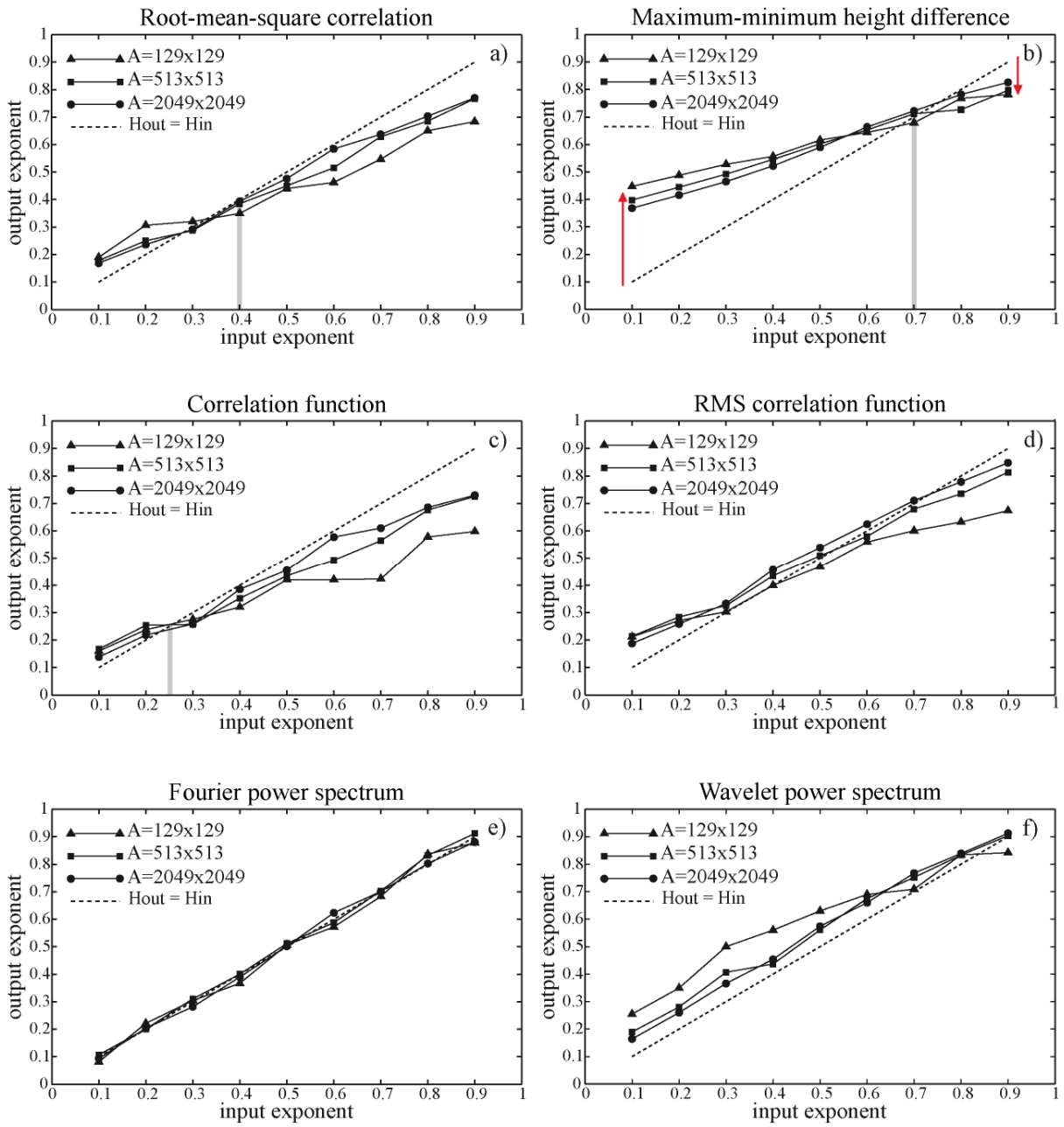
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1022 **Figure 1.**



1023

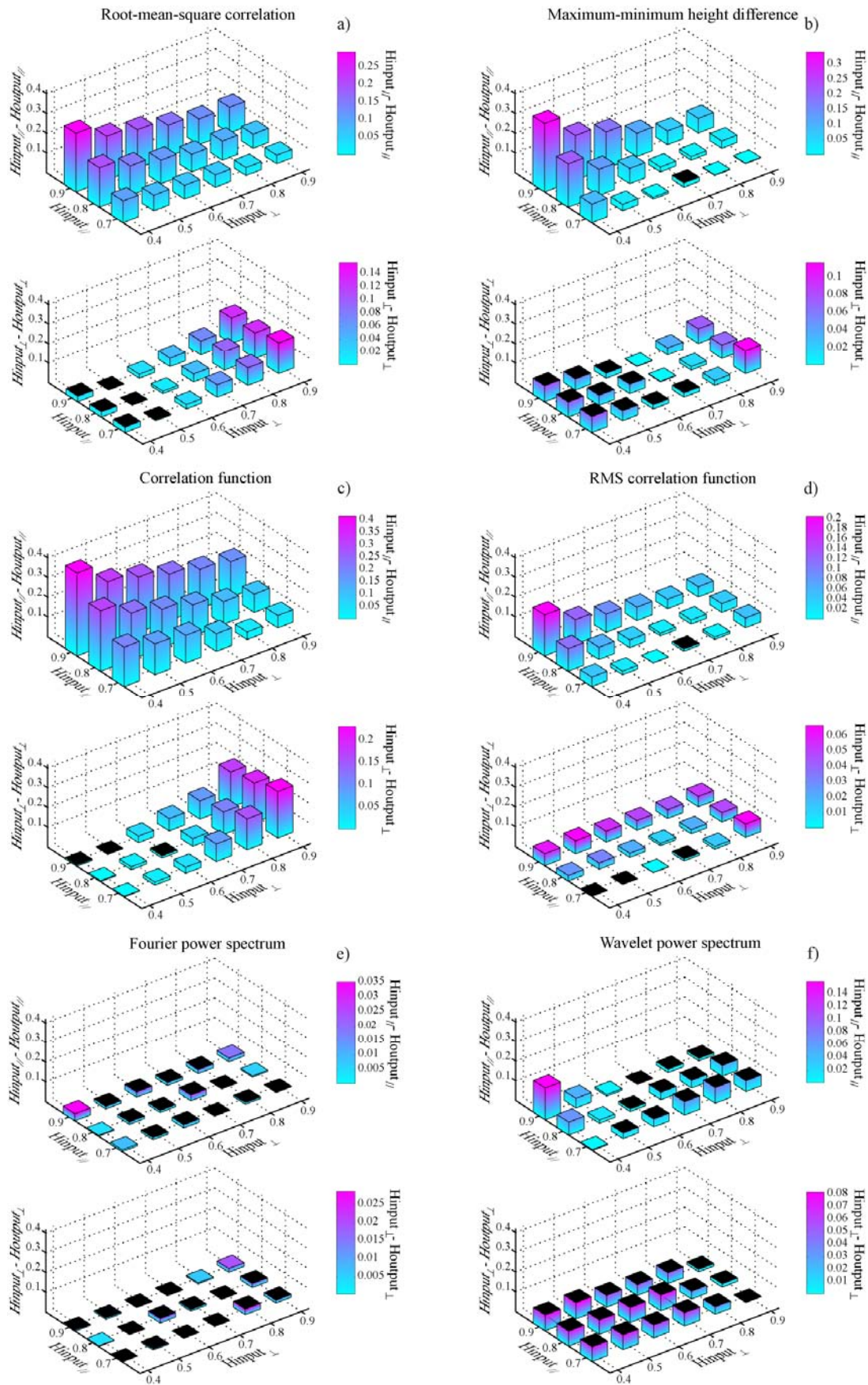
1024 **Figure 2.**



1025

1026 **Figure 3.**

1027

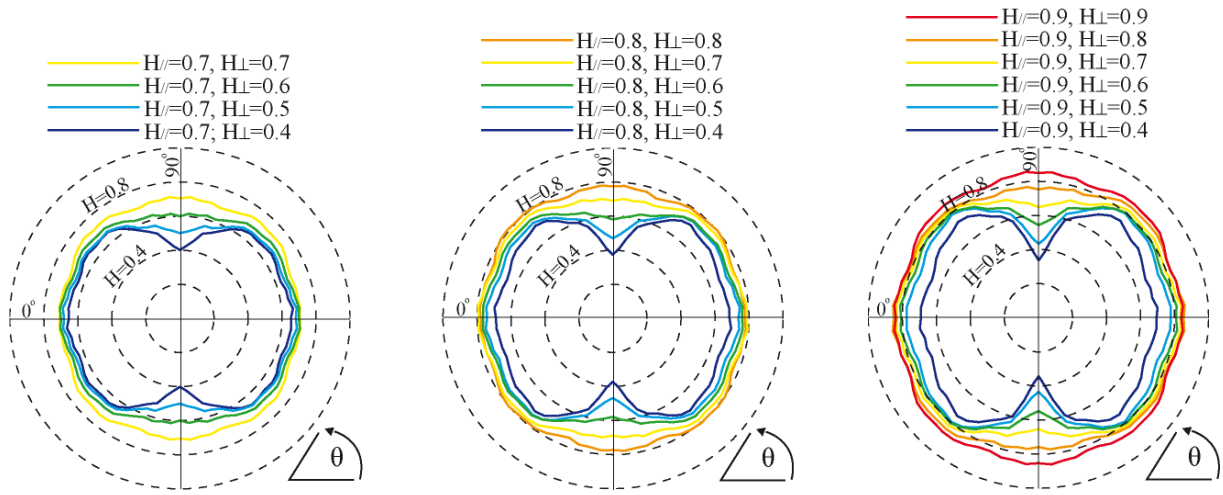


1028

1029 **Figure 4.**

1030

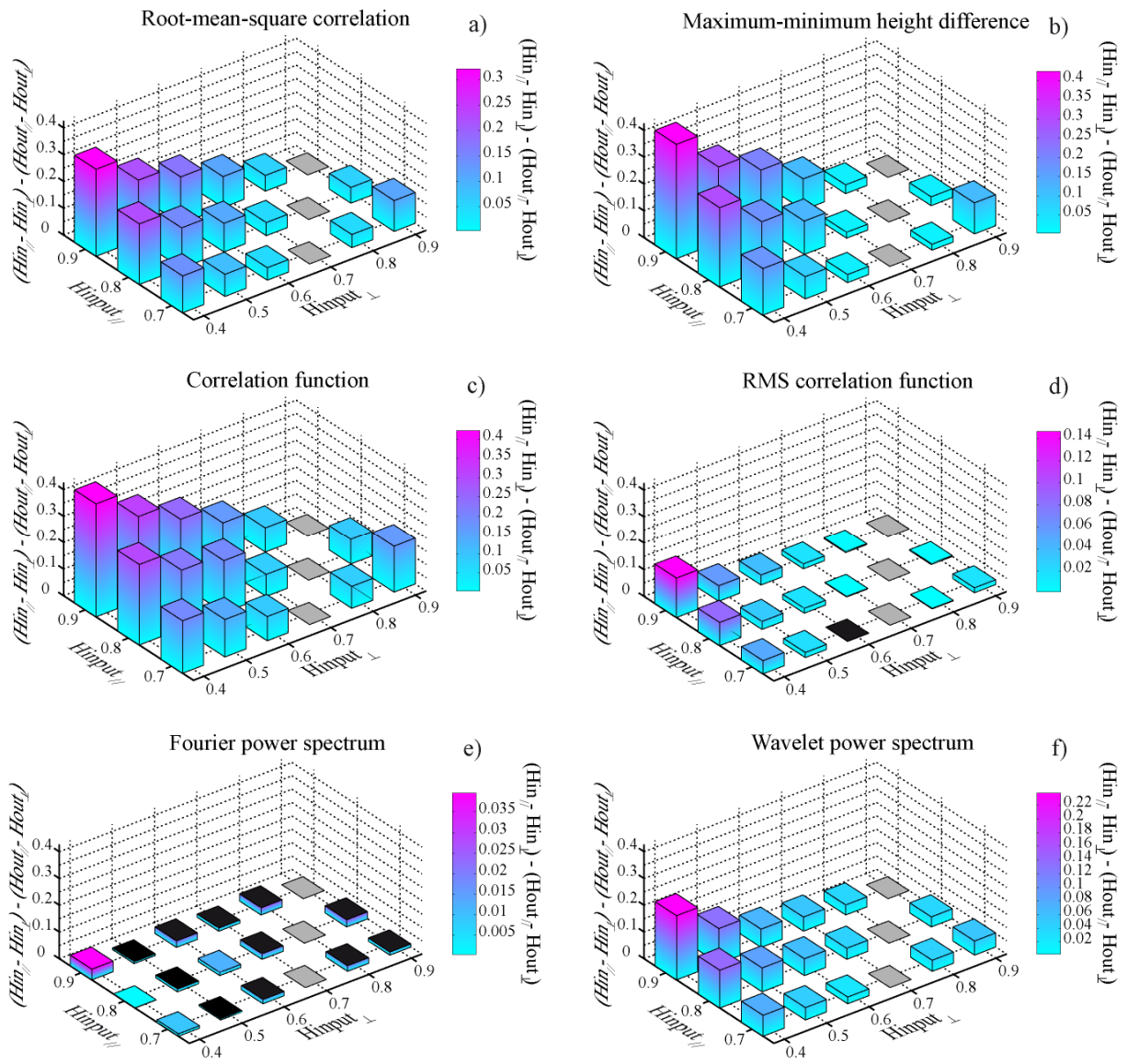




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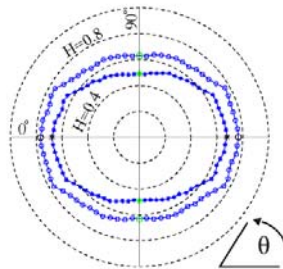
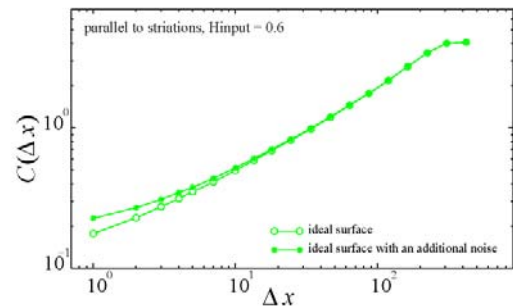
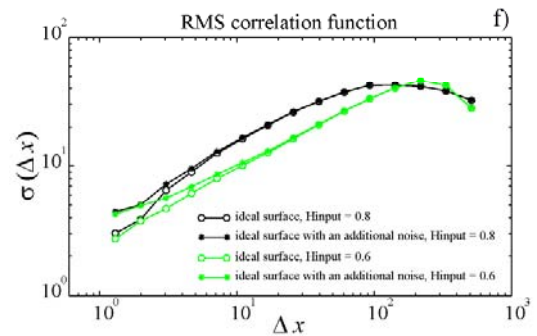
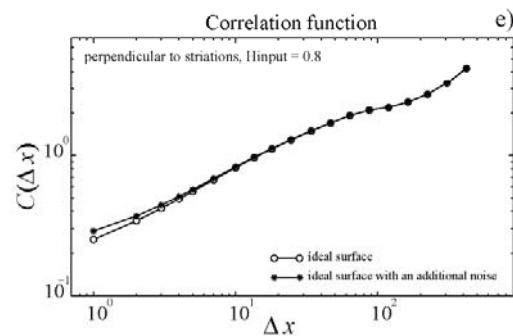
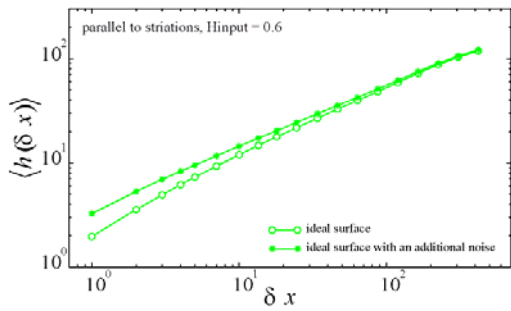
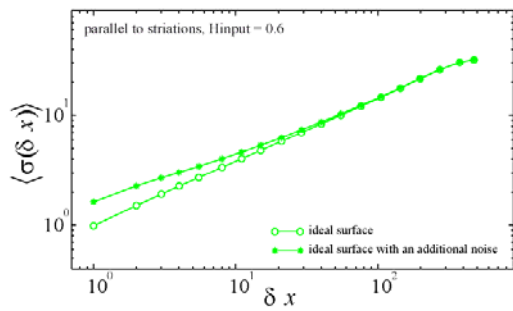
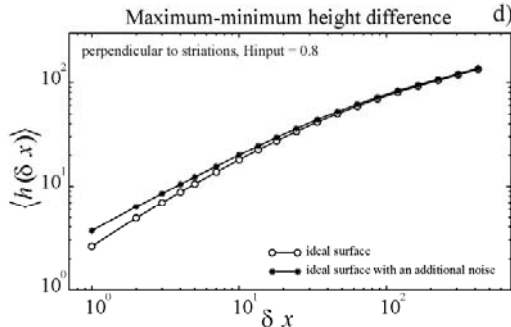
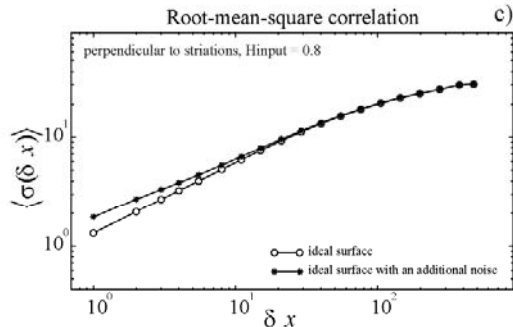
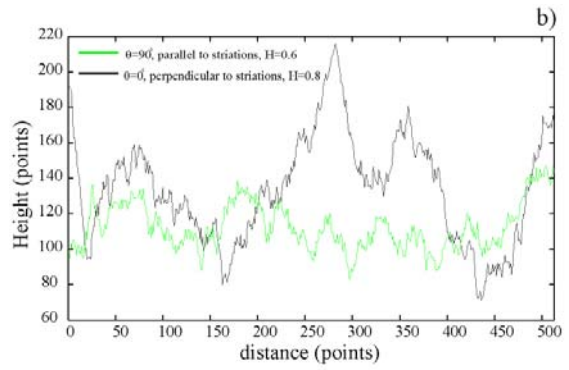
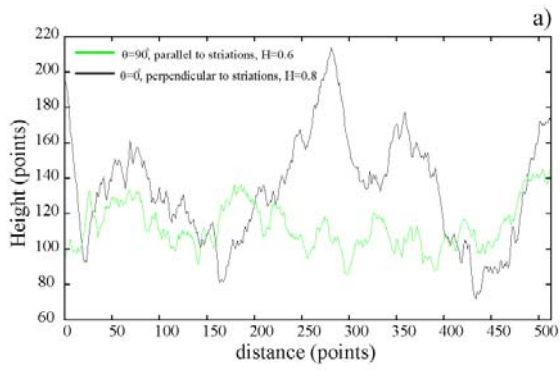
1032 **Figure 5.**

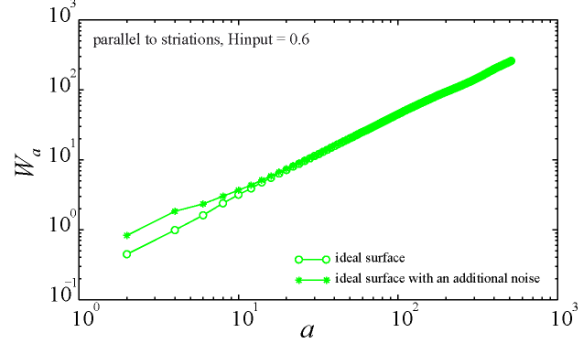
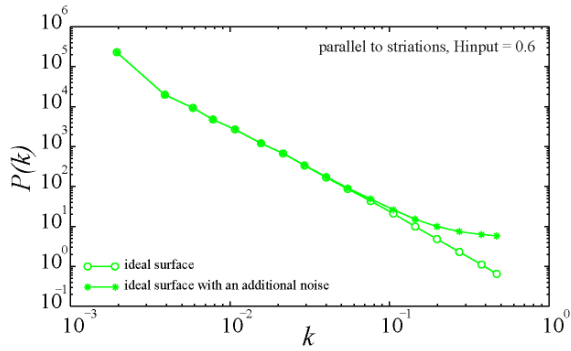
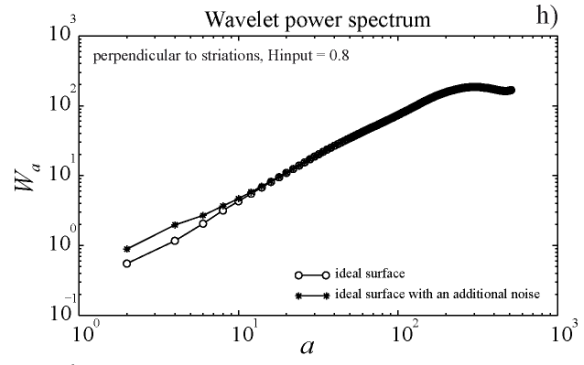
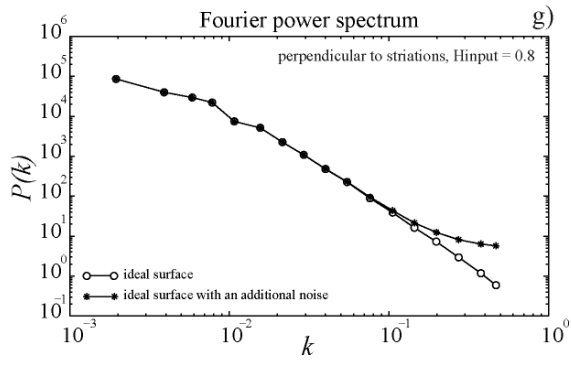
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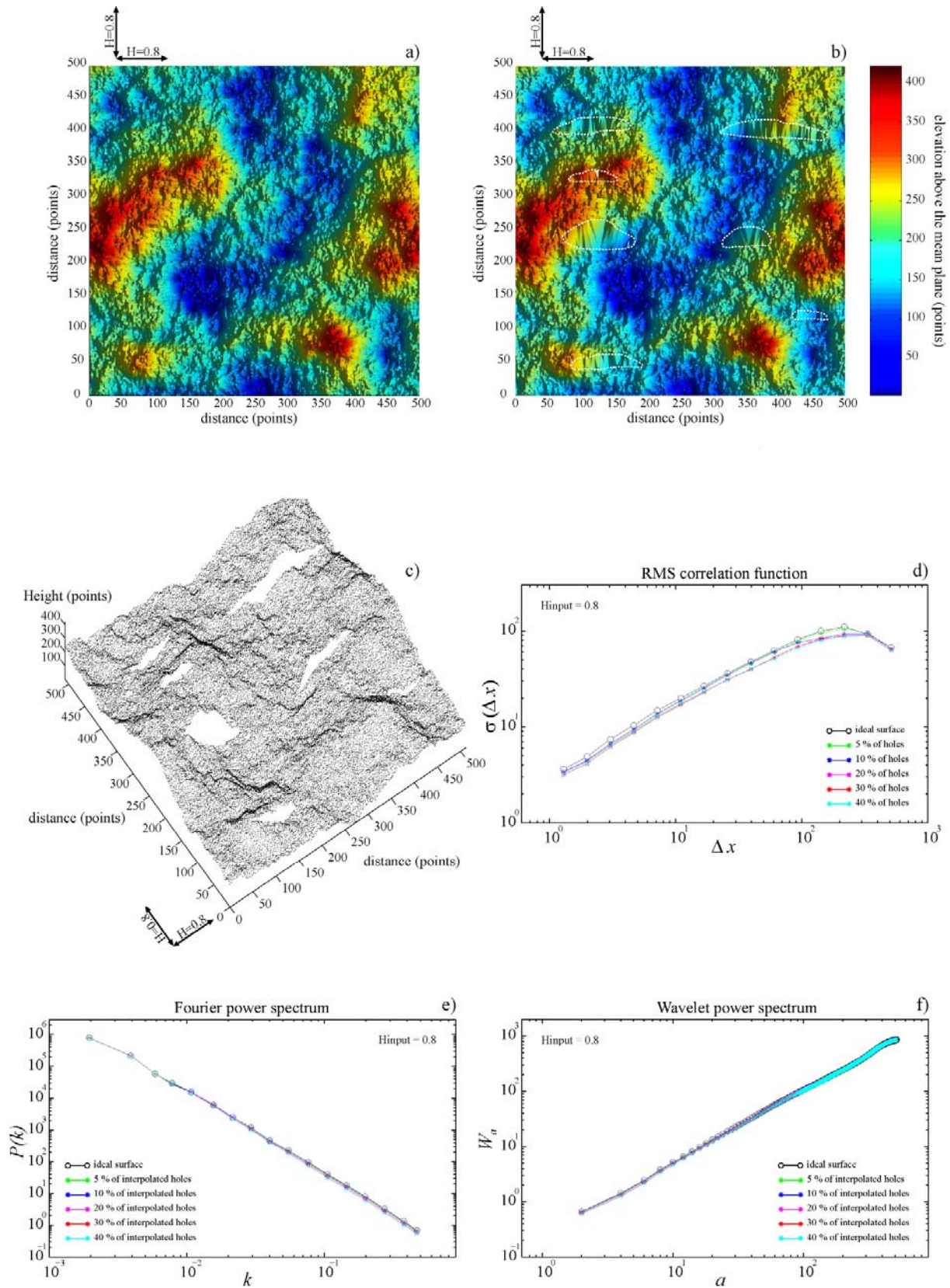
1035 **Figure 6.**





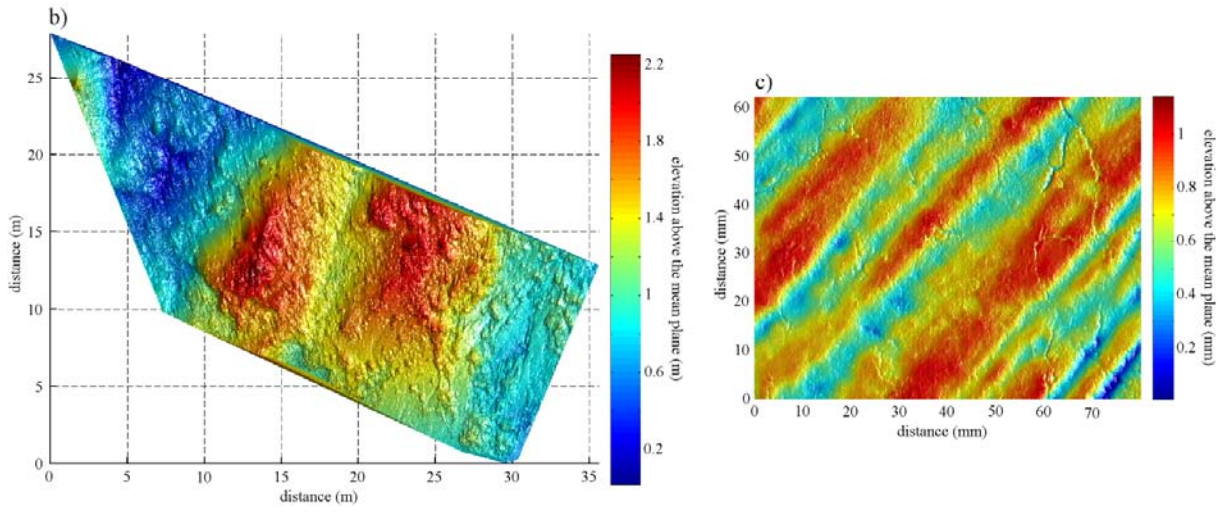
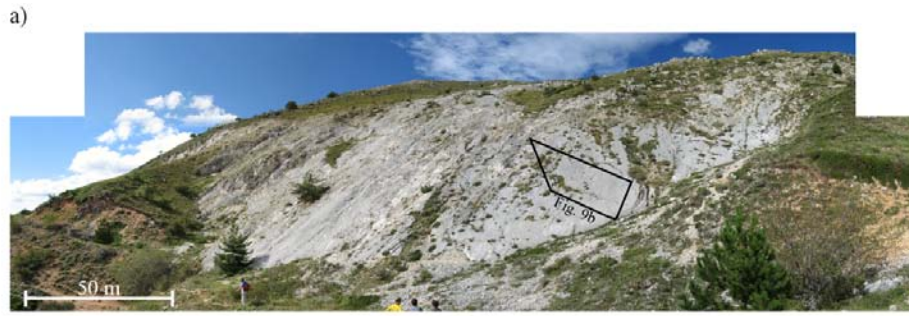
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1038 **Figure 7.**



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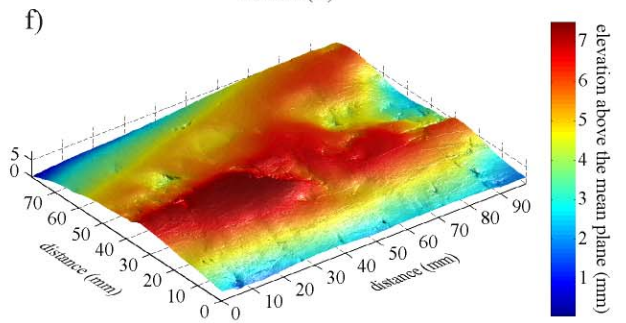
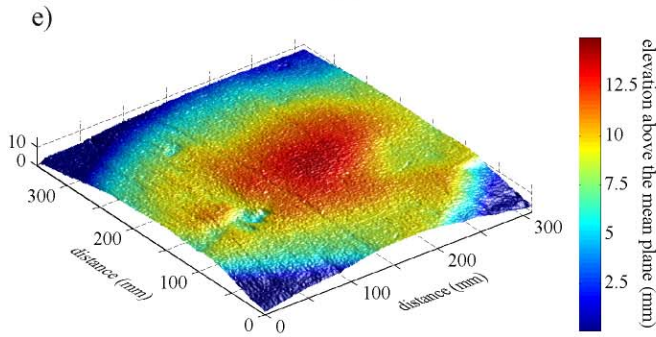
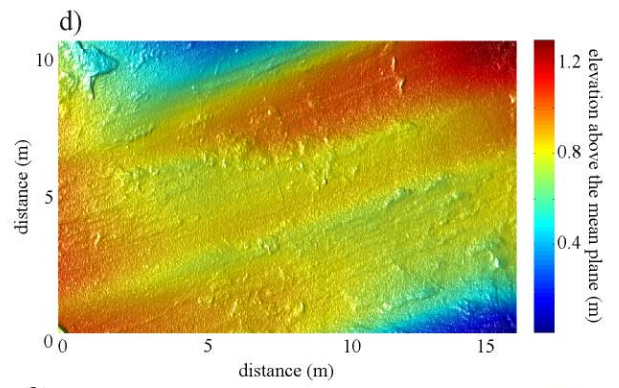
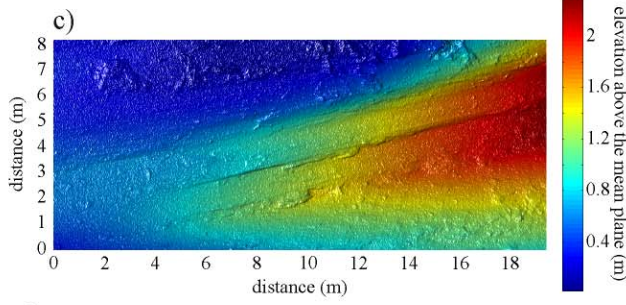
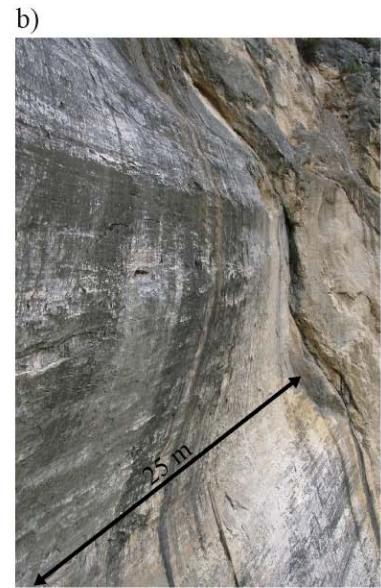
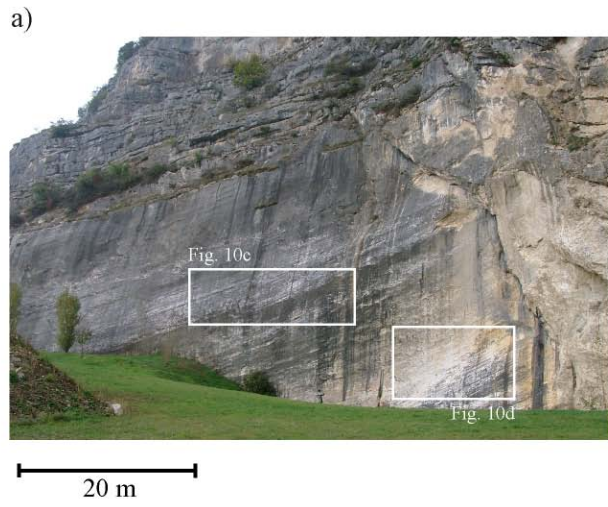
1040 **Figure 8.**



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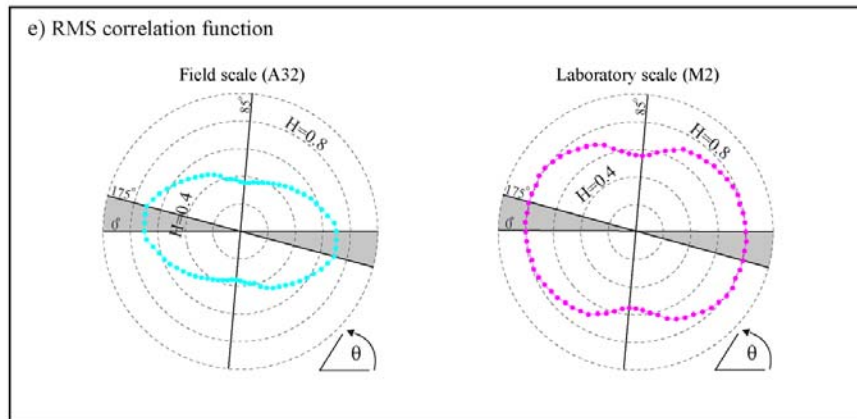
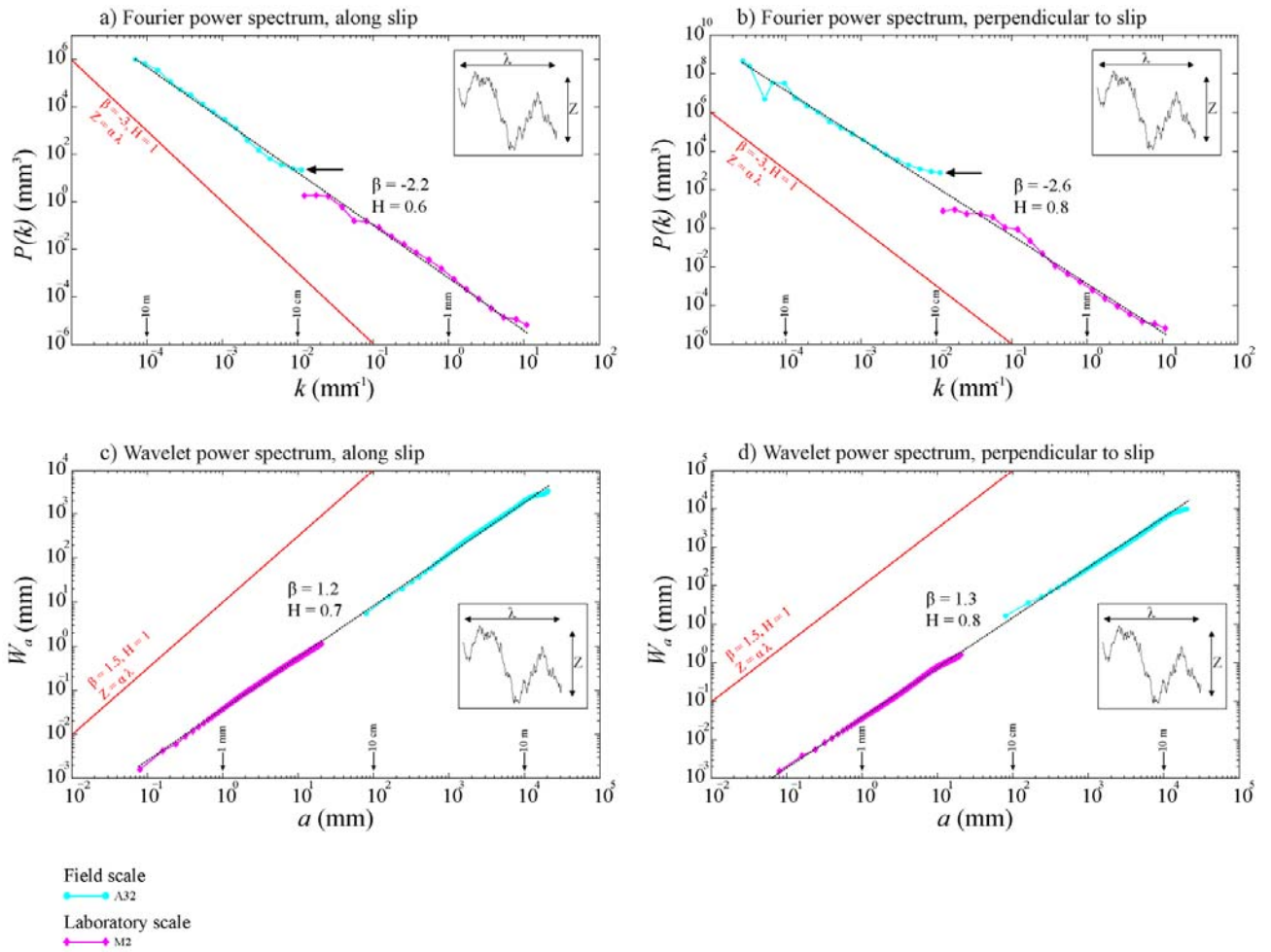
1042 **Figure 9.**

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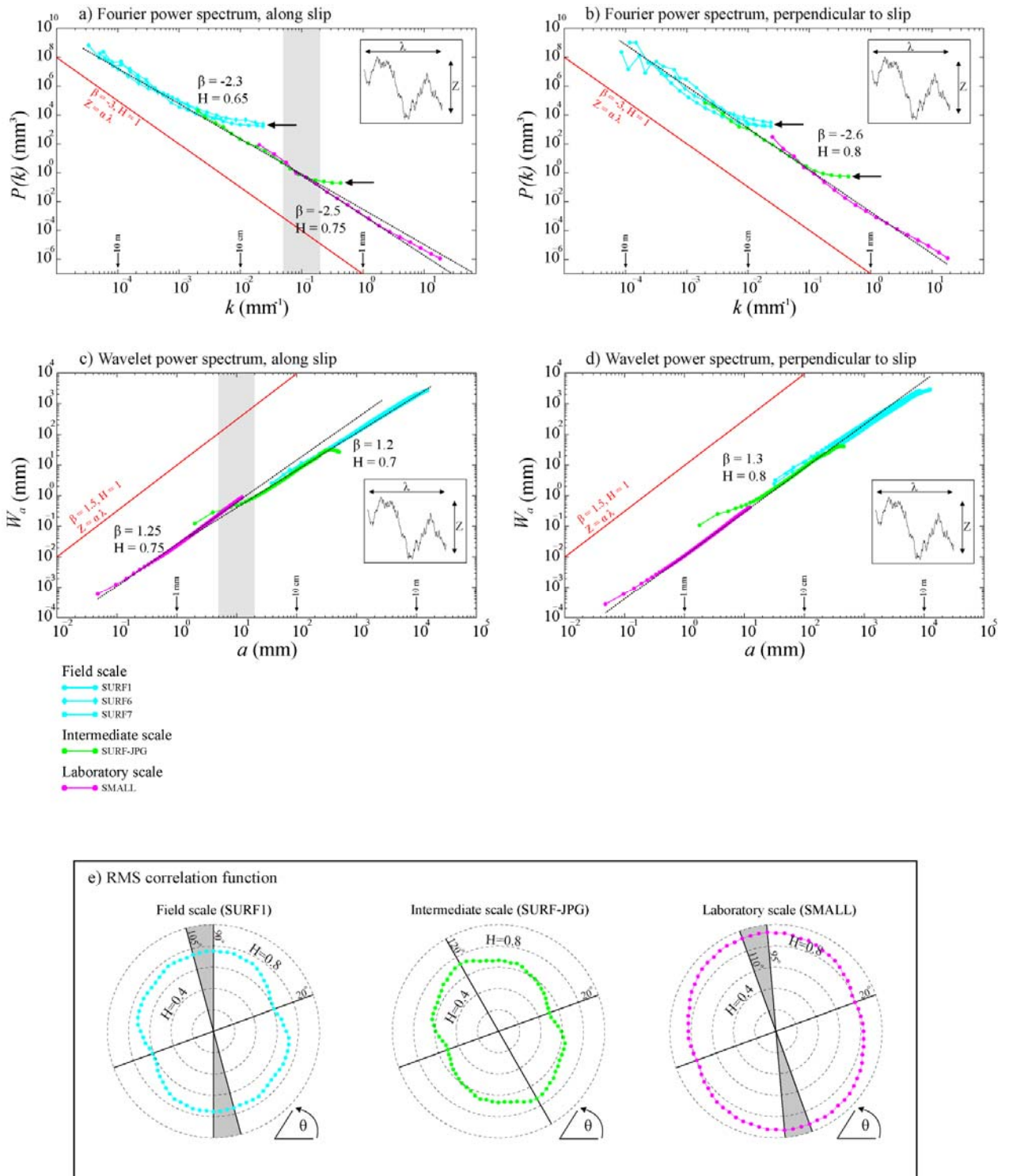
1046 **Figure 10.**



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1048 **Figure 11.**





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1050 **Figure 12.**