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# Comparing Slip Distribution of an Active Fault System at Various Timescales: Insights for the Evolution of the Mt. Vettore-Mt. Bove Fault System in Central Apennines

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1        **Comparing slip distribution of an active fault system at various timescales:**  
2        **insights for the evolution of the Mt. Vettore- Mt. Bove fault system in Central**  
3        **Apennines**

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8

9        **Key Points:**

- 10        • 2016 coseismic ruptures along the Mt. Vettore fault system are compared with Holocene  
11        offsets on fault scarps and Quaternary geological throws.
- 12        • Maximum fault throw has been localized at the system southern tip over the last 18 kyr
- 13        • Pre-existing thrust acts as a transversal barrier for the southward fault system’s evolution
- 14        • .

15        **Abstract**

16        In 2016, the Mt. Vettore-Mt. Bove normal fault system (VBFS) broke during three earthquakes  
17        (Mw 6.0, Mw 5.9, and Mw 6.5), associated with clear coseismic ruptures. Based on high-resolution  
18        topography and geological field data, we determined the displacements of the VBFS. The  
19        distributions of the coseismic and post-glacial displacements exhibit similar asymmetric shapes,  
20        suggesting self-similar slip profiles over the last 18 kyr. The highest displacement during the 2016  
21        events is localized on the southern Mt. Vettore segments, the southern tip of the VBFS, which also  
22        showed the maximum throw of 32 m over the last 18 kyr yielding to a very fast throw rate of 1.6  
23        ±0.5 mm/yr. Assuming a constant throw rate, the geological displacement we determined suggests  
24        an inception age of 200-250 kyr for the surface rupturing faults that ruptured in 2016 on the Mt.

25 Vettore sector. This value can be interpreted as the minimum age for the onset of those faults in the  
26 Mt.Vettore and might result from a southward shift of VBFS activity with a change of the fault  
27 system pattern. We infer that the observed slip distribution, maximum at Mt. Vettore and tapering-  
28 off southward, might be due to the VBFS lengthening processes toward the Laga Fault and its  
29 interaction with pre-existing structure such as OAS thrust that might play a key role in controlling  
30 the VBFS's evolution.

## 31 **1 Introduction**

32 Long-term fault escarpments are built by the addition of incremental earthquakes and thus contain  
33 key information on earthquake rupture processes, where the rupture stopped and where it has  
34 propagated during those past events. Several studies have proposed that earthquake ruptures may be  
35 arrested by structural and/or geometrical complexities, such as fault intersections and step-overs,  
36 (Wesnousky 1988, Bejar-Pizarro et al. 2013; Klinger 2000). Constraining the spatial extent of a  
37 coseismic rupture (e.g., where it may be arrested during an earthquake), is fundamental for deriving  
38 the expected earthquake magnitude, essential for seismic design and population preparedness.  
39 However, few datasets exist to unravel whether the segmentation seen in coseismic ruptures is  
40 characteristic through time and, if yes, over which time scales. The seismic sequence that occurred  
41 in 2016 in Central Italy represents a great chance to observe and understand how a normal fault  
42 system evolves because the detailed pattern of the 2016 coseismic throw can be compared to the  
43 cumulative displacements that can be constrained from geological and geomorphological analysis.  
44 This sequence has been characterized by three spatially and temporally clustered mainshocks that  
45 are localized within a 25 km-long area that is oriented NNW-SSE (the active Mt. Vettore-Mt. Bove  
46 fault system, VBFS): 24 August, Mw 6.0; 26 October, Mw 5.9; and 30 October, Mw 6.5 (Civico et  
47 al., 2018, Villani et al., 2018a). The surface faulting that is associated with the 30 October  
48 earthquake (maximum dip-slip displacement of  $\sim 2$  m; Villani et al., 2018a) is one of the clearest  
49 and most spectacular coseismic ruptures that have been observed after an earthquake in the

50 Mediterranean area in recent decades. The coseismic slip, however, is complex and is distributed  
51 within several rupturing segments. How the rupture propagated through these various segments and  
52 what role inherited structures plays in this complex pattern are still debated (see Porreca et al. 2020  
53 for a complete discussion and references therein). In particular, several models have been proposed  
54 that emphasize the presence and the role of structural barriers at depth in the rupture propagation  
55 and arrest (e.g., Chiaraluce et al., 2017; Chiarabba et al., 2018; Falcucci et al., 2018; Lavecchia et  
56 al., 2016; Pizzi et al., 2017; Scognamiglio et al., 2018; Walters et al., 2018).

57 Here we provide a set of data of the surface fault displacement at different time scales allowing to  
58 discuss the temporal and spatial evolution of this active normal fault system. We investigated the  
59 entire VBFS displacement at three different time scales, hereafter referred to as: “long-term”, (~ 1  
60 Myr); i.e. based on the geological slip accumulation during Quaternary extension; “mid-term” (~  
61 last 18 kyr), i.e. derived from geomorphic evidence of faulting following the Last Glacial Maximum  
62 (see further explanation in section 3); “short-term”, during an instantaneous seismic event. Iezzi et  
63 al., (2018), Brozzetti et al. (2019) and Porreca et al. (2020) have also compared the geological and  
64 the co-seismic displacement but focusing on the Mt Vettore fault.

65 We compared the 2016 coseismic slip distribution along the entire VBFS system with  
66 morphological and geological throws (i.e., vertical-displacement component) from topographic  
67 profiles, cross-sections, geological horizons, and field surveys. Our results can better constrain how  
68 a normal fault system evolves in the short-, mid- and long-term and how its evolution is influenced  
69 by fault segmentation and structural barriers. We also investigate the link between surface  
70 observations and structures at depth.

## 71 **2 Seismotectonics of the area**

### 72 **2.1 Regional geological framework**

73 The Apennine chain is an NE-verging imbricate fold-and-thrust belt that developed from the  
74 Oligocene along the margin of the Adriatic microplate (Carminati & Doglioni, 2012; Patacca et al.,

75 2008 and reference therein). The chain is now experiencing post-orogenic ENE-oriented Quaternary  
76 extension (Barchi et al., 2000; Calamita & Pizzi, 1994; Galadini & Galli, 2000; Lavecchia et al.,  
77 1994; Pizzi et al., 2002) with regional extension rates of 3-4 mm/yr (D'Agostino et al., 2008; Faure  
78 Walker et al., 2009) related to the relative motion between the Adriatic microplate and the  
79 Tyrrhenian coastal region (D'Agostino et al., 2011; D'Agostino, 2014; Devoti et al., 2017). In the  
80 study area, the main structure of the chain is represented by the Olevano-Antrodoco-Sibillini (OAS)  
81 thrust, an arc-shaped thrust front that strikes NW to the north and NNE to the south with respect to  
82 the Mt. Vettore pivot, or obliquely to the NNW-SSE-trending Quaternary normal fault systems  
83 (Figure 1). The OAS thrust affects Mesozoic-Tertiary sedimentary successions that are  
84 characterized by platform-to-basinal limestones, marly limestones, and marls and Messinian  
85 turbidite siliciclastic deposits by superposing the carbonate units over the Messinian deposits of the  
86 Laga Fm (Figure 2.a; Calamita & Deiana, 1988; Mazzoli et al., 2005; Pierantoni et al., 2013).

87 The location and orientation of the OAS thrust seem to have been strongly controlled by a pre-  
88 existing Early Jurassic normal-fault zone: the NNE-SSW Ancona-Anzio lineament. This lineament  
89 has been interpreted as a high-angle fault zone that is approximately one hundred kilometers long  
90 and acted during the Mesozoic–Early Tertiary as a syn-sedimentary extensional fault system  
91 (Castellarin et al., 1982; Parotto & Praturlon, 1975). This fault separated the Umbria–Marche  
92 pelagic domains to the west from the Lazio–Abruzzi carbonate platform domain to the east  
93 (Castellarin et al., 1978). During the Neogene, this regional paleogeographic boundary experienced  
94 positive inversion through a fold-and-thrust belt contractional phase, which worked as an oblique  
95 high-angle thrust ramp (e.g., Calamita et al., 2011; 2012; Lavecchia, 1985; Tavarnelli et al., 2004).

96 On the other hand, the shallower portion of the OAS thrust surface, i.e., the first 2-3 km, shows  
97 low-angle geometry and is locally folded by NW-SE-/NNW-SSE-trending anticlines that developed  
98 in its footwall (Alberti et al., 1996; Di Domenica et al., 2012, Porreca et al., 2018).

99 In recent decades, several authors suggested that the OAS thrust could represent an oblique  
100 structural barrier to the growth and associated seismicity of active Quaternary seismogenic

101 extensional faults (Pizzi & Galadini, 2009; Di Domenica et al., 2012). Evidence consistent with this  
102 idea was presented by the spatial and temporal evolution of the 2016 seismic sequence, where the  
103 OAS played a major role in the slip propagation rupture halting, or in fault slip accommodating  
104 extension (e.g. Chiaraluce et al., 2017; Pizzi et al., 2017, Walters et al., 2018).  
105 Additionally, the structural setting of the area is complicated by the presence of other pre-, syn- and  
106 post-thrusting normal faults from different extensional phases that are widely recognized in the  
107 Apennines, such as the Neogene normal faulting occurred alongside crustal and lithospheric  
108 foreland flexural processes, influencing the deposition of foredeep sequences (Tavani et al., 2015;  
109 Tavarnelli & Peacock, 1999). Those faults experienced a Neogene positive inversion with the  
110 compressional phase and, then, a negative inversion during the Quaternary (e.g. Di Domenica et al.,  
111 2012 and reference therein). The Quaternary normal faults overprinted the Neogene contractional  
112 structures (e.g., Calamita and Pizzi, 1994; Lavecchia et al., 1994; Galadini & Galli, 2000), since at  
113 least the Early Pleistocene (1.1-1.2 Ma according to Blumetti and Dramis, 1992; Coltorti et al.,  
114 1998; Calamita et al., 1999).

## 115 **2.2 Monte Vettore –Monte Bove fault system**

116 The Mt. Vettore-Mt. Bove normal fault system (VBFS), which was responsible for the 2016 Central  
117 Italy seismic sequence, represents one of the easternmost active fault systems that affect the  
118 Central-North Apennines at the Sibillini Mt. Range (Figure 1). The VBFS is located in the hanging  
119 wall of the OAS thrust and consists of a ~26 km-long, N150°-striking, SW-dipping normal-fault  
120 system with prevailing Quaternary activity, alongside dozens of 1-4 km-long en echelon segments  
121 that are accompanied by synthetic and antithetic splays in the main fault's hanging wall (Figure 2).  
122 The VBFS's activity strongly controls both the Quaternary deposition and present-day  
123 physiography in the Sibillini Mts., which are characterized by two different morphologies in their  
124 eastern and western flanks (Figure 2.b). The uplifting footwall block coincides with the eastern  
125 flank of the mountain range, while the hanging wall hosts a gentle planation surface westward. The  
126 eastern portion consists of several valleys, of which many are narrow canyons that are oriented E-W

127 and flow eastward into the Adriatic Sea. The drainage divide is located at the ridge crest of the  
128 Sibillini Mts. Close to the range's top, moraines deposits in glacial valleys and cirque morphologies  
129 testify the presence of local glaciers above 1750 m at around 28 kyr, contemporaneous to those on  
130 the Gran Sasso Massif, with a minor final expansion at 18 kyr (Giraudi, 2003). The western flank  
131 has a smoother morphology characterized by large valleys mainly oriented N-S (Coltorti &  
132 Farabollini 1995; Pizzi et al., 2002). Several authors (Blumetti et al., 1993; Calamita & Pizzi, 1994;  
133 Coltorti & Pieruccini, 2000; Pizzi & Scisciani, 2000) described this smooth topography as a major  
134 and unique planation surface from the late lower Pliocene. The VBFS's trace is visible in the  
135 morphology and is associated with an abrupt change in the mountain slope that underlined well-  
136 preserved fault scarps throughout the system except in areas where erosional/depositional processes  
137 are strong like in the Ussita valley.

138 This system was mapped and described in detail for the first time by Calamita & Pizzi (1992).  
139 These authors recognized a main NNW-SSE fault trend that was marked by the presence of several  
140 kilometer-long sub-parallel primary and secondary faults (both synthetic and antithetic) with  
141 oblique transfer-fault segments, en echelon patterns, and relay zones. In the southernmost sector,  
142 two distinct en echelon segments can be recognized at high elevations along Mt. Vettore's western  
143 slope, while N160° basal faults with large geologic throws (i.e., >1000 m) border a large endorheic  
144 basin: the Piano Grande (Castelluccio Basin), a 12 km-long and 8 km-wide intermountain basin at  
145 ~1300 m a.s.l. (Figure 2). The faults high on the flanks of the Mt. Vettore and the one bounding the  
146 Piano Grande may sole into a major structure at depth. The development of this basin is also  
147 controlled by other differently oriented normal faults around the marginal depression, showing  
148 conjugated faults that trend N20° as recognized by tomography (e.g., Villani et al., 2018). The SW-  
149 dipping fault bounding the Piano Grande exhibits a great geological displacement of 1000 m (e.g.,  
150 Calamita et al., 1992; Pierantoni et al., 2013), but there is no morphological evidence of recent  
151 activity with alluvial fans and debris-slope deposits that appears undisturbed since the Middle  
152 Pleistocene (Coltorti and Farabollini, 1995). Galadini and Galli (2003) revealed a recent activity

153 (i.e. at least 3 events before the 2016 event) on a secondary fault (i.e., total morphological throw  $\leq 3$   
154 m and 960 m-long, Figure 2) running 900 m west far from the basin-bounding fault, in the Piano  
155 Grande (Pierantoni et al. 2013). The most recent paleoseismological investigations on the antithetic  
156 and synthetic splays of the VBFS that ruptured in 2016 suggest that those splays have also  
157 experienced earthquakes of  $M_w \geq 6.5$ -6.6, over the last 9 kyr (Galli et al., 2019, Cinti et al., 2019).  
158 The 2016 seismic sequence began on 24 August with a  $M_w$  6.0 earthquake NW of Amatrice  
159 (Chiaraluce et al., 2017). The sequence continued on 26 October with a  $M_w$  5.9 event and epicenter  
160 close to Visso (Castelsantangelo sul Nera), and then the major Norcia event ( $M_w$  6.5) occurred on  
161 30 October, one of the strongest historical events in Central Italy (Figure 1). The focal-mechanism  
162 solutions of these major events are fully consistent with the normal-fault kinematics of the NNW-  
163 striking VBFS and, generally, the Central Apennines extension, indicating an ENE-stretching axis.  
164 The first earthquake produced surface faulting for a length of  $\sim 5$ -6 km along the southernmost  
165 portion of the VBFS, with an average vertical offset of  $\sim 0.10$ -0.15 m and local peaks over 0.30 m  
166 (Lavecchia et al., 2016; Pucci et al., 2017). The 26 October event caused surface faulting in the  
167 northernmost portion of the VBFS (Pizzi et al., 2017; Civico et al., 2018; Brozzetti et al., 2019).  
168 Surface faulting from the last event involved almost the entire length of the VBFS, overprinting the  
169 ruptures from the Amatrice earthquake (e.g. Villani et al., 2018b), and some of the 26 October event  
170 (Wedmore et al., 2019). All the faults that ruptured during the 2016 seismic sequence, according to  
171 Villani et al. (2018b) database, are reported in Figure 2 as red solid lines.  
172 As observed through detailed geological mapping (e.g., Livio et al., 2016; Pucci et al., 2017 and  
173 references therein) and analysis of seismological slip data (e.g., Chiaraluce et al., 2017;  
174 Scognamiglio et al., 2018; Improta et al., 2019), the rupture process and surface-deformation  
175 patterns that characterized the 2016 seismic sequence were very complex. The sequence involved  
176 the VBFS alongside the Laga Fault (LF in Figure 1) and OAS thrust (Lavecchia et al., 2016; Pizzi  
177 et al., 2017; Villani et al., 2018b; Falcucci et al., 2018). The complex surface-deformation patterns  
178 that were reconstructed by GPS and DInSAR data inversion (e.g. Cheloni et al., 2017;



179 Scognamiglio et al., 2018) revealed interesting information regarding fault linkages and interactions  
180 and the role of structural barriers between the VBFS and the Laga Faults. Some authors highlighted  
181 how the OAS thrust appears to modulate the evolution of the sequence interfering with coseismic  
182 slip distribution and the fault segments interaction ( Chiaraluce et al., 2017; Scognamiglio et al.,  
183 2018; Ragon et al., 2019). This interference in the slip propagation is also supported by the rupture  
184 interruption for each earthquake in the sequence that determined their respective magnitudes and  
185 prevented cascading rupture in a single earthquake of Mw 6.7 or larger (Walters et al., 2018).

### 186 **3 Materials and Methods**

187 To analyze the VBFS in detail, we subdivided the fault system into four main fault sectors that  
188 show continuous fault traces and homogeneous structural and geomorphological characteristics.  
189 From south to north, these sectors are the Mt. Vettore, Mt. Porche, Mt. Bove, and Cupi-Ussita  
190 synthetic faults and the San Lorenzo antithetic fault, alongside 13 smaller associated fault segments  
191 (0.9-2.5 km long) (Figure 2). We define “MV” as the Mt. Vettore-related fault sector, “MP” as the  
192 Mt. Porche (and San Lorenzo)-related fault sector, “MB” as the Mt. Bove-related fault sector and  
193 “CU” as the Cupi-Ussita-related fault sector.

194 The MV sector consists of synthetic faults that dip SW and strike between N140° and N175° on the  
195 mountain flank that borders the Piano Grande. Although the 30 October earthquake caused surface  
196 faulting of a fault in the SW portion of the basin, this antithetic fault has not been analyzed because  
197 limited data were available and coseismic ruptures were evident only in a tunnel that remained  
198 closed after the earthquakes (Galli et al., 2017). The antithetic and synthetic segments of the MP  
199 sector define a graben morphology, while two N150° main parallel synthetic segments comprise the  
200 MB and CU sectors. We distinguished the latter two into two sectors because no continuity between  
201 fault traces was observed across the Ussita valley (Figure 2).

#### 202 *3.1 Short-term co-seismic displacement*

203 The short-term displacement of the VBFS has been determined through original field measurements  
204 of the coseismic ruptures and integrated with the available database of Villani et al., (2018a).  
205 Because of the high variability of the throws along the fault strike, we identified 84 points and we  
206 determined the arithmetic mean of the all throw measurements in the range of 25 meters around  
207 each point.

### 208 *3.2 Mid-term cumulative displacements*

209 We refer to mid-term displacements to characterize well-preserved geomorphic evidence of faulting  
210 following the Last Glacial Maximum. The Last Glacial Maximum corresponds to a period where  
211 changes in the modes of erosion are likely to have controlled the preservation of tectonic offsets  
212 (e.g., Peltzer et al., 1988). Due to the presence of the former neighboring ice sheets (e.g., Giraudi et  
213 al., 2003), the study area, at elevations between 1300 and 2400 m asl on average, was likely  
214 subjected to periglacial conditions during the last glacial phase. In this context, earlier cumulative  
215 offsets and fault scarps were potentially erased due to erosional processes (e.g., Peltzer et al., 1988).  
216 This assumption is also supported by  $^{36}\text{Cl}$  exposure dating of bedrock fault scarps in the Apennines  
217 that yields ages not older than 12-18 kyr (e.g. Palumbo et al., 2004, Benedetti et al. 2013, Cowie et  
218 al. 2017). In particular, the preservation of bedrock fault scarps along active normal faults is related  
219 to a strong reduction in rates of rock weathering and erosion, associated with the transition from  
220 glacial to interglacial climate (Tucker et al., 2011). Although bedrock fault scarps are more resistant  
221 to diffusional processes, they are still subjected to geomorphic processes that shape their surface  
222 expression such as channel incisions or landsliding. We thus carefully chose portions of the scarps  
223 that did not undergo through erosion or debris flow processes (i.e. no gullies), avoided areas with  
224 colluvial sediments or scree deposits (Bubeck et al., 2015).

225 To evaluate mid-term cumulative displacements, we used a high-resolution DEM from Pleiades  
226 images that were acquired after the 2016 earthquakes with a resolution of 2 m (courtesy of A.  
227 Delorme from IPGP); numerical computations were performed on the S-CAPAD platform, IPGP,  
228 France by using MicMac (Rosu et al., 2015; Pleiades image from 2017-01-12). Specifically, we

229 extracted 66 topographic profiles from the DEM along the VBFS. Pleiades images were not  
230 available for the area north of the Ussita River (CU sector), so we performed the same analysis by  
231 using the available 10-m DEM from Tarquini et al. (2012), although this approach implied  
232 considering a larger confidence interval when evaluating possible measurement errors.

233 The profiles were densely spaced (every  $\sim 200$  m) in areas where the fault scarp is well preserved,  
234 while we traced fewer profiles in areas where the cumulative offset is not adequately detectable, and  
235 only where measurements were possible (e.g.; Mt. Biccio fault profile, average spacing  $\sim 300$  m).

236 These profiles exhibited fault scarps with common characteristic features such as a displaced  
237 reference surface, a degraded scarp, a free face, and a colluvial wedge (Figure 3.a). The reference  
238 surface constituted a marker topographic horizon that could be distinguished in both the footwall  
239 (upper surface) and the hanging-wall (lower surface) of the fault and that was displaced following  
240 repeated faulting events affecting a regular topography that was previously leveled by a glacial  
241 phase. The free face is the approximation of the fault plane that began to be eroded after  
242 exhumation (by earthquakes), accumulating in the colluvial wedge at the base above the lower  
243 surface.

244 In general, fault-related scarps are generally strongly affected by degradation and aggradation  
245 processes (diffusion) that modify their original shape (Civico et al., 2015), especially in slowly  
246 deforming tectonic environments such as Italy, Greece or Spain (Caputo et al., 2013; Galli et al.,  
247 2008; Perez et al., 2006). As the footwall of a normal fault undergoes continuous uplift by repeated  
248 earthquakes, the upper surface goes through erosional processes, which modify the original slope  
249 angle. To distinguish these characteristic features, all the profiles were drawn with a length of 300  
250 m to better identify the displaced upper and lower surfaces, reducing the uncertainty from erosional  
251 processes. Because of the low steepness ( $\sim 3^\circ$ ) in correspondence with the Piano Grande, we traced  
252 four profiles with a length of 1000 m to ensure the morphological detection of the fault (MV5).

253 We measured the vertical displacement that was recorded by the upper and lower reference surfaces  
254 for each profile. For each topographic profile, we manually identified two reference surfaces (red  
255 line in figure S4) in the upper and the lower part having the same slope.

256 In some cases, the footwall slope is steeper than the one on the hanging wall and the identification  
257 of the reference surface is not easy. In that case, thanks to the high density of the performed  
258 topographic profiles (every ~200 m) we use as reference surface the one of a well-constrained  
259 proximal profile. In addition, when it was possible (e.g. Profiles MV 4.3, MV 4.5, MV 4.7), we  
260 defined more than one reference surface and we determined an average value of sloping surface  
261 with the associated error (see supplementary). The manual analysis was associated, for some  
262 profiles, to the semi-automated algorithm SPARTA (Scarp PARameteTer Algorithm) analysis,  
263 developed by Hodge et al. (2019). Specifically, this algorithm calculates the parameters of the fault  
264 scarp (i.e. height, width, and slope) from a scarp topographic profile by performing a best-fit  
265 calculation to a scarp-like template. Moreover, it enhances the clarity of the elevation profiles by  
266 filtering a range of non-tectonic features, such as vegetation peaks in DEMs from Pleiades images,  
267 through four digital filters (see details in Hodge et al. 2019 and references therein).

268 The vertical offsets determined by SPARTA and by manual measurements were very similar (see  
269 the supplementary material for details). Among the analyzed 66 profiles, 40 were qualified as  
270 poorly constrained and could not be analyzed by SPARTA. This is related to the badly preserved  
271 topographic fault scarp, such as in the Mt. Porche sector, or the poorly constrained upper and lower  
272 surfaces for example in the Mt. Vettore and Mt. Bove sectors mainly because of the presence of a  
273 great amount of scree deposits in the hanging-wall block. Those profiles were thus associated with a  
274 higher uncertainty (see the supplementary).

275 Where a topographic slope dips in the same direction as the fault dip, the topographic offset is less  
276 than the true vertical displacement; wherever the two dips have opposite directions, the topographic  
277 offset is larger than the real throw (Bull, 2009). Thus, we corrected the topographic offsets ( $T_o$ ) to

278 obtain true vertical displacements ( $Tr$ ) by using the equation of Bull (2009), who considered the dip  
279 angle of the fault ( $\alpha$ ) and steepness ( $\beta$ ) of the displaced topographic surface (Figure 3.a):

$$280 \quad Tr = (To [\sin\alpha * \sin(90^\circ + \beta)]) / \sin(\alpha - \beta) \quad (1)$$

281 The dip angles of the faults ( $\alpha$ ) are from field measurements and the database of Villani et al.  
282 (2018a). The dip angles vary between  $56^\circ$  and  $90^\circ$  with the most frequent values being between  $70^\circ$   
283 and  $73^\circ$  (19%), and between  $76^\circ$  and  $77^\circ$  (17%) (Fig. S2 in supplementary) and a mean value of  $73$   
284  $\pm 6.7^\circ$ . Where the bedrock fault plane is not outcropping (e.g. MP-sector) and the fault dip angle is  
285 unknown we use this mean dip angle value. Considering the most frequent values of the dip angles  
286 are  $70^\circ$ - $77^\circ$ , the uncertainty on the down-throw is  $\pm 5\%$ . Whereas, considering the two end-  
287 member values of  $56^\circ$  and  $90^\circ$ , the related uncertainty would be  $\pm 8\%$ .

### 288 *3.3 Long term Geological displacements*

289 We constructed seven geological cross-sections (traces in Figure 2.a) to determine the long-term  
290 geological down-throw of the VBFS with particular focus on the faults that were active in 2016.  
291 Starting from the available geological maps by Calamita et al. (1992) and Pierantoni et al. (2013),  
292 original field mapping was conducted to integrate and update the geological structural map of the  
293 area (Figure 2.a). Field surveys were conducted in some key areas (e.g., Mt. Bicco, Mt. Porche and  
294 Mt. Lieto in Figure 2) to better constrain the fault throw.

295 Given the complexity of the structural evolution of the study area (see section 2), we used the  
296 Marne a Fucoidi Fm. (Lower Cretaceous) as a reference marker to determine the vertical offset  
297 along the cross-sections. We made this choice because this formation is present throughout the  
298 region, has a constant thickness between 50 and 80 m, and records the total extension across the  
299 structures as a pre-Quaternary horizon. However, distinguishing pre-Quaternary displacements from  
300 the total down-throw is sometimes difficult, and the Quaternary fault displacements and slip rate  
301 can be overestimated (see section 2). Therefore, we analyzed only normal faults that showed  
302 morphological evidence of activity (i.e., after 18 kyr). Finally, we estimated the accuracy for around  
303 30 m of the geological throw measurements both in the field and on the geological maps.

## 304 **4 Results**

305 This section is divided into three sub-sections: (1) a presentation of long- and mid-term throw data  
306 plotted along a transect line that approximates the average strike of N150° for the VBFS (see the  
307 location in Figure 2), (2) a comparison with the 2016 coseismic throws plotted over the same  
308 transect line, and (3) an interpretation of the three databases and the determination of the throw  
309 rates.

### 310 **4.1 Geological throw (long-term)**

311 The throw values that are obtained from geological cross-sections define the long-term history of  
312 the VBFS and are useful for understanding the relative age of the fault segments, helping us define  
313 a constant long-term throw rate for Quaternary active normal faults. Figure 4.a displays the  
314 geological throw distribution along the entire fault system. To compare the throw values among the  
315 long-, mid- and short-term datasets, we plotted the throw values that were measured on active faults  
316 (in this study, those with evidence of post-LGM activity). The lowest geological throws for faults  
317 having geomorphological evidence of activity (red faults in Figure 2.a) were in the southern portion  
318 of the VBFS (100-150 m for faults in the Mt. Vettore sector), whereas the central-northern sector  
319 of the VBFS showed higher values of 200-400 m at Mt. Porche and Mt. Bove. The maximum was  
320 at Mt. Bove, where the geological throw reached 400 m for a single fault and 800 m for the  
321 cumulative throw.

### 322 **4.2 Morphological throws (mid-term)**

323 The morphological throw that was related to the post-LGM activity of the VBFS was evaluated  
324 through fault-scarp recognition and measurements on high-resolution topographic profiles  
325 following the method in section 3.

326 Measured throws depend on the slip vectors (net slip) and their direction. When fault planes are  
327 exposed at the base of a fault scarp, striae provide measurements of the net-slip vector (see Figure  
328 3.b). Depending on the variability of the strike of the fault, i.e., some faults that deviate from pure

329 ENE extension, the slip vector may show a slight strike-slip component (Perouse et al., 2018). The  
330 throw corresponds to the vertical component of the slip, which we assume represents the dip-slip  
331 component (Figure 3.b). In the hypothesis of an oblique vector, the net slip is distributed on the  
332 vertical (dip slip) and horizontal components (strike slip). Therefore, before analyzing the throw  
333 variation, we first question how much the strike-slip component, which is mostly present where the  
334 fault plane produces strike-bending, can influence the measured topographic offset along the  
335 VBFS.

336 Figure 5 shows the bedrock fault-plane measurements (the site's location is indicated in the  
337 supplementary materials) with strong strike-slip (left- or right-lateral) components; each  
338 measurement has three components, all shown in meters to facilitate comparison with the measured  
339 topographic offset (i.e., the down-throw), namely, the net slip (total slip vector), dip slip, and strike  
340 slip.

341 The field structural data showed that the strike of the bedrock fault planes ranged between N120°  
342 and N190°, with kinematic indicators showing rake values between 70° and 96°. We determined the  
343 net-slip vector of each site by considering the slip-vector geometry from these data and the down-  
344 throw from the measured topographic offset. When considering a 70° rake angle, the net slip  
345 comprised at most 34% of strike slip component. This only occurs in the MV sector, where there is  
346 a quite strong strike slip component (Perouse et al., 2018) but still it is not affecting the results since  
347 it is within the uncertainties that we get for the down throw in this area. As shown in Figure 5, the  
348 lateral component is lower than 20% and still within the uncertainties of the down throw. Thus, we  
349 can assume that the topographic offset is within uncertainty similar to the net slip in most areas  
350 along the VBFS.

351 To show the contribution from each fault segment to the VBFS's mid-term growth, we plotted the  
352 throw value for each post-glacial fault scarp along the transect line in Figure 4.b, where the fault  
353 segments are color-coded. Figure 4.b shows the maximum throw at around 4-6 km on the transect  
354 line (MV sector), with an offset displacement of 24 m for a single segment that decreases towards

355 the tip of the system to the south and reaches 5 m of throw 2-3 km northward. In the MP sector (7-  
356 13 km on the transect line), the vertical-slip distribution rises at a constant average value of 15-20 m  
357 for both synthetic and antithetic faults. In the MB sector (13-20 km on the transect line), a ~20-m  
358 peak sharply decreases to zero. Northward, the Ussita valley has no evidence of cumulative fault  
359 activity, whereas the CU sector (20-26 km on the transect line) has 10 m of maximum vertical  
360 displacement.

361 The total cumulative mid-term throws (i.e. the summed throws at each point) along the transect line  
362 showed a slip distribution that matched the throws of each segment for the same sector. In  
363 particular, the maximum/minimum total cumulative throws correspond to the location of the  
364 maximum/minimum throws at the same position along strike; this pattern suggests sites of preferred  
365 surface slip along the VBFS.

#### 366 **4.3 Comparison with the 2016 coseismic throw (short-term)**

367 The short-term throw, which was measured in the field after the 2016 seismic events, varied along  
368 the VBFS. The coseismic ruptures showed maximum throws in the southern portion of the fault  
369 system, reaching almost 2 m and lower values north of the MV sector, where the throws did not  
370 exceed 1 m (Villani et al. 2018a).

371 The comparison of the profile shapes from the analysis of the three different time scales for the  
372 active faults denoted an agreement between the mid- and short-term throw profiles. The maxima of  
373 the two throw profiles are located in the same positions along the strike. The coseismic throw  
374 profiles and mid-term cumulative-throw profiles from the addition of several earthquakes developed  
375 asymmetric patterns, with the highest throw in the southern area (MV sector, between 4 and 6 km  
376 on the transect line). The profiles both showed a decrease in the throw, which reached zero within 2  
377 km, at the southern tip of the VBFS.

378 In addition to the good match between post-LGM (mid-term) and short-term throws in the southern  
379 sector, the coseismic rupture pattern throughout the fault system sometimes deviated from what was  
380 recorded on the morphology. For instance, the coseismic ruptures in the MP sector (9 km along the



381 transect line, Figure 4.c) reached a value of 95 cm above the mountain crest. However, we did not  
382 observe any morphological evidence of a fault scarp in this area. Between 16 and 18 km, two  
383 different throws were found in the Mt. Bove sector for the mid- and long-term scales (i.e.,  
384 geological throw = 800 m and post-LGM throw = 30 m), which were not observed in the short-term  
385 profile (i.e., 50 cm of coseismic rupture).

386 Common elements at all time scales for the active faults at the surface were observed between 18  
387 and 20 km on the transect line in the Ussita valley. No evidence of geological fault traces  
388 characterized the area (Pierantoni et al., 2013; Pizzi et al., 2017; Brozzetti et al., 2019; Porreca et  
389 al., 2020), suggesting that this region was not affected by faulting over the last 18 kyr. This lack of  
390 faulted areas matches the evidence that the Ussita River is the only westward-flowing river that  
391 bypasses the drainage divide of the Central Apennines range. In addition, no clear coseismic  
392 ruptures occurred in this area during the 2016 seismic sequence. The occurrence of the coseismic  
393 ruptures north of this valley (at the Cupi-Ussita segments) suggests that the northernmost tip of the  
394 system is on the other side of the Ussita valley. Thus, rather than an area not interested by the faults,  
395 we observed a zone of minimum surface slip, persistent in time.

396 According to a quantitative analysis of the matching shape profiles, the mid- and short-term throw  
397 distributions in the Mt. Vettore sector showed a very good relationship. In particular, the cumulative  
398 profiles at mid- and short-term are very similar: both have the maximum throw between 4 and 6 km  
399 along the transect line and decrease rapidly within 2 km (Figure 4.b and c). The highest and lowest  
400 values are constantly recorded on the fault segments MV2 and MV5, respectively. Moreover, the  
401 ratio between the short- and mid-term throw values is shown for each segment in the MV sector and  
402 at each measured point, having a good correlation factor ( $r = 0.7$ , Figure 6).

#### 403 **4.4 Throw rates and fault-system evolution**

404 Based on the above data, we could reconstruct the VBFS's evolution from its onset in the Early  
405 Quaternary to the present. The evolution through time of VBFS has been determined from the  
406 vertical slip rates. We traced cross-sections that were orthogonal to the reference transect line, along

407 which we summed the maximum cumulative displacement of all the fault segments belonging to  
408 each fault sector (MV, MP, MB, and CU). To avoid overestimation, we choose the cumulative  
409 displacement from the best-constrained topographic profile, having low errors in the offset  
410 measurements. In addition, we calculated the slip rate along the fault considering that the  
411 cumulative offset is bracketed between the total cumulative offset and the total cumulative offset  
412 minus the measured 2016 coseismic offset, assuming a periodic behavior. We implied the highest  
413 throws for each sector, so the obtained values are to be considered the maximum throw rates for  
414 each sector. Significant variations in the throw distribution and throw rates appeared in both time  
415 and space.

416 For the mid-term maximum throw rate, thus the rate calculated over 18 kyr, we found a  
417 heterogeneous pattern of the VBFS. The MV sector's throw rate is  $1.65 \pm 0.05$  mm/yr (total  
418 cumulative offset 31.8 m and coseismic offset of 2.8 m). The throw rates for the MP sector is  $0.95$   
419  $\pm 0.5$  mm/yr (total cumulative offset 18 m and coseismic offset of 0.9m), for the MB sector  $1.25 \pm$   
420  $0.5$  mm/yr (total cumulative offset 24 m and coseismic offset of 0.7 m); and for the CU sector the  
421 velocity is 0.5 mm/yr (total cumulative offset 9.1 m and coseismic offset of 0.1 m). The throw rate  
422 determined on the fault with the highest throw (MV2) is  $1.3 \pm 0.1$  mm/yr and it matches the value  
423 of  $1.31 \pm 0.27$  mm/yr determined by Brozzetti et al. (2019) over the last 15 kyr.

424 The long-term slip history of the VBFS is affected by uncertainties that are related to the absence of  
425 accurate chronology on the onset of the segments and the duration of activity along these faults  
426 without evidence of activity after the LGM. To determine the long-term throw rates, we considered  
427 only active faults (all faults with morphological evidence) and calculated their velocities since the  
428 beginning of extension (1.1-1.2 Ma, Blumetti and Dramis, 1992; Coltorti et al., 1998; Calamita et  
429 al., 1999). The Mt. Bove and Mt. Porche sectors hosted the active segments with the highest throws  
430 (800 m of cumulated displacement and 500 m as the highest throw for single fault segment),  
431 suggesting major activity along these faults over long time scales. We found a maximum throw rate  
432 of 0.8 mm/yr when considering the highest vertical geological displacements of the entire VBFS.

433 The obtained value was within the range of slip rates that were estimated by Pizzi et al. (2002) for  
434 the VBFS (0.6-0.9 mm/yr). The throw rates of the Central Apennines' fault systems range between  
435 <0.2 and 1-2 mm/yr (Barchi et al., 2000; Benedetti et al., 2013; Roberts & Michetti, 2004;  
436 Papanikolaou et al., 2005; Civico et al., 2015b; Cowie et al., 2017). The high values of the VBFS  
437 are reached by the Fucino fault: from 0.55 (at the tips) to 2 mm/yr (in the center of the system). The  
438 variation in the throw rate along the Fucino fault system was interpreted to be an increase in the  
439 growth rate over the last 700 kyr (Cowie & Roberts, 2001; Roberts & Michetti, 2004).

440 Throw rates for the VBFS are higher than some faults in the Northern Apennines, such as the  
441 Colfiorito fault that is suggested to have a rate of 0.3 mm/yr by Barchi et al.(2000), and Mirabella  
442 (2016) and  $0.67 \pm 0.13$  mm/yr by Mildon et al. (2016).

443 From our results, it appears that the segments with high geological displacement but without post-  
444 LGM activity are mainly located at a low elevation close to the Quaternary basin's boundaries (e.g.,  
445 MV8 fault bounds the Piano Grande). Whereas fault associated with the highest mid- and short-  
446 term throws are generally located at a higher elevation close to the ridges (e.g., MV2 fault at Mt.  
447 Vettore), or even on the ridge close to the drainage divide (e.g., MP2 fault at Mt. Porche). This  
448 observation suggests that the most recently activated segments are located on the footwall of the  
449 faults that were formerly active probably during an earlier stage of the extension, suggesting there  
450 might be a shift of the activity at least for about 18 kyr.

451 Moreover, the maximum activity (in terms of throws pattern) at mid- and short-term scales were  
452 concentrated in the southern sector of Mt. Vettore with high throw rates. The good linear correlation  
453 between the short- and mid-term scales (Figure 6) might suggest that the fault system evolved with  
454 a similar pattern over time since at least the last 18 kyr. Figure 7 shows the evolution of the throw  
455 both in time and space of the VBFS. The maximum throw is localized on the MV- sector since the  
456 last 18-kyr associated with a higher rate of slip increment compared to the other sectors of MP, MB,  
457 and CU.

458 Thus, assuming a constant maximum throw rate of  $1.65 \pm 0.5$  mm/yr, calculated from the mid-term,  
459 and considering 380 m of cumulative geological displacements, evaluated by the sum of the max  
460 displacement of each segment in the cross-sections, we could infer an origin of the active faults at  
461 the surface at Mt. Vettore at about  $\sim 200$ -250 kyr ago. Considering the general onset of the VBFS  
462 was 1.1-1.2 Myr (Blumetti and Dramis, 1992; Coltorti et al., 1998; Calamita et al., 1999; see section  
463 2), and the uncertainties about the age and throw of the basin boundary fault (see section 2), the  
464 MV sector would be characterized by younger faults. The resolution of the available sub-surface  
465 data (Porreca et al., 2018) does not allowed determining how the active faults and the basin  
466 boundary fault are related at depth. But from our surface data the presence of these young faults  
467 might be interpreted or as a consequence of the southward propagation of the fault system (i.e.  
468 from the MB-MP- sectors to the MV- sector) or due to an activity “replacement” of the older  
469 basin boundary fault at the surface, probably at  $\sim 200$ -250 kyr.

470 This southern tip of the system hosts high-density, widespread, short unlinked and newly formed  
471 faults, marking a relatively more distributed deformed volume than a single master fault that  
472 accommodated seismic slip in a narrower zone, such as in the northern VBFS (Figure 7).

## 473 **5 Discussion**

474 The detailed mapping of the 2016 coseismic ruptures clearly showed that a well-defined peak at its  
475 southern tip in the MV sector characterized the throw-distribution pattern along the VBFS. In  
476 particular, in agreement with many authors (Lavecchia et al., 2016; Livio et al., 2016; Pucci et al.,  
477 2017; Civico et al., 2018; Villani et al., 2018b), the coseismic throws at Mt. Vettore were  $\sim 0.10$ -  
478 0.15 m (with a local maximum of 0.30 m), and  $\sim 1.5$  m (locally reaching 2 m) for the 24 August  
479 event (Mw 6.0), and the 30 October event (Mw 6.5), respectively. These high values went beyond  
480 the expected values from the empirical relationships between the magnitude vs surface  
481 displacement (Wells & Coppersmith, 1994). In particular, the recorded slip at Mt. Vettore after the

482 30 October event exceeded the power-law and exponential scaling by two orders of magnitude  
483 (Villani et al., 2018b).

484 According to the slip models obtained from strong motions, GPS, and DInSAR for 24 August and  
485 30 October 2016 events (e.g. Chiaraluce et al., 2017; Cheloni et al., 2017; Scognamiglio et al.,  
486 2018; Walter et al., 2018; Ragon et al., 2019), the rupture propagated to the surface mainly in the  
487 MV sector. In this sector, the rupture propagated to the surface producing in 6–8 seconds the  
488 highest observed coseismic slip of the entire system (Wilkinson et al., 2017), along with significant  
489 off-fault deformation that occurred close to those faults with spectacular surface offsets (Delorme et  
490 al., 2020).

491 Furthermore, some authors (e.g. Scognamiglio et al., 2018; Walters et al., 2018) suggested that the  
492 ruptures did propagate at depth, in the first ~5-6 km, at the fault intersections between the VFBS  
493 and the LF, where also slip occurred.

494 The earthquakes on both 24 August and 30 October with epicenters located to the south and north  
495 of the trace of the OAS thrust ramp, respectively, produced the maximum surface displacement  
496 along the same fault segments in the MV sector (e.g., Brozzetti et al., 2019; Gori et al., 2018). The  
497 throw distribution pattern of the 2016 coseismic rupture has been defined by many authors (e.g.,  
498 Villani et al., 2018b; Brozzetti et al., 2019) as an anomaly in the slip concentration at the MV sector  
499 (both 24 August and 30 October).

## 500 **5.1 Slip profiles and fault throw at various time scales**

501 One of the main results from our study noted that the anomalous slip concentration in the MV  
502 sector is not a phenomenon that only refers to the 2016 seismic sequence, but rather constitutes the  
503 characteristic method through which the Mt. Vettore fault has broken during at least the last 18 kyr.

504 The similarity between the along strike displacement recorded in the short-term and mid-term  
505 profiles in the MV-sector can be interpreted either as the faults have experienced a similar rupturing  
506 pattern over the last 18 kyr; or as individual successive earthquakes with variable slip distributions

507 produce an overall cumulative pattern over the last 18 kyr similar, to the one observed for the 2016  
508 short-term one.

509 Paleoseismological trench studies (Galadini and Galli, 2003; Galli et al., 2019; Cinti et al., 2019),  
510 suggest that not only the MV sector but the entire system experienced at least seven events of  $M_w \approx$   
511 6.5, thus similar to the 2016 Norcia-type (or larger) surface-faulting event, over the last 22 kyr.  
512 Comparing the vertical displacements of the penultimate event found in the trenches (E2 occurred  
513  $\sim 4^{\text{th}}\text{-}5^{\text{th}}$  century CE) for segments MV, MP4, and MP5, we found a pattern that seems to agree quite  
514 well with the constant growth pattern of the mid- and short-time scale (Figure 8). Those results also  
515 infer that the rupturing pattern is similar to the one observed in 2016, with multiple fault segments  
516 rupturing during a single individual event. This evidence strengthens the first hypothesis of the  
517 repeating self-similar rupturing pattern, where different seismic events produce the analogous slip  
518 distribution, with maxima throws always on the same fault segments. Thus, the asymmetric,  
519 triangular throw profiles of the VBFS that were created in tens of seconds (2016 coseismic  
520 ruptures) and over tens of thousands of years (cumulative fault scarp) resemble each other (see Figs.  
521 4 and 9).

522 This similarity has also been observed by Brozzetti et al. (2019), Iezzi et al., (2018) in some faults  
523 of the Mt. Vettore (specifically, MV1, MV2, MV3, MV4 and MV5 in our study), whether at  
524 morphological, geological scale or in terms of the largest topographic relief. A different  
525 interpretation, however, has been hypothesized for this evidence. In particular, Iezzi et al. (2018)  
526 interpreted this highest slip concentration in the Mt. Vettore faults as a consequence of the  
527 particular local structural fault geometry suggesting that throw increased because of a slip vector  
528 accommodation due to a bending of the fault strike of  $\sim 28^\circ$  and to the related fault dip angle  
529 increase. Brozzetti et al. (2018) suggested that this anomaly might be due to irregularities of the  
530 fault at depth due to local tectonic factors, such as the suggested back tilting that amplified the  
531 coseismic displacement in this area (Testa et al., 2019).

532 Our results also suggest that the segment MV2 in the Mt.Vettore is not the only one to exhibit such  
533 high throw since all the other segments in this sector displayed relatively high throw compared to  
534 the other segments of the VBFS. If we consider the ratio between the height of the post-LGM fault  
535 scarp and the value of the 2016 coseismic ruptures along the main fault at Mt. Vettore and its sub-  
536 parallel segments, we obtain a constant value. Thus, we interpret the MV sector of the VBFS as  
537 having homothetic growth behavior, with an anomalous high displacement on all the segments,  
538 suggesting that those are interacting (Gupta and Scholz, 2000; Mirabella et al., 2016).

539 As observed by Duross et al. ( 2016) in the Wasatch Fault Zone (Basin and Range Province) from  
540 paleoseismological studies, the possibility of interaction between segments in areas of structural  
541 complexity seems to permit more complex fault ruptures, such as the multi or partial rupturing of  
542 segments observed in the 2016 seismic sequence (Villani et al., 2018b). In addition, as we observed  
543 for the MV sector in the VBFS, the Wasatch Fault Zone corresponds to the fault tip of a wider fault  
544 system. Studies on vertical displacements performed on this latter showed how the Wasatch Fault  
545 Zone is characterized by the highest fault throws, ~20 m of throw versus ~10 m in the other  
546 “zones” (Friedrich et al., 2003 and reference therein). This exceeding throw at the Wasatch Fault  
547 Zone has been interpreted as an acceleration in the throw rates during the Holocene (Friedrich et al;  
548 2003).

549 Furthermore, according to the classification of fault structural maturity described by Dolan et al.  
550 (2014) and Nicol et al. (2010), the frequent fault-strike variation associated with the VBFS’s  
551 southern sector would suggest that it is structurally immature compared to the northern area (MP-  
552 MB-CU sectors), where the deformation is concentrated on the main fault structures. Moreover, the  
553 overall low velocities of slip propagation at depth were 3.1 km/s for the Mw 6.0 event, 2.7 km/s for  
554 the Mw 5.9 event and 2.7 km/s for the Mw 6.5 event, as obtained by finite-fault analysis (Tinti et  
555 al., 2016 and Chiaraluce et al., 2017). These values, as well the fault parameters that define the  
556 structural maturity in Perrin et al. (2016) and references therein, indicate that the entire system

557 VFBS system is actually classified as immature (e.g. rupture velocities of  $<3$  km/s, fault length  $<$   
558 300 km, initiation age  $<$  few Ma).

## 559 **5.2 Role of inherited structures**

560 In an evolving extensional active system such as the VBFS, what can cause such preferred slip  
561 zones towards a tip of the fault system, thus an activity concentration and a slip gradient increasing?  
562 Two possibilities have been previously suggested for such observation: (1) a fault-linkage zone,  
563 where the slip is concentrated at the tips of two overlapping faults (e.g., Peacock and Sanderson,  
564 1991), and (2) a fault-barrier zone, where the fault slip increases as a response to the inhibition of  
565 lateral fault propagation because of interference with a major “barrier” at depth (e.g., Madariaga,  
566 1979; Lay & Kanamori, 1981; Das & Kostrov, 1983; Mendoza, 1993; Ruff & Miller, 1994;  
567 Somerville et al., 1999; Das, 2003; Manighetti et al., 2001; 2005).

568 In the hypothesis of a “fault-linkage zone”, the asymmetric maximum displacement in the VBFS  
569 would be the result of the natural evolution of the fault system that starts to interact with another  
570 fault system, in agreement with the evolutionary model of a fault system as observed in Gawthorpe  
571 and Leeder (2000). The southern tip of the VBFS would be propagating toward the Laga Fault (LF),  
572 which in turn has an asymmetric geological displacement profile with a maximum in its northern  
573 part (Boncio et al., 2004), through a zone with no evidence of faulting at the surface. The  
574 interaction at depth between the VBFS and the LF, however, seems supported by the occurrence of  
575 the location of the Mw 6.0 event on 24 August (Chiaraluce et al., 2017) in the relay zone of the  
576 two systems, away  $\sim 9$  km and  $\sim 7$  km from the VBFS and LF, respectively (see Figures 1 and 9).

577 The second broad class of studies suggest the presence of a “fault-barrier zone”. Although the  
578 concept of a “barrier” is still debated by many authors, this terminology can describe a zone that  
579 prevents slip propagation and allows high-throw gradients to be maintained (Manighetti et al.,  
580 2005). Whatever the process, these areas are affected by specific mechanical or rheological  
581 properties and a resistance to the coseismic rupture. In the context of the VBFS, the geometrical



582 relationship with a potential barrier at depth is still debated and difficult to reconstruct due to the  
583 lack of robust subsurface data.

584 But the occurrence of the 2016 seismic event provided new insights in understanding the interaction  
585 (both at the surface and depth), of the VBFS with the crustal pre-existing oblique OAS thrust ramp,  
586 which previous authors assumed as a structural barrier (Pizzi and Galadini, 2009). At the surface  
587 (Figure 9), the coseismic ruptures of the VBFS crosscut the trace of the OAS thrust (e.g., Bonini et  
588 al., 2016; Livio et al., 2016; Civico et al., 2017; Pizzi et al., 2017; Iezzi et al., 2018; Villani et al.,  
589 2018a,b; Brozzetti et al., 2019; Porreca et al., 2020). While at depth, slip models from different  
590 datasets showed how the mainshocks- rupturing process interacted with the deep high-angle part of  
591 the OAS thrust (Tinti et al., 2016; Chiaraluce et al., 2017; Cheloni et al., 2017; Scognamiglio et al.,  
592 2018; Ragon et al., 2019; Gallovič et al., 2019).

593 Furthermore, the slip model of Ragon et al. (2019), which was derived from GPS analysis,  
594 suggested that the rupture on 24 August had a bi-lateral propagation direction. The slip, which was  
595 plotted on a 45°-dipping fault plane, was confined to the south in a narrow zone 2-5 km deep  
596 (Walters et al., 2018), and to the north was more distributed , propagating both downdip (until 8-9  
597 km depth) and climbing up towards the surface (above 3 km depth in the MV sector). In agreement  
598 with Ragon et al. (2019, and references therein), we suggest that the modalities of the northward  
599 slip transfer could have been controlled by the presence of the high-angle OAS thrust ramp, which  
600 prevented the lateral northward propagation of the rupture. On the other hand, the hypocenter of the  
601 24 August event was located on the footwall of the OAS thrust, while the rupture reached the  
602 surface only on its hanging-wall. This observation suggests that the rupture bypassed the OAS  
603 thrust only in its shallowest and low angle portion, producing coseismic surface rupturing in the  
604 MV sector. In other words, this vertical propagation might have been confined in an area where the  
605 OAS thrust halted northward lateral propagation (Figure 10.a). Despite the lithology that might  
606 control the slip propagation to the surface, minor surface ruptures can occur in the Laga Fm., as  
607 Vignaroli et al. (2020) suggested over the late Quaternary.

608 The event on 30 October was modeled by Scognamiglio et al. (2018) through strong-motion data  
609 (Figure 10.b). The slip model was plotted on a 47°-dipping fault plane, highlighting rupturing that  
610 was confined above ~7 km depth. The slip propagated to both the north, where the rupture reached  
611 the surface at Mt. Bove and only affected the first 2 km, and the south, reaching the surface at Mt.  
612 Vettore-Mt. Porche. The hypocenter was at 9.5 km depth, where the rupture nucleated and mainly  
613 expanded towards the surface. In correspondence with the OAS thrust at depth, this rupturing only  
614 crossed it between 5 and 7 km depth, triggering a small patch of around 50-100 cm of slip south of  
615 the OAS thrust. All the patches with slip above 100 cm were located north of the OAS thrust,  
616 defining a rupture area whose southward limit seemed to follow the OAS thrust. On the other hand,  
617 Scognamiglio et al. (2018) and Improta et al. (2019) modeled the rupture distribution with the OAS  
618 thrust as a source in their kinematic inversion. Although we agree that some slip could have  
619 occurred on the OAS thrust ramp, we believe the VBFS was the major source of this event  
620 according to our results and the focal mechanism, which corresponds to an NNW-SSE dip-slip  
621 fault.

622 Therefore, these two slip models for the 24 August and the 30 October suggest a major slip  
623 interference at depth (below ~ 5 km), that may be interpreted as a barrier producing an interruption  
624 in the lateral slip propagation (northward and southward, respectively), in favor of a transferring  
625 rupture toward the surface, at the MV sector.

626 In this hypothesis, the presence of a deep barrier is observed at the surface from a major fault slip  
627 accumulation and other features such as fault interactions, and fault fragmentation associated with  
628 bends (Manighetti et al., 2005).

629 Based on our long- mid- and short-term surface data and the 2016 rupturing scenario from the after-  
630 mentioned inversion slip models, we interpret the maximum throw in the southern tip at the MV  
631 sector, as the result of southward increase in the rate of fault system activity (occurred between 1.2  
632 Ma and 18 kyr, see Figure 7). The suggested southward growth in fault activity (see section 4.4)  
633 could indicate an ongoing linkage process with the Laga Fault and an incipient development of a

634 secondary fault in the relay zone (where the 24 August hypocenter is located) without surface  
635 evidence (see point 4 in Figure 9).

636 On the other hand, this evidence along with the observed segment interactions and the more  
637 widespread deformed area in the MV sector (see section 4.4) suggest that the maximum throw could  
638 be related to the presence of a main structural barrier at depth. The barrier may likely coincide with  
639 the high-angle OAS thrust (below 5 km of depth) that prevents the natural free southward  
640 propagation and the fault linkage, enhancing the deformation through increment vertical  
641 displacement.

## 642 **5 Conclusions**

643 The multi-temporal analysis that we performed on the vertical displacements of the active faults  
644 (i.e., with post LGM activity) of the Mt. Vettore-Mt. Bove fault system (VBFS) characterized its  
645 spatial and temporal evolution. The 2016 seismic events ruptured the entire VBFS producing a  
646 maximum displacement in the southern sector of the Mt. Vettore sector. Our results, in agreement  
647 with Brozzetti et al. (2019), showed that these maximum values of displacements localized in the  
648 south, are persistent at least over the last 18 kyr (post-LGM), and are mainly located on the faults on  
649 the western flank of the Mt.Vettore. While the basin boundary fault associated with the highest  
650 geological displacement has no evidence of recent ( Post-LGM) activity.

651 On the contrary, the active faults display the highest geological displacement related to the onset of  
652 extension (i.e. 1.1-1.2 Myr) in the central northern sectors of the VBFS, at the Mt. Bove sector.

653 The throw distributions pattern along the VBFS length of the coseismic (short-term) and post LGM  
654 (mid-term) displacements exhibited a similar, asymmetric shape. Thus, the Mt. Vettore sector  
655 experienced homothetic growth, with all the segments maintaining the same throw profile through  
656 time. This suggests a similar growth pattern over the last 18 kyr in the VBFS system  
657 notwithstanding with a different amount of displacement depending on the magnitude of the  
658 earthquake, as occurred for the 24 August and the 30 October 2016 events, as also observed in

659 paleoseismological studies (Galadini and Galli, 2003; Galli et al., 2019; Cinti et al., 2019). In the  
660 Mt. Vettore sector, the rates at which this evolution occurred from the last 18 kyr were  $1.65 \pm 0.5$   
661 mm/yr. If we assume this throw rate constant over time, and we consider the cumulated geological  
662 displacement, we can determine an age for this sector of around 200-250 kyr. This age can be  
663 interpreted as the onset of the faults in the Mt. Vettore western flank due to a southward shift of  
664 activity that produces the highest throws.

665 We interpreted the maximum displacements at mid and short-term at the southern tip of the system,  
666 as related to an ongoing linkage process with the Laga Fault. Several observations, including the  
667 sharp decrease in throw at the intersection between the Mt. Vettore sector and oblique structure of  
668 the OAS thrust, suggest that this inherited structure may also act as a barrier in this scenario. In this  
669 perspective also the origin of the Mt. Vettore fault and its very high slip rate could indicate that  
670 starting from ~200-250 kyr, the VBFS is trying to overcome the barrier. In this way, the barrier  
671 concentrates the stresses within the Mt. Vettore sector and prevents the southward lengthening of  
672 the system, which instead accommodates deformation through high throws. However, a small  
673 portion of the OAS thrust between 5 and 7 km depth appears to have been offset by the Mt. Vettore-  
674 Mt. Bove fault system. This phenomenon could be the first step to link the VBFS with the LF.

675 Furthermore, The good-to-perfect match between the short- and mid-term throw profiles showed  
676 that faults with post 18 kyr morphological evidence of activity are more prone to break in a future  
677 seismic event and should be considered as having a higher risk of rupturing in the seismic-hazard  
678 assessment. This suggests that an upper limit of fault activity of 18 kyr could be reasonable to  
679 discriminate active and capable faults, at least for similar morphological and seismotectonic  
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1073 **Figure 1.** The neotectonic framework of the Central Apennines and location of the Central Italy

1074 2016 seismic sequence. In black are the active fault systems from Benedetti (1999), Tesson et al.

1075 (2016), and references therein. The study area (blue rectangle) is the Mt. Vettore-Mt. Bove fault  
 1076 system (VBFS). The other faults are the Laga Fault (LF) and Gorzano Fault (GF). The main  
 1077 Neogene thrusts are shown in grey: Valnerina Line (VL), Olevano-Antrodoco-Sibillini (OAS), and  
 1078 Gran Sasso (GS) (Calamita et al., 2011; Di Domenica et al., 2014). The focal mechanism of the  
 1079 1997 Colfiorito earthquake is from the CMT catalog (Dziewonski et al., 1981; Ekström et al.,  
 1080 2012). The focal mechanisms of the 2009 to 2017 events are from the INGV web page  
 1081 (<http://cnt.rm.ingv.it>). Historical events (white circles) with their dates (AD) are from the CPTI15  
 1082 catalog (Rovida et al., 2016) Inset: study area at a large scale. Modified after Perouse et al. (2018).

1083 **Figure 2.** a) Geological map of the VBFS in the Central Apennines; see Figure 1 for the location.  
 1084 Modified after Pierantoni et al. (2013): Calcare massiccio Fm. (MAS), Bugarone Fm. (BU),  
 1085 Corniola Fm. (COI), Rosso Ammonitico Fm. (RSA), Calcari a Posidonia Fm. (POD), Marne del  
 1086 Serrone Fm. (MSE), Calcari Diasprigni Fm. (CDU), Maiolica Fm. (MAI), Marne a Fucoidi Fm.  
 1087 (FUC), Scaglia Bianca Fm. (SBI), Scaglia Rossa Fm. (SAA), Scaglia Variegata Fm. (VAS), Scaglia  
 1088 Cinerea Fm. (SCC), and Laga Fm. (LAG). The dashed lines are the cross-section traces (in the  
 1089 supplementary Figure S5). The structural symbols are the same as those in Figure 2.b. b) Shaded  
 1090 relief map of the VBFS from a 10 m-resolution DEM. The red stars indicate the locations of the  
 1091 three 2016 mainshocks with their focal mechanisms. The blue transect line indicates the fault  
 1092 system's average strike of  $N150^\circ$  and the main sectors of the system: Mt. Vettore (MV), Mt. Porche  
 1093 (MP), Mt. Bove (MB) and Cupi-Ussita (CU). The active normal faults (solid red lines) are faults  
 1094 that ruptured during the 2016 earthquakes and showed morphological evidence on the topography.  
 1095 The inferred active normal faults (red dashed lines) are faults with morphological evidence that did  
 1096 not rupture in 2016.

1097 **Figure 3.** a) Characteristic features of fault scarps that were used for measurements on high-  
 1098 resolution topographic profiles. The topographic offset ( $T_o$ ) for each profile is the vertical  
 1099 separation between two portions of a unique marker surface (with slope  $\beta$ ) that was displaced by a  
 1100 fault (with dip angle  $\alpha$ ). b) Components of a net-slip vector on the fault plane. The fault down-throw  
 1101 ( $Tr$ ) is the projection on a vertical plane of the net-slip vector. See the text for an explanation of the  
 1102  $Tr$  evaluation. The degraded scarp and colluvial wedge are the results of erosion processes that  
 1103 smooth the fault scarp over time.

1104 **Figure 4.** Throw along-strike at three timescales for VBFS. Location of measurements indicated by  
 1105 red squares placed on the projected position along the Transect line. Dashed faults indicate faults  
 1106 with no available data but with throws (at long/mid/short term)  $> 0$ . A grey area defines cumulative  
 1107 total displacement for each position along the Transect line (both east and west-dipping faults). a)

1108 Long-term geological displacements b) Mid-term morphological throws, c) Short-term coseismic  
1109 throws.

1110 **Figure 5.** Downthrow and slip components values (net, dip and strike-slip components) in Mt  
1111 Vettore area for each segment. The measured rake at each site is also displayed. The strike-slip  
1112 component is always small with respect to dip-slip portion, and downthrow is not affected by the  
1113 strike-slip component (see the supplementary for the data locations).

1114 **Figure 6.** Cumulative throw vs coseismic throw diagram. The thick red line defines the proportional  
1115 envelope between the two datasets. The thinner lines are related to the trends of each fault segment  
1116 and are color-coded according to the corresponding segments. The colored data indicate orange  
1117 MV1 fault, light-blue MV2 fault, purple MV4 fault, and grey MV5 fault.

1118 **Figure 7.** Map of the throw evolution through time: a) short-term throw, b) mid-term throw, c)  
1119 long-term throw. The color scales show the range of vertical displacement at each time frame. d)  
1120 Cumulative displacement profile at each time scale (synthetic plus antithetic faults). The red point  
1121 indicates the maximum throw position: in the mid-term, there is a southward migration of this point.

1122 **Figure 8.** Correlation among a) short-term throw, b) mid-term throw, and c) throw of the  
1123 penultimate event found in the trenches excavated in segments MV5 (Galadini e Galli, 2003), MP4  
1124 (Cinti et al., 2019) and MP5 (Galli et al., 2019); d) summary of the timing events, modified from  
1125 Cinti et al., (2019). The values shown in panels a) and b) are related to the data where the trench has  
1126 been dug (i.e. MP5.1, MP 4.1, MV 5.3).

1127 **Figure 9.** Block diagram that shows the relationships between the VBFS and OAS and the locations  
1128 of the 2016 mainshock hypocenters at depth (from Chiaraluce et al., 2017) along the fault plane  
1129 (simplified as a single and long plane). (1) Southernmost MV sector, which recorded the highest  
1130 throw of the system during the last 18 kyr. This feature reflects the prominent southward evolution  
1131 of the system, which is inhibited by the presence of a major barrier at depth: the OAS thrust ramp.  
1132 Thus, the fault system accumulates higher displacement. (2) To the south, the VBFS intersects the  
1133 OAS thrust ramp at depth, which is cross-cut in its shallowest portion (first 2 km from Porreca et  
1134 al., 2018 and 2020; see T1). (3) To the north, the VBFS intersects, and it is rooted on the OAS  
1135 thrust ramp. (4) South of the VBFS, no evidence of clear surface faulting is observed, even though  
1136 the 24 August event revealed the presence of a fault at depth. We interpret this zone as a relay  
1137 between the VBFS to the north and LF to the south. (5) The throw deficit at all time scales in the  
1138 Ussita valley to the south of the CU sector. (6) Complex fault zone of barrier (see text).

1139 **Figure 10.** Distribution of the 24 August and 30 October coseismic ruptures at depth. The slip  
1140 models are plotted on fault planes (24 August event: Ragon et al., 2019; 30 October event:  
1141 Scognamiglio et al., 2018). The trace of the low-angle OAS thrust is reported. The red stars indicate  
1142 hypocenters, and the red arrows are the main slip propagation directions. The solid red lines  
1143 indicate the surface patterns of the coseismic throws that were produced by the two mainshocks.  
1144 The black dashed line is the morphological throw of the VBFS.