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1 **Bedrock fault roughness resolves slip increments of large earthquakes, case studies**
2 **from Central Italy**

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35 **Abstract**

36 While the cyclic nature of tectonic strain build-up and release is at least conceptually
37 well understood (known as the earthquake cycle), it is not clear how variable the corresponding
38 earthquake sizes and the time intervals between them are. Additional observations from past
39 earthquakes are required to better constrain these aspects.

40 In this context, we investigate the roughness of bedrock normal fault scarps along the
41 Mt. Vettore fault and Roccapreturo fault (Italy), motivated by field observations that roughness
42 positively correlates with profile height: higher sections of the fault surface are rougher than
43 lower sections, ostensibly because the scarps were created by subsequent exposure events (e.g.,
44 earthquakes), exposing the higher sections for longer periods of time to subaerial weathering
45 processes. Using high-resolution topographic models of the two fault surfaces, we calculate
46 local roughness metrics and determine how they change as a function of profile height. In doing
47 so, we are able to identify step-like changes in fault roughness, suggesting that the studied
48 portions of the Mt. Vettore and Roccapreturo fault scarps were formed respectively by at least
49 6 and 4 large earthquakes, with slip increments ranging from 0.2 m to 1.7 m and corresponding
50 magnitudes ranging from **M6.1** to **M6.8**. Comparing our results for the Roccapreturo scarp
51 with a previous cosmogenic radionuclide (CRN) investigation at this site indicates that we were
52 able to a) find previously identified earthquakes and b) find additional, previously unresolved
53 ones. Apparently, fault surface roughness may increase at a higher rate than CRNs accumulate
54 over the same time, providing additional fidelity to resolve a bedrock scarp's exposure history.

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66 **Introduction**

67 One of the main goals of the active tectonics community is to better resolve the details
68 of the earthquake cycle, which to first order comprises alternating phases of interseismic strain
69 accumulation and coseismic strain release (e.g., Reid, 1910; McCalpin, 2009; Scholz, 2019).
70 Respective studies aim, for example, to determine a fault’s geologic slip-rate (variation) and
71 investigate the recurrence of earthquakes that release interseismically accumulated strain, using
72 the tools from paleoseismology and tectonic geomorphology (with augmenting insights from
73 historical accounts of earthquake occurrence and instrumental recordings of the earthquake
74 cycle, as provided by seismic and geodetic data). Paleoseismic studies typically analyze
75 deformed stratigraphic units, exposed via trench excavations, to constrain the time and size of
76 past earthquakes at a specific site along a fault (e.g., Sieh et al., 1989; Grant et al., 1994; Weldon
77 et al., 2004; Zielke and Strecker, 2009; Akciz et al., 2010; Scharer et al., 2014). Tectono-
78 geomorphic studies, on the other hand, commonly analyze tectonically displaced or deformed
79 landforms, such as alluvial fans, river terraces, or channel beds, to constrain a fault’s slip-rate
80 and its slip accumulation pattern along larger stretches of a fault (e.g., Wallace, 1968; Sieh,
81 1978; McCalpin, 2009; Zielke et al., 2010; Klinger et al., 2011). Utilizing these kinds of
82 approaches, a set of end-member models for earthquake recurrence and along-fault slip
83 accumulation was postulated (e.g., Shimazaki and Nakata, 1980; Schwartz and Coppersmith,
84 1984; Youngs and Coppersmith, 1985; Sieh, 1996) and finds application in seismic hazard
85 assessment. Since then, numerous studies extended on this work and used fault slip and age
86 data, spanning many different time scales (from a few thousands to millions of years), to
87 produce fault growth and earthquake recurrence models that reconcile fault slip accumulation
88 over a range of time scales (e.g., Friedrich et al., 2003; Nicol et al., 2005; Mouslopoulou et al.,
89 2009; Carafa et al., 2022).

90 While paleoseismic and tectono-geomorphic techniques dominate the tool set that is
91 used to constrain the details of the earthquake cycle, other techniques exist. For example,
92 measuring the concentration of cosmogenic radionuclides (CRNs) along the free face of
93 bedrock fault scarps (for convenience, we will refer to “free faces of bedrock fault scarps” as
94 “fault surfaces” for the remainder of this text) may indicate the time and size of the scarp-
95 forming earthquakes. So far, this approach has been mainly applied on limestone bedrock
96 normal fault scarps, based on the observation that Ca produced ^{36}Cl , an unstable cosmogenic

97 nuclide, when exposed to cosmic radiation. The concentration of these CRNs is, among other
 98 factors, a function of exposure intensity and time (e.g., Dunai, 2010; Schimmelpfennig et al.,
 99 2009). Distinct changes in the ^{36}Cl concentration along a fault surface's height may therefore
 100 indicate the occurrence of subsequent earthquakes (Fig. 1; e.g., Schlagenhauf et al., 2010;
 101 Benedetti et al., 2013; Ren et al., 2018, Tesson and Benedetti, 2019). Another relative dating
 102 technique that is aimed at identifying the number of paleoearthquakes on limestone fault
 103 surfaces is the REE method. This method measures changes in the geochemistry across a fault
 104 surface (identifying the depletion and enrichment of certain elements due to fault surface
 105 exhumation and erosion; e.g., Manighetti et al., 2010; Mouslopoulou et al., 2011, 2012).
 106 Additional insight is provided by the Schmidt hammer method (Tye and Stahl, 2018; Stahl and
 107 Tye, 2020), revealing weathering contrasts in limestone fault scarps via its rebound values (R-
 108 values).
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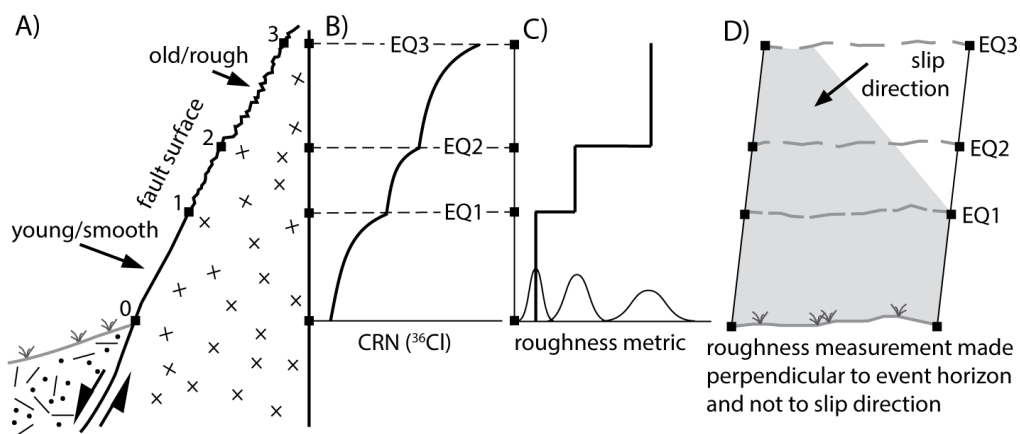


Figure 1. Schematic representation of a normal fault surface, highlighting its roughness and cosmogenic radionuclide CRN concentration as a function of profile height. A) Qualitative observations find that fault surface roughness increases with height. Numbered squares show the height of paleo-earthquake event horizons, indicating where the ground surface of the hanging wall (gray line) touched the footwall at the time of an earthquake. B) CRN concentration profiles may exhibit distinct breaks, indicative for individual exposure events (e.g., earthquakes). C) Similarly, distinct step-like changes in surface roughness along a scarp profile may indicate exposure events. Bell-shaped curves represent the histogram of roughness observations. D) Note that roughness measurements (like CRN measurements) are taken perpendicular to event horizons (indicated by sub-horizontal dashed lines) and not perpendicular to slip direction (black arrow). Doing the latter would mean to mix fault surfaces with different exposure age if the slip vector is distinctly oblique (gray area indicates this for EQ1).

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111 In the present study, we also aim to identify abrupt changes in fault surface exposure
112 time and hence to identify the occurrence of past earthquakes (i.e., their slip increments) along
113 bedrock fault scarps. The approach is motivated by qualitative field observations indicating
114 that fault surface roughness (of exposed normal fault scarps) changes systematically with scarp
115 height. For example, fault surfaces along the Mt. Vettore fault (central Italy) are rougher at
116 higher portions of the fault scarp, relative to its lower portions (Fig. 1A). Similar observations
117 were made previously along various faults and quantitatively documented, utilizing lidar or
118 image-based approaches to measure a fault scarp's surface roughness (e.g., Giaccio et al., 2002;
119 Reicherter et al., 2011; Wei et al., 2013; Bubeck et al., 2015; He et al., 2016; Mechernich et
120 al., 2018; Zou et al., 2020; Corradetti et al., 2021).

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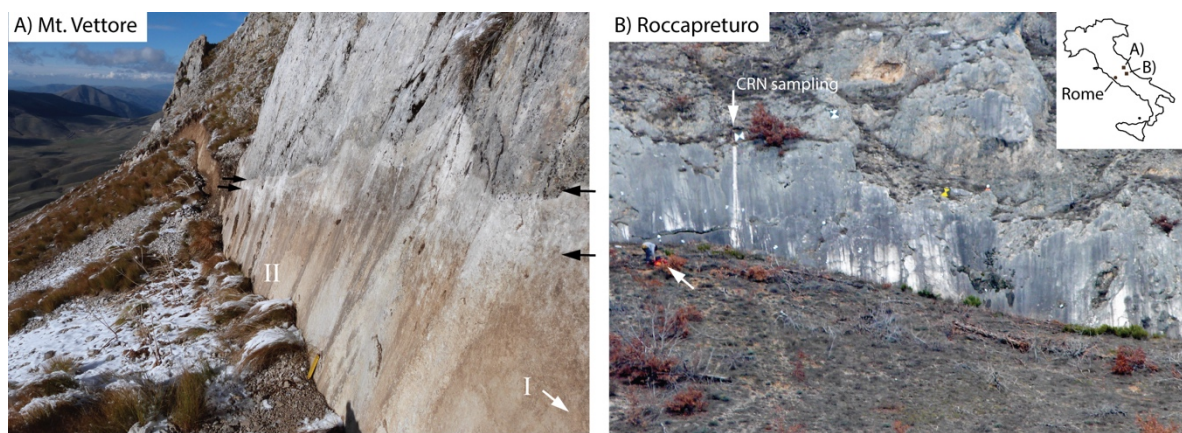


Figure 2. Photographs of the two analyzed fault scarps. A) Imaged here is part II of the Mt. Vettore fault scarp (see Methods section) while part I is located a few meters further to the south (white arrow). Distinct color changes along the scarp (black arrows) reveal the event horizons and hence slip increments of the two most recent earthquakes (August and October 2016, ~0.2 m and ~1.2 m respectively). B) A 10-m long profile was analyzed at the Roccapreturo site for CRN concentrations to determine the age and slip of the scarp-forming earthquakes by Schlagenhauf (2009; white downward-pointing arrow shows sample location). A person is shown for scale in the center left of the image (white arrow). Inset map indicates the location of both study sites with respect to the Italian peninsula and its capital, Rome.

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123 A causal relationship between fault surface roughness and surface age is intuitively plausible,
124 considering that the fault surface is exposed to persistent physical and chemical weathering.
125 The underlying assumption of our study is therefore that prolonged exposure to (subaerial)
126 weathering processes increases the roughness of a fault surface (Fig. 1). Further assuming that

127 roughness was initially homogeneous across the fault surface may enable us to correlate step-
128 like changes in fault surface roughness to discrete exposure events (e.g., Coradetti et al., 2021).
129 That is, if an initially homogeneously rough fault surface is getting exposed sequentially (e.g.,
130 due to the occurrence of subsequent earthquakes), then we may find distinct changes in fault
131 roughness perpendicular to the (paleo-) ground surface if a) a sufficient amount of time has
132 passed between subsequent earthquakes to create measurable changes in fault surface
133 roughness, and b) a sufficient amount of slip has occurred during individual earthquakes to
134 produce consistent roughness values along continuous portions of the fault surface (Fig. 1).
135 The assumption of initially homogenous roughness across the fault surface is supported for the
136 Mt. Vettore site, where the newly-exposed fault surface (exposed by the 2016 earthquakes) is
137 indeed homogeneously rough, without apparent systematic roughness changes. It is further
138 supported by lithological observations, indicating that the exposed fault surface spans a
139 micritic, compact, and homogeneous Jurassic limestone without observable varying lithologic
140 character (e.g., Pierantoni et al. 2013). Similar observations are made for the Roccapreturo site,
141 where Cretaceous limestone is exposed.

142 Based on this understanding, we analyze the roughness of bedrock fault surfaces along
143 the Monte Vettore fault and Roccapreturo fault (Fig. 2) to resolve the slip increments of past
144 earthquakes (e.g., Wei et al., 2013; He et al., 2016; Zou et al., 2020). Both faults feature sites
145 with well-developed limestone fault scarps –some of which investigated previously, therefore
146 providing a contextual framework for our own investigation (e.g., Giaccio et al., 2003;
147 Schlagenhauf, 2009; Falcucci et al., 2015; Galli et al., 2019; Coradetti et al., 2021; Goodall et
148 al., 2021). The two faults are located in the central Apennines (Italy), a NW-trending, ~400 km
149 long and ~100 km wide mountain range that undergoes NE-SW extension at a rate of 3-4 mm/yr
150 (D’Agostino, 2014). Extension is accommodated by 10-30 km long normal faults (such as the
151 Mt. Vettore and Roccapreturo faults), arranged in several sub-parallel, segmented fault systems
152 that are located along the ridge belt (Galadini and Galli, 2000; Vai and Martini, 2013). This
153 belt has been the host to many destructive earthquakes over the last millennium (Rovida et al.,
154 2021). The most recent earthquake episode occurred in 2016, when 9 successive shocks (**M**5
155 to **M**6.5) ruptured several portions of a ~60 km long fault system in less than half a year (e.g.,
156 Perouse et al., 2018 and references there in). Prominent surface ruptures, with maximum throws
157 of 80 to 130 cm, were observed along the Mt. Vettore fault after the largest shock of the

158 sequence (M6.5) occurred on 30th October 2016 (Civico et al., 2018). Our first study site is
159 located on this fault, near a place called Scoglio del'Aquila, where the 2016 coseismic surface
160 displacement reached its maximum and where the fault surface (i.e., bedrock fault scarp) is
161 particularly well expressed (Fig. 2A). Paleoseismic studies at other locations along the Mt.
162 Vettore fault system revealed that six surface faulting events (including the most recent ones
163 in 2016) occurred within the past 9 kyrs, with an average return period of 1.8 ± 0.3 kyr
164 (Galadini and Galli, 2003; Galli et al., 2019). To our knowledge, no incremental slip amount
165 has been attributed to the individual earthquakes, preceding the most recent one(s).

166 The second study site is located along the Roccapreturo fault. This fault belongs to the
167 Middle Aterno fault system, which is composed of several NW-SE trending, ~10-20 km long
168 faults (Galadini and Galli, 2000). A range of morphological features (e.g., triangular facets,
169 channel knickpoints, strong incision and alluvial fan development) along this fault segment
170 indicate the fault's long-term (10^4 - 10^5 yr) as well as recent (10^3 - 10^4 yr) tectonic activity. The
171 Quaternary activity of the Roccapreturo fault was shown also by Falcucci et al. (2015) who
172 found early-Pleistocene continental deposits on both sides of the fault, being offset by ~270m.
173 Falcucci et al., (2015) further found paleoseismic evidence for at least two surface rupturing
174 earthquakes since 3.9 to 7.5 kyrs ago, with an accumulated minimum offset of 0.3 m and 1.8
175 m. Additionally, a CRN investigation by Goodall et al. (2021) suggested that the most recent
176 earthquake occurred ~2.6 kyr ago, in agreement with the findings by Falcucci et al. (2015).
177 Following, we describe our data set and analysis approach before presenting our results.

178

179 **Methodology**

180 To quantitatively investigate roughness variations across a fault surface, we adopt the
181 structure-from-motion approach (e.g., Triggs et al., 1999; Lowe, 2004; Brown and Lowe, 2005;
182 Johnson et al., 2014; Corradetti et al., 2017), enabling us to generate very high-resolution
183 surface models by combining a large number of photographs that image the area of interest
184 from many different angles. In total, 271 photos were acquired in November 2016 for the Mt.
185 Vettore site (imaging two separate parts, I and II, of this fault surface) and 213 photos were
186 acquired in 2019 for the Roccapreturo site. Additionally, one portion of the Mt. Vettore fault
187 surface (part I) was also photographed in September 2016 (in-between the August and October
188 earthquakes, 143 photos) and in June 2018 (108 photos). The resulting point clouds, covering

189 areas of different sizes, contain more than 37 million data points (Mt. Vettore, part I, 11/2016),
 190 46 million data points (Mt. Vettore, part II, 11/2016), 6 million data points (Mt. Vettore, part
 191 I, 09/2016), 8 million data points (Mt. Vettore, part I, 06/2018), and 22 million data points
 192 (Roccapreturo, 2019). The Mt. Vettore data sets, acquired in November 2016, are publicly
 193 available at unavco.org.
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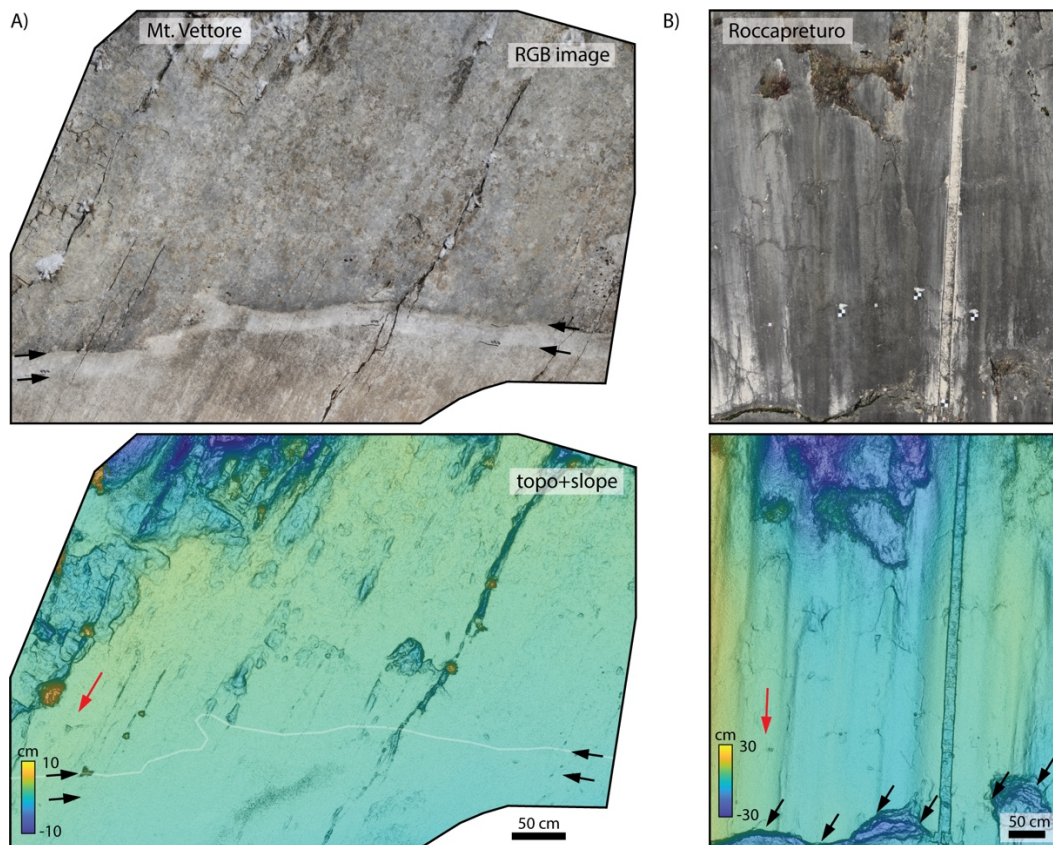


Figure 3. RGB images (top) and combined topography+slope plots (bottom, colors indicate height relative to regression plane) of the investigated fault scarps. Striations across both scarps provide a good indication of respective fault slip direction (red arrows). A) Black arrows indicate the two earthquake event horizons (i.e., the pre-earthquake contact line between hanging wall and footwall) of the August and October 2016 earthquakes. The event horizon of August 2016 earthquake is also shown in the bottom plot (white line). B) The nearly vertical, slot-like feature is due to CRN sampling from Schlagenhauf (2009). Note that the lower portion of the fault surface was dislodged (black arrows indicating trace). The ~1 m high, newly exposed fault surface below this trace is not included in the roughness analysis.

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196 We rotate the point clouds into local coordinate systems where the x-/y-/z-axis
197 correspond to the along-strike-/along-dip-/out-of-plane direction. Next, we linearly interpolate
198 the rotated point clouds to a grid, providing a uniformly spaced data set. We follow Hu et al.'s
199 (2003) suggestion regarding the recommended grid size s which is informed by the data set's
200 average observation point density in the area of interest (observations n per area A) and
201 calculated as $s = \sqrt{A/n}$. For all data sets, we have observation point densities in exceedance
202 of 80 cm^{-2} , indicating a permissible grid size of $\sim 1 \text{ mm}$ (Fig. 3).

203 To measure changes in fault surface roughness, we define a circle that is moved across
204 the fault surface in 0.5 cm steps in strike- and dip direction (Fig. 4A). We use circles of three
205 different sizes (2, 4, and 6 cm diameter) to ensure measurements consistency. For each step
206 that the circle is moved across the fault surface, we collect all data points that fall within the
207 circle. Hence, the 2-cm circle contains approximately 300 data points while the 4-cm and 6-cm
208 circles contain $\sim 1,200$ and $\sim 2,800$ data points respectively. Next, we perform a principal
209 component analysis on this circular subset to remove linear trends from its topography. This
210 step requires for the circle's dimension to be distinctly larger than the topographic signal of the
211 circular subset, indicating the existence of a lower limit for the circle's dimension, relative to
212 the surface's roughness. If this requirement is met, then the first and second principal
213 components define two in-plane coordinate axes, while the third principal component, being
214 perpendicular to the first two, defines the local, detrended topography z of the circular subset.

215 We measure the circle's roughness by calculating roughness metrics from topography
216 z . In correspondence to choosing different circle sizes, we use three different local roughness
217 metrics (namely the L_2 -norm, L_4 -norm, and the peak-to-valley method; Gadelmawla et al.,
218 2002; Santos and Julio, 2013) to ensure measurement consistency. The peak-to-valley P2V
219 roughness metric measures the absolute height difference between the highest and lowest point
220 (value of z) within the circular subset, normalized by the circle's diameter D (EQ1; e.g.,
221 Gadelmawla et al., 2002). The L_2 -norm refers to the common root-mean-square approach for
222 roughness quantification (EQ2; e.g., Power and Tullis, 1991; Santos and Julio, 2013). The L_4 -
223 norm (EQ3) differs from the L_2 -norm only in the power that is used, making the L_4 -norm in
224 principle more sensitive to outliers i.e., more sensitive to roughness variations (Menke, 2012).

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226
$$P2V = \frac{1}{D} (z_{max} - z_{min}) \quad (1)$$

227
$$L_2norm = \frac{1}{D} \sqrt{\frac{1}{N} \sum_{i=1}^N z_i^2} \quad (2)$$

228
$$L_4norm = \frac{1}{D} \sqrt[4]{\frac{1}{N} \sum_{i=1}^N z_i^4} \quad (3)$$

229

230 By moving the circle across the fault surface in small steps (0.5 cm), we typically
 231 generate hundreds of roughness measurements for each profile height. Given our assumption
 232 that subaerial weathering processes gradually increase fault surface roughness over time, we
 233 group the roughness measurements by profile height and then take a low-number percentile to
 234 represent the minimum fault roughness at that height (Fig. 4). As a result, we obtain low-
 235 roughness vs. height profiles (e.g., 1st and 5th percentile of L_4 -norm, Fig. 4B), smoothed with
 236 a causal (down-dip looking) moving average filter of 10-cm window size. The smoothed
 237 roughness profiles are then normalized to range from 0 to 1, respectively representing its
 238 minimum and maximum values. In correspondence to approaches taken in CRN studies, we
 239 compute histograms from the smoothed and normalized roughness profiles (Figure 4B, bar
 240 plot). Here, histogram peaks indicate profile sections that share the same roughness character
 241 while histogram valleys between them indicate profile sections where roughness changes
 242 abruptly. The profile heights at which roughness begins to deviate away from the histogram
 243 peaks in the up-dip direction constitute event horizons, separating portions of the profile that
 244 were exposed to subaerial weathering before and after an exposure event (i.e., surface-rupturing
 245 earthquake; Fig. 4B, dashed lines and arrows). To better resolve the event horizons heights,
 246 we stack all the roughness profiles we obtained for a given circle size (stacking normalized
 247 profiles from different percentile values and roughness metrics) and analyze them collectively,
 248 along with the corresponding stacked histogram. This further reduces the data set's noise and
 249 helps focusing on signals (e.g., event horizons) that are consistent throughout our observations.

250 Not all parts of the imaged surface represent the initial bedrock fault scarp (i.e.,
 251 slickensides) whose degradation by persistent, gradual weathering processes we aim to resolve.
 252 Our surface models may contain areas where snow or plants cover the fault surface or where
 253 rocks have been plucked and dislodged from it, removing the original slickensides (e.g., upper
 254 left part of Fig. 3A, top and bottom part of Fig. 3B). We exclude these non-representative areas

255 from the roughness analysis by defining polygons that outline the data set sections that we
256 analyze (see auxiliary online material, Fig. S1).

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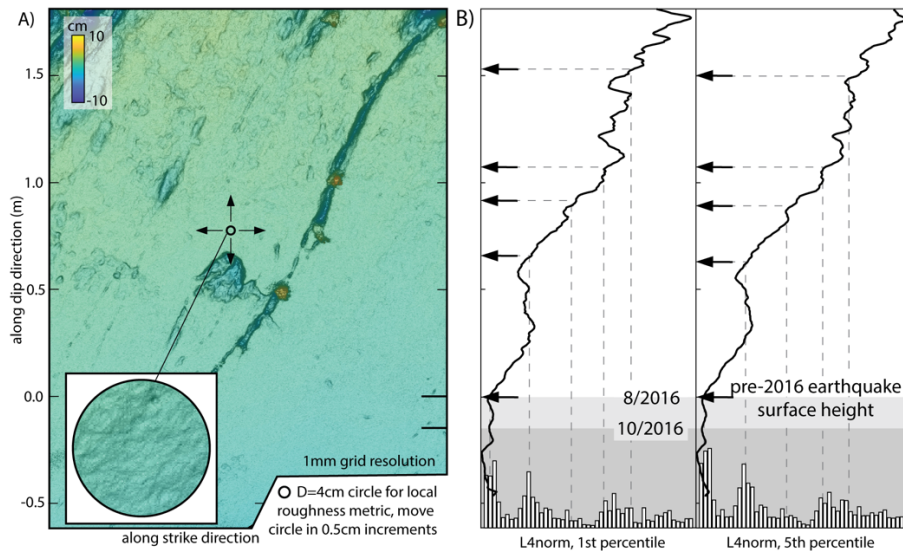


Figure 4. Measurement approach for fault roughness determination. A) A circular sample area is swept across the investigated fault surface. The roughness metric (e.g., L_4 -norm) is calculated for each circle position. B) Exemplary, this metric's 1st and 5th percentile are plotted as a function of profile height, smoothed with a 10-cm moving average window (see Methods section). The profile lines and the corresponding histograms indicate which roughness values are more common than others, implicitly revealing profile portions with similar exposure time and the height of event horizons that separate them (black arrows).

258

259 **Results**

260 Following the outlined approach, we analyze how fault roughness (i.e., its low-
261 percentile representation) changes as a function of profile height at the Mt. Vettore and
262 Roccapreturo sites. In total, we analyzed 5 sections of the fault surface at the Mt. Vettore site
263 and 1 section at the Roccapreturo site. As noted before, three of the Mt. Vettore sections are
264 spatially overlapping, capturing part I of the fault surface (Fig. 3A) at three different times
265 (09/2016, 11/2016, and 06/2018; our measurements on the 09/2016 and 06/2018 data sets may
266 be found in the auxiliary online material; Fig. S2). The other sections are spatially separated,
267 covering different parts of the fault surface as documented by the 11/2016 data set. Performing
268 the analysis on sections that cover different parts of the fault surface (i.e., the same part at
269 different times) further ensures measurement consistency. Unfortunately, we were not able to

270 take multiple measurements for the Roccapreturo site, where only one fault surface model is
271 available. For each analyzed fault surface section, we provide three subplots (respectively for
272 a 2-, 4-, 6-cm circle size), each of them containing 15 roughness profiles and a stacked
273 roughness histogram (1st to 5th percentile for 3 roughness metrics; Figs. 5 and 6). Profile lines
274 are semi-transparent to emphasize where they share similar values and overlap.

275 For section 1 of the Mt. Vettore fault surface, we identified five histogram peaks and
276 hence five exposure event horizons (Fig. 5A). Three of them, at 0.0 m, 0.7 m, and 1.5 m, are
277 distinctly larger than the other two at 0.9 m and 1.1 m. The smaller size of the latter two
278 histogram peaks (the one at 0.9 m being the smallest) is due to the short profile sections (~20
279 cm) that exhibit this roughness character, which makes them presumably less reliable.
280 However, our analysis of section 1, based on the 09/2016 and 08/2018 data sets (Fig. S2),
281 indicates consistency between measurements –even the weakly developed histogram peaks at
282 0.9 m and 1.1 m are found in the 09/2016 and 06/018 data sets, albeit at slightly shifted heights
283 of 1.0 m and 1.3 m and 0.9 m and 1.2 m respectively (Fig. 5A and S2). This slight shift in
284 height is caused by differences in polygon outlines (Fig. S1), combined with the curviness of
285 the event horizons which is well exemplified for the most recent earthquakes (e.g., Figs. 2A
286 and 3A). Further note that the 09/2016 data set (Fig. S2A) also revealed a histogram peak at
287 1.8 m, which is not fully resolved in Fig. 5A because of this profile’s limited length. The
288 identified event horizon heights, reported relative to height of the August 2016 event horizon,
289 are listed in Table 1.

290 For section 2 of the Mt. Vettore fault surface (Fig. 5B), we find four well developed
291 histogram peaks, located at 0.0 m, 0.9 m, 1.2 m, and 1.7 m. The changes between profile
292 sections with similar roughness character are overall sharp and discrete (i.e., step-like),
293 especially for the smaller circle sizes (Fig 5B, left and middle). Given the clear expression of
294 the 0.9 m event horizon in section 2 (i.e., its histogram peak), relative to the corresponding one
295 in section 1 (Fig. 5A), leads us to suggests that they are not related to the same exposure event.
296 Instead, we suggest that the 0.9 m event horizon in section 2 correlates to the 0.7 m event
297 horizon in section 1 and further suggest that the 0.9 m event horizon in section 1 is not resolved
298 in section 2 (otherwise, the 0.7 m event horizon from section 1 is not resolved here). Likewise,
299 we suggest that the 1.7 m event horizon in section 2 correlates to the 1.5 m event horizon in
300 section 1.

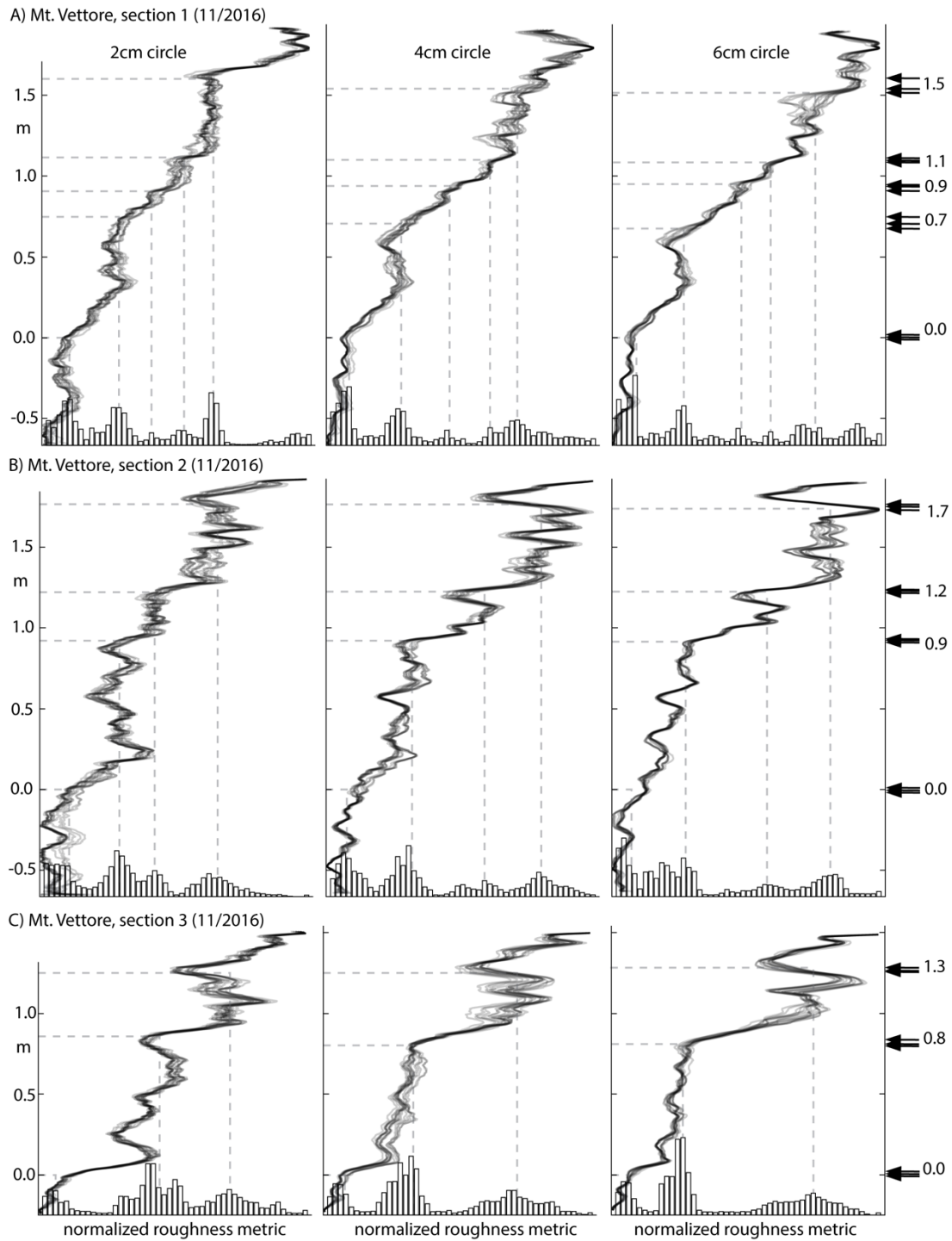


Figure 5. Fault surface roughness as function of profile height for three sections of the Mt. Vettore data set (acquired in 11/2016). See auxiliary online material for section outlines (Fig. S3). Profile heights are relative to the August 2016 event horizon (Fig. 3A). Each subplot contains 15 smoothed and normalized roughness profiles and a stacked roughness histogram (see Methods sections). Dashed lines and black arrows indicate histogram peaks and the corresponding event horizon height.

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For section 3 of the Mt. Vettore fault surface (Fig. 5C), we find three well developed histogram peaks, located at 0.0 m, 0.8 m, and 1.3 m, separated by sharp and step-like changes in roughness. Note that this profile is ~0.5 m shorter than those of section 1 and 2, therefore not capturing the higher event horizon at 1.5 m (i.e., 1.7 m). Following the same approach as for section 2 (based on relative expression of the step-like change in roughness and size of the associated histogram peak), we suggest that the 0.8 m event horizon in section 3 correlates to the 0.7 m event horizon in section 1.

Mt. Vettore site	event horizon height (m) section 1 (11/2016)	event horizon height (m) section 1 (09/2016)	event horizon height (m) section 1 (06/2018)	event horizon height (m) section 2 (11/2016)	event horizon height (m) section 3 (11/2016)	Average height of event horizon (m)	Apparent slip increment (m)
EQ 1	0.0	0.0	0.0	0.0	0.0	0.0	0.2, 1.2
EQ 2	0.7	0.7	0.6	0.9	0.8	0.7	0.7
<i>EQ3</i>	<i>0.9</i>	<i>1.0</i>	<i>0.9</i>	-	-	0.9	(0.2)
EQ4	<i>1.1</i>	<i>1.3</i>	<i>1.2</i>	1.2	1.3	1.2	0.5 (0.3)
EQ 5	1.5	1.6	-	1.7	-	1.6	0.4
EQ 6	-	1.8	-	-	-	1.8	0.2

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Table 1. Identified event horizon heights (meters) and corresponding earthquake as derived for the different fault surface sections of the Mt. Vettore site. Italic font indicates weakly expressed event horizons. Also shown are the average heights of event horizons and apparent slip increments. The reported slip increments for EQ1 (the August and October 2016 earthquakes) are from the literature (e.g., Perouse et al., 2018).

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Overall, we find that the event horizon heights for the Mt. Vettore site (Table 1) are markedly similar across the different roughness metrics, percentile values, circle sizes, and analyzed fault surface sections, attesting for the consistency of these measurements. Including the 2016 earthquake sequence, we identified 6 exposure event horizons, respectively at 0.0 m, 0.7 m, 0.9 m, 1.2 m, 1.6 m, and 1.8 m profile height (relative to the 08/2016 event horizon height). Assuming that these event horizons represent individual earthquakes, the

323 corresponding slip increments range from 0.2 m to 1.2 m (Table 1). That said, we want to note
 324 that a direct correlation between exposure events, as identified from distinct changes in
 325 roughness metric, and individual earthquakes is likely not permissible. Multiple surface
 326 rupturing earthquakes may contribute to a single exposure event if these earthquakes occurred
 327 shortly after one another, in which case it is better to attribute event horizons to phases of
 328 substantial fault activity (potentially encompassing multiple surface ruptures). We will address
 329 this point in more detail in the following section.
 330

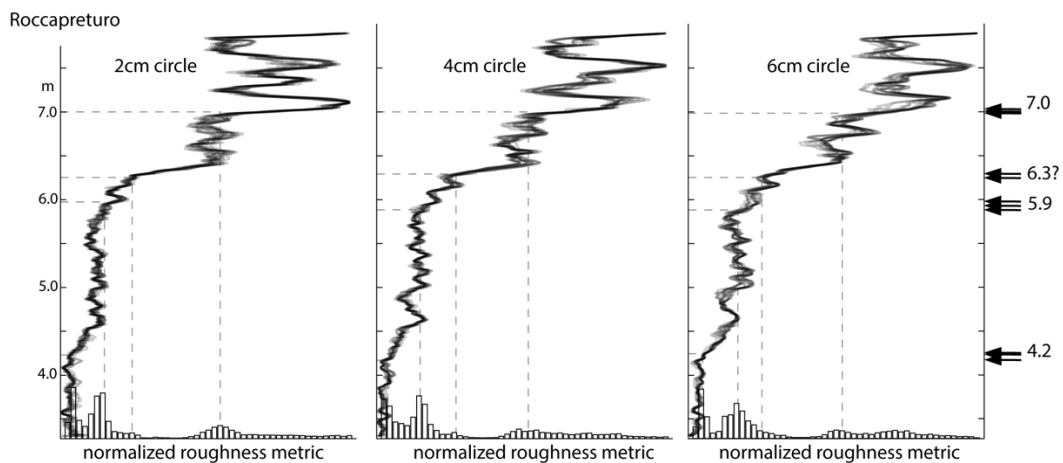


Figure 6. Fault surface roughness as function of profile height for the Roccapreturo data set. See auxiliary online material for section outline (Fig. S4). Profile heights are relative to the base of a 10-m spanning CRN analysis profile (Schlagenhauf, 2009; Fig. 3B). Each subplot contains 15 smoothed and normalized roughness profiles and a stacked roughness histogram (see Methods sections). Dashed lines and black arrows indicate histogram peaks and the corresponding event horizon height.

331
 332 While positioned along another fault, our findings for the Roccapreturo site are broadly
 333 consistent with our findings for Mt. Vettore site (Fig. 6): Fault roughness and its variability
 334 increases with profile height, exhibiting profile portions of similar roughness that are separated
 335 by sharp, step-like roughness changes. For the Roccapreturo site, we find 3 well developed
 336 histogram peaks (i.e., event horizons) at 4.2 m, 5.9 m, and 7.0 m as well as 1 weakly developed
 337 peak at 6.3 m. The latter peak is more apparent in the roughness profiles from which the
 338 histograms are derived –the corresponding profile section being bracketed by sharp changes in
 339 roughness metric (Fig. 6). Overall, the identified histogram peaks are separated by distinct
 340 valleys in the roughness histogram, indicative of sharp, step-like changes in roughness metric

341 when moving from one histogram peak to the next (i.e., moving from one exposure event to
 342 the next). Hence, we identified 4 exposure events for the Roccapreturo site with slip increments
 343 ranging from 0.4 m to 1.7 m (Table 2). Conveniently, the Roccapreturo site was also the
 344 location of a CRN investigation that aimed to determine the exposure history of this fault scarp.
 345 This investigation identified event horizons at ~4.4 m and ~7.1 m, with corresponding ages of
 346 2.9 kyrs and 4.5 kyrs (Schlagenhauf, 2009). Our roughness analysis is therefore able to recover
 347 these events (EQ1 and EQ4; Table 1; Fig. 6) and presumably able to resolve additional events
 348 that were not found in the CRN analysis (at 5.9 m and 6.3 m profile height), highlighting the
 349 added value that may come from the roughness analysis. Apparently, the fault surface
 350 roughened more quickly than cosmogenic radionuclides accumulated, therefore enabling to
 351 resolve smaller variations thereof. Because of lacking data overlap, we were not able to
 352 correlate our findings to the paleoseismic study by Falcucci et al. (2015) or the CRN study by
 353 Goodall et al., (2021) that were also conducted along the Roccapreturo fault.

354

Roccapreturo	section 1 (2019)	Apparent slip increment (m)
EQ 1	4.2	-
EQ 2	5.9	1.7
<i>EQ 3</i>	6.3	(0.4)
EQ 4	7.0	1.1 (0.7)

355

356 Table 2. Identified event horizon heights (meters) and corresponding earthquake number as
 357 derived for the different fault surface sections of the Roccapreturo site. Italic numbers indicate
 358 weakly expressed event horizons. Also shown are the average heights of event horizons and
 359 apparent slip increments. If EQ3 does not represent a separate exposure event, then its slip
 360 increment would be accommodated by EQ4 (bracketed values indicate case where EQ3 is
 361 assumed to be an exposure event).

362

363 **Discussion**

364 Our investigation along the Mt. Vettore and Roccapreturo bedrock fault scarps indicates
 365 that fault surface roughness changes systematically along profile height, alternating between
 366 a) profile sections with similar roughness characteristics and b) approximately step-like
 367 changes in roughness over short profile sections. We suggest that these step-like roughness

368 changes constitute event horizons, separating profile sections that were exposed to subaerial
369 weathering processes for different time periods. In our analysis, we were able to identify 6
370 event horizons for the Mt. Vettore site and 4 event horizons for the Roccapreturo site,
371 respectively spanning a combined profile height of 3.2 m and 2.8 m (for the Mt. Vettore site,
372 this includes the 2016 earthquakes). Intuitively, we may assume a direct correlation between
373 these event horizons and individual earthquakes. However, this correlation is not sensible as is
374 indicated by observational evidence and was noted before. For example, for the Mt. Vettore
375 site, we know that the ~1.4 m offset from 2016 (EQ1 in Table 1; Fig. 2A) contains the slip
376 contribution of two successive events (August 2016 earthquake with ~0.2 m and October 2016
377 earthquake with ~1.2 m of slip at the site; Perouse et al., 2018). The slip amount of the August
378 2016 earthquake and importantly the time interval between these two earthquakes (~3 month)
379 is small, prohibiting to distinguish these events through surface roughness analysis. Hence, the
380 reported histogram peaks and event horizons should not be correlated to individual earthquakes
381 but rather to phases of substantial fault activity, potentially spanning more than one surface-
382 rupturing earthquake. The reported offset increments (Tables 1 and 2) therefore represent the
383 combined slip amount of these phases, potentially containing slip contributions from more than
384 one earthquake (e.g., Grant Ludwig et al., 2010) as is also inferred for the record obtained from
385 the ³⁶Cl exposure dating (Beck et al., 2018, Tesson and Benedetti, 2019).

386 This understanding raises the question how many earthquakes contributed to each offset
387 increment (i.e., activity phase) that we identified and how variable their respective offsets are.
388 Unfortunately, we are not able to answer this question because we are lacking the necessary
389 observational data (e.g., knowing the event horizon ages to correlated them with paleoseismic
390 studies; e.g., Galli et al., 2019). That said, earthquake physics, rupture simulations, and
391 observational constraints suggest that slip accumulation along faults is dominated by large,
392 full-rupture earthquakes (e.g., Schwartz and Coppersmith, 1984; Youngs and Coppersmith,
393 1985; Pacheco et al., 1992; Sieh, 1996; Manighetti et al., 2005; Zielke and Arrowsmith, 2008;
394 Akciz et al., 2010; Schlagenhauf et al., 2011; Zielke et al., 2015). With this conceptual
395 framework, we can provide a lower-bound estimate for the number of earthquakes that
396 contributed to fault scarp formation (i.e., the portions we analyzed here) while further assuming
397 that other (non-tectonic) mechanisms that may expose a fault surface can be neglected (e.g.,
398 Giaccio et al., 2002; Wiatr et al., 2015; Mechernich et al., 2018). That is, the 3.2-m high scarp

399 at the Mt. Vettore site was formed by at least 6 surface-rupturing earthquakes, with maximum
400 offsets ranging from 0.2 m to 1.2 m. If these offsets are indeed due to the occurrence of a single
401 earthquake, then the corresponding magnitudes would range from **M6.1** to **M6.7** (Manighetti
402 et al., 2007; Thingbaijam et al., 2017) –plausible values in comparison to the 2016 earthquake
403 sequence. Likewise, if the offset increments at the Roccapreturo site (ranging from 0.4 to 1.7
404 m) are caused by the occurrence of single, full-rupture earthquakes, then the corresponding
405 magnitudes would range from **M6.3** to **M6.8**. Note that these magnitude estimates for the Mt.
406 Vettore and Roccapreturo faults are consistent with rupture length to average slip scaling
407 relationships, implying corresponding rupture lengths of 20 to 30 km –comparable to the
408 reported length of these faults systems (Manighetti et al., 2007; Thingbaijam et al., 2017).

409 Going one step further with this line of thinking, we might correlate the 6 event horizons
410 that we identified for the Mt. Vettore scarp (spanning 3.2 m of fault scarp) with the 6 surface-
411 rupturing earthquakes that occurred within the last 9 kyrs along the Mt. Vettore fault (Galli et
412 al., 2019), implying a throw-rate of ~0.3 mm/yr. This rate is consistent with the minimum rate
413 of 0.26-0.38 mm/yr as derived from a single splay fault of a wide zone of deformation (Galli
414 et al., 2019; Cinti et al., 2019; Pucci et al., 2021). However, it is distinctly lower than the fault’s
415 long-term rate of 0.7-1.6 mm/yr (Pizzi et al., 2002; Puliti et al., 2020), indicating that either a)
416 the throw-rate slowed down over time, b) the 3.2-m high scarp we investigated was formed by
417 less than 6 earthquakes, c) more than 6 surface-rupturing earthquakes occurred during the last
418 9 kyrs, or d) a combination of these possibilities. To begin resolving this discrepancy, we would
419 first need to know how old the event horizons (from our roughness analysis) are.

420 The Roccapreturo site gives us the opportunity to validate our analysis by comparing it
421 to a previous CRN investigation along this scarp (Schlagenhauf, 2009). We were able to
422 reproduce these earlier findings and further to identify additional surface-rupturing events,
423 implying that fault roughness measurements, under the right conditions, may provide a higher
424 resolution of bedrock scarp exposure events. It appears that fault roughness may change more
425 quickly than CRN can accumulate and hence enable to identify and resolve smaller changes in
426 surface exposure time. However, as noted before, one important missing aspect when it comes
427 to constraining the slip accumulation history at these two sites by solely using roughness
428 measurements is to determine the age of the identified exposure events. At this time, we do not
429 know when these events occurred. Incorporating CRN analysis along these fault scarps to

430 determine the exposure ages directly above the identified event horizons would improve our
431 understanding, as was possible for the Roccapreturo site. However, defining these ages directly
432 from our roughness measurements requires a) to quantify the relative importance of all acting
433 physical and chemical weathering processes that are responsible for roughness modification,
434 and b) to determine their respective rates, along with the parameters that control them. While
435 this endeavor is beyond the scope of the present study, we anticipate extending in this direction.

436

437 **Conclusion**

438 In the present study, we analyze high-resolution surface models of exposed fault
439 surfaces from two sites along two faults in Central Italy to determine how fault roughness varies
440 as function of profile height and if it can be used to resolve slip increments of successive
441 earthquakes. In doing so, we can identify 6 and 4 event horizons, respectively spanning a
442 combined height of 3.2 m and 2.8 m for the Mt. Vettore and Roccapreturo site. Making the
443 simplifying assumption that the corresponding slip increments, ranging from 0.2 to 1.7m, were
444 caused by individual subsequent surface-rupturing earthquakes, suggests the repeated
445 occurrence of **M6.1** to **M6.8** earthquakes along these faults.

446 Our findings indicate that, under the right conditions, fault roughness measurements
447 along exposed fault surface provide the means to identify event horizons of fault exposure,
448 indicating distinct phases of fault activity. This analysis approach likely performs better for
449 slow-moving faults, providing more time in between successive earthquakes to form and
450 increase fault surface roughness. We suggest that a combination of surface roughness analysis,
451 as we performed it here (to identify event horizons), and CRN analysis (to assign an age to
452 these event horizons) may further improve our ability to resolve details of the earthquake cycle
453 along bedrock fault scarps.

454

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458

459 **Data Availability**

460 The point cloud data for the Mt. Vettore site may be found at
461 <https://tls.unavco.org/projects/U-067/PS01/SV02/>. Other data are contained in this manuscript
462 and the auxiliary online material.

463

464 **Appendices**

465 The auxiliary online material contains two additional figures that a) show the sampling
466 locations for the Mt. Vettore and Roccapreturo sites and b) additional results from the Mt.
467 Vettore site, section 1 (results from the « in-between » data set of 09/2016 and from two years
468 after the 2016 earthquake sequence).

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