1   **Occurrence of partial and total coseismic ruptures of segmented normal fault systems:**

2   **insights from the Central Apennines, Italy.**

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16

17   **Abstract**

18

19   Normal faulting earthquakes rarely rupture the entire extent of active normal faults, and can

20   also jump between neighbouring faults. This confounds attempts to use segmentation models

21   to define the likelihood of future rupture scenarios. We attempt to study this problem

22   comparing the offsets produced in single earthquakes with those produced by multiple

23   earthquakes over longer timescales, together with detailed studies of the structural geology.

24 We study the active normal fault system causative of the Mw 6.3 2009 L'Aquila earthquake

25 in central Italy, comparing the spatial distribution of coseismic offsets, cumulative offsets

26 that have developed since 15 ±3 ka, and the total offsets that have accumulated since the

27 faults initiated at 2-3 Ma. Our findings suggest that: 1) faults within a segmented fault system

28 behave as a single interacting fault segment over time periods including multiple earthquake

29 cycles (e.g. 2-3 Ma or 15±3ka), with single earthquakes causing either partial or total ruptures

30 of the entire system; 2) an along-strike bend causes throw and throw-rates enhancements

31 within the bend throughout the seismic history of the fault system. We discuss the

32 synchronised and geometrically controlled activity rates on these faults in terms of the

33 propensity for floating earthquakes, multi-fault earthquakes, and seismic hazard.

34

35 **1. Introduction**

36

37 Normal faulting earthquakes commonly occur within fault systems that consist of multiple

38 closely-spaced fault surfaces, both along and across strike (Jackson et al., 1982; Crone et al.,

39 1987; dePolo et al., 1991; Suter, 2015; Civico et al., 2018; Villani et al., 2018). The summed

40 slip across all the faults that developed over the entire history of faulting (herein defined as

41 long-term slip, also known as total or finite slip) commonly displays a coherent pattern with a

42 slip maxima decreasing along strike to zero at the overall tips of the system (e.g. Roberts and

43 Michetti, 2004). However, some earthquakes can float along a single fault within the system,

44 rupturing either small portions or the entire length of the fault (Visini et al., 2019), whilst

45 others rupture several faults during a single seismic event producing multi-fault earthquakes

46 (also known as multi-rupture or multi-segment earthquakes) (Caskey and Wesnousky, 1996;

47 Morewood and Roberts, 2001; Suter, 2015; Brozzetti et al., 2019). Hence, it can be unclear

48 how the coseismic slip distribution in one earthquake relates to the summed long-term slip

49   distribution. This uncertainty in the relationship between coseismic slip and longer-term slip

50   is important because it limits our ability to plan for specific coseismic slip distributions and

51   expected earthquake magnitudes during seismic hazard assessment given knowledge of the

52   longer-term faulting. In this paper we attempt to show some key features involved in this

53   process, relating long-term slip magnitudes to fault geometries such as along-strike bends,

54   highlighting the fact that coseismic ruptures do not necessarily inhabit the whole fault length

55   or reflect the location of maximum strain accumulation in the longer term.

56

57   For example, during the 2016-2017 Central Italy seismic sequence (Chiaraluce et al. 2017),

58   two large earthquakes with different magnitudes ruptured the network of faults that comprise

59   the Mt. Vettore normal fault system in central Italy (Figure 1). The 24th August 2016 M$_w$ 6.0

60   earthquake ruptured the ground surface along the SE end of the fault system (Figure 1a.i;

61   Livio et al., 2016). Only 67 days later, following a M$_w$ 6.2 event on the 26th October, the 30th

62   October 2016 M$_w$ 6.5 earthquake re-ruptured the same location as the 24th August event, but

63   also propagated further along strike, rupturing what appears to be almost the entire extent of

64   the Mt. Vettore fault system (Figure 1a.ii; Civico et al., 2018; Villani et al., 2018; Brozzetti et

65   al., 2019). In an attempt to constrain the long-term slip-distribution of the fault system that

66   ruptured in these earthquakes, and how this relates to single ruptures, Iezzi et al. (2018)

67   mapped the ruptures and constructed geological cross-sections that showed that the total

68   along strike length of the fault system is ~27.5 km (Figure 1b.i). The 24th August 2016 M$_w$

69   6.0 earthquake produced surface ruptures along a single fault in the system for ~5 km along

70   strike from the SE tip, accounting only for the ~18% of the total fault system length. In

71   contrast, the 30th October 2016 M$_w$ 6.5 earthquake ruptured what appears to be the entire

72   length of the fault, and several faults within the system, revealed by comparison between the

73   geological throw and the surface traces of the coseismic ruptures (Figure 1b). It is noteworthy

74 that the maximum coseismic slip for both the earthquakes was located within an along-strike

75 fault bend, where the longer term cumulative geological throw increases to the maximum

76 value of ~1400m producing marked asymmetry in that throw profile (Figure 1b).

77

78 The key observations from the 2016 Mt. Vettore examples are that (1) the longer-term slip is

79 asymmetric, with the largest offset (~1400 m) within an along-strike fault bend (Figure 1b.i;

80 Iezzi et al., 2018); (2) the coseismic throw profiles for both earthquakes were also

81 asymmetric, but with opposite senses (either skewed to the NW or SE), with the largest

82 offsets (~30 cm and ~234 cm) located within the same along-strike fault bend (Figures 1b.ii

83 and 1b.iii; Iezzi et al., 2018); (3) multiple fault strands were activated in single earthquake

84 (e.g. the 30th October 2016 Mw 6.5 earthquake; Ferrario and Livio, 2018), contributing to the

85 long-term throw. Thus, the along-strike fault bend, and associated multiple fault strands,

86 appear to be a recurrent control on slip that produces the long-term slip distribution. Although

87 bends are commonly considered locations where the propagation of ruptures stop (Biasi and

88 Wesnousky, 2017), the Mt. Vettore example shows that in some cases, propagation of

89 coseismic ruptures across fault bends produces enhancement of slip along the fault bend

90 (Iezzi et al., 2018). Enhancement of slip within along strike fault bends on single normal

91 faults has been reported from previous coseismic slip distributions for single earthquakes

92 (e.g. Mildon et al. 2016) and from time periods containing multiple earthquakes such as the

93 time period since the last glacial maximum (LGM, 15 ± 3ka; Wilkinson et al. 2015). Faure

94 Walker et al. (2009) provide quantitative descriptions of why slip enhancement is expected

95 within along strike fault bends along single normal faults, showing that across an along-strike

96 fault bend the throw rate must vary in order to conserve the strain rate along the fault and

97 within the fault bend, due to spatial changes in the strike and dip of the fault, but constant

98 horizontal extension. Less is known about slip enhancement across along strike bends where

99 multiple faults are involved.

100

101 In this paper we ask whether activation of multiple faults during single earthquakes and the

102 largest long-term and coseismic offsets within fault bends, as described for the Mt. Vettore

103 earthquakes, can be identified for other normal faulting examples where multiple faults were

104 involved. We study the 6th April 2009 Mw 6.3 L'Aquila earthquake that occurred 50 km to

105 the SW of the 2016 earthquakes on the Mt. Vettore fault. We show that (1) the long-term slip

106 is again asymmetric, (2) the strike of the multiple fault strands in the area change across a

107 zone defining an along-strike bend in the fault system, (3) the long-term slip maximum is

108 located within the fault bend, (4) in contrast to the 2016 earthquakes, the 2009 ruptures

109 occurred outside the bend so that the location of maximum coseismic slip does not match the

110 location of longer-term maximum fault slip, and (5) a previous earthquake on this fault

111 system in 1703 AD appears to have had an alternative geometry and spatial extent. We

112 discuss the complexity exhibited by the 3 modern earthquake ruptures in April 2009, August

113 2016 and October 2016, and that in 1703 AD, to investigate if rupture extent in one

114 earthquake can be a good guide to the ruptures that may occur in the longer-term history of

115 an individual fault. Moreover, we discuss how this complexity, in particular with regard to

116 along-strike fault bends, should be taken in account for seismic hazard assessments and when

117 attempting to study the growth of normal faults.

118

119 **2. Geological background**

120

121 The 2009 L'Aquila earthquake ruptures occurred in the Aterno Valley, a narrow NW-SE

122 trending tectonic depression located in the central part of the Apennines chain, central Italy

123   (Figure 2). The Apennines are a formerly-active fold-and-thrust belt, with NE-directed

124   shortening, mainly in Miocene in times, that in general overthrust Mesozoic and Cenozoic

125   limestones onto Miocene flysch deposits (Anderson and Jackson, 1987; Doglioni, 1993). By

126   the late-middle Pliocene (last 2-3 Ma), SW-NE directed extension began in the Apennines

127   (Cavinato and De Celles, 1999; Roberts et al., 2002), causing the growth of a NW-SE normal

128   fault system in this new stress field (Patacca et al., 1990; Pizzi and Scisciani, 2000; Cavinato

129   et al., 2002; Pizzi and Galadini, 2009). The active normal faults are organized with both en-

130   echelon and end-on along-strike arrangements, have lengths of ~20-40 km, and show overall

131   pure dip-slip faulting, with a mean fault slip direction of 222º±4º (Roberts and Michetti,

132   2004).

133

134   Studies of fault scarps on the active normal faults that survived since erosion rates decreased

135   during the demise of the LGM (15 ±3ka) suggest that these faults have throw-rates up to 1.5

136   mm/yr (Roberts and Michetti, 2004; Papanikolaou et al., 2005; Faure Walker et al., 2010,

137   2012). Fault-specific earthquake recurrence times are of the order of hundreds to thousands

138   of years (Pace et al., 2006; Galli et al., 2008), and the faults are considered to have the

139   potential to release earthquakes of magnitude up to M_w 7.0 (Blumetti et al., 1993; Cello et al.,

140   1997; Galadini & Galli, 2000; Boncio et al., 2004). Calculations of the extension rate across

141   the central Apennines using fault slip data show regional horizontal extension occurring at up

142   to ~3mm/yr, matching estimates made with geodesy and seismic moment summations (Faure

143   Walker et al., 2010, 2012; D'Agostino et al. 2011). Calculations of the extension rate since

144   15±3 ka also prompt the idea that earthquake slip is related to dynamic topographic effects

145   that induce slip on viscous shear zones that form the roots of the upper crustal brittle faults

146   (Cowie et al., 2013). This study showed that rates of slip measured across brittle faults at the

147   surface, when averaged over 15 ±3 ka and across the strike of parallel faults, imply along-

148   strike variations in horizontal strain-rates that correlate with along-strike elevation changes.

149   The correlation shows a power-law relationship, mimicking power law viscous flow laws for

150   crustal materials, where strain-rate is proportional to the topographic elevation (stress driver)

151   raised to a power, n = 3. In turn this implies that (1) dynamic topographic effects drive the

152   extension by activating slip in underlying viscous shear zones that drive the rates of overlying

153   earthquake slip, and (b) 15 ± 3 ka is a time period that appears long enough to reveal the

154   longer-term behaviour of the fault system.

155

156   With this rheological framework in mind, we note that on the 6th April 2009, the Aterno

157   Valley was struck by a M_w 6.3 earthquake, which caused severe damage to the city of

158   L'Aquila and surrounding villages, with 309 fatalities, followed on the 7th April 2009 by a

159   M_w 5.6 aftershock (Figure 2; Chiaraluce et al., 2011). Seismological and geodetic data

160   suggest a slip distribution with a SE-striking, SW-dipping, 12-19 km long rupture extent at

161   depth (Atzori et al., 2009; Walters et al., 2009; Cheloni et al., 2010; Cirella et al., 2010;

162   Papanikolaou et al., 2010; D'Agostino et al., 2012; Lavecchia et al., 2012). Coseismic surface

163   ruptures showed that the Paganica fault was the fault that ruptured in the earthquake, with

164   maximum measured coseismic offset of about 10 cm (Figures 2 and 3; Falcucci et al., 2009;

165   Boncio et al., 2010; Emergeo Working Group, 2010; Galli et al., 2010; Wilkinson et al.,

166   2010; Vittori et al., 2011). DInSAR analysis exhibited a distributed coseismic slip of 25 cm,

167   possibly including the contribution of the 7th April event to the deformation field

168   (Papanikolaou et al., 2010). DiNSAR analysis also demonstrated that 66% of the deformed

169   area subsided whereas the 34% was uplifted, with an overall footwall uplift versus

170   hangingwall subsidence ratio of about 1/3 (Papanikolaou et al., 2010).

171

172 The Paganica fault is characterized by several smaller fault segments that juxtapose Cenozoic

173 limestones and calcarenites with Pleistocene-Holocene deposits (Vezzani and Ghisetti, 1998;

174 ISPRA, 2009; Pucci et al., 2015). Different studies agree that the slip-rate in the Holocene is

175 ~ 0.4 mm/yr (Galli et al., 2010; Roberts et al., 2010; Cinti et al., 2011; Moro et al., 2013).

176 However, we point out that the Paganica fault is only one of a number of faults that deform

177 the region, controlling the geomorphology and contributing to the summed long-term fault

178 slip. In fact, following compilation of palaeoseismic results from trench studies conducted on

179 a number of the faults, Galli et al. (2011) suggested that previous earthquakes, such as the

180 1703 A.D. Mw 6.7 event, may have ruptured multiple faults within the system (Figure 4).

181 The question arises as to which rupture scenario (compare Figure 4 a and b) should be used to

182 plan for future coseismic slip distributions and expected earthquake magnitudes during

183 seismic hazard assessment. Measurements of the long-term slip, accumulated over the entire

184 activity of the faults, can provide information on whether the faults are interacting over a

185 time span which encompasses all the seismic cycles that the faults have experienced, and

186 therefore it may provide insights into the occurrence of multi-fault earthquakes in the Aterno

187 Valley Fault System. In order to assess whether information on the long-term slip can help

188 with this question we have (1) constructed 39 geological cross-sections across the Aterno

189 Valley Fault System to quantify the along-strike long-term throw profile for the entire fault

190 system (Figures 5a and 5b); (2) made new measurements of post-LGM throw and throw-

191 rates, collated these with published values, and constructed an along-strike profile of the

192 values (Figures 6 and 7); (3) studied the large-scale relief associated with the footwall

193 escarpment of the Aterno Valley Fault System, obtained with topographic profiles derived

194 from 10 m resolution DEM; (4) studied the along-strike arrangements of faults, in order to

195 observe how the fault strike varies along the fault system (Figure 8); (5) compared the longer

196 term throw profile with the distribution of the coseismic ruptures following the 2009

197   L'Aquila earthquake, in order to better understand the relationships between faults of the

198   Aterno Valley Fault System and the role of the 2009 earthquake in the long-term seismic

199   history of the region (Figure 9).

200

201   **3. Methods**

202

203   We have identified fault segments showing evidence of post-LGM and Holocene activity

204   (Figure 2) by combining results from our fieldwork, published geological maps,

205   palaeoseismology, structural geology and high-resolution imagery such as Google Earth[TM]

206   and a 10 m resolution DEM (opendata.regione.abruzzo.it).

207

208   We have constructed 39 approximately serial geological cross-sections across pre-rift strata

209   along the strike of the Aterno Valley Fault System, based on published geological maps and

210   our own mapping (Figures 5a and 5b; Vezzani and Ghisetti, 1998; ISPRA, 2009; Pucci et al.,

211   2015). We use these cross-sections in order to define the long-term slip of the analysed faults,

212   stretching back to 2-3 Ma (Cavinato and De Celles, 1999; Roberts et al., 2002). The cross-

213   sections were constructed perpendicular to the fault traces, in order to avoid measurements of

214   apparent fault dip. The cross-sections were chosen in order to avoid effects of inherited throw

215   associated with cross faults with pre-Quaternary tectonic history (e.g. Pizzi and Galadini,

216   2009). The long-term throw has been measured as the vertical distance between the

217   hangingwall and footwall cut-offs of the Meso-Cenozoic bedrock formations that were in

218   place before the onset of the extension across the Apennines, and therefore record all the slip

219   accumulated by the faults (since 2-3 Ma). The bedrock formations exhibit significant

220   variability in thickness across the fault system (Vezzani and Ghisetti, 1998). Therefore, to

221   incorporate uncertainty in the thickness of a formation, for example under the sedimentary

222   fill of the Aterno Valley, we considered the maximum stratigraphic thickness provided by

223   Vezzani and Ghisetti (1998), but used local geological observations to gain appropriate

224   values. In places where the fault trace is complex, formed by both synthetic and antithetic

225   fault segments, we considered the total throw as the sum of the single measurements of throw

226   on each fault segment. Some faults present in the geological map have not been included in

227   the Aterno Valley Fault System because a lack of evidence of Holocene or post-LGM

228   activity. Also, some faults with Holocene or post-LGM activity, as revealed by

229   geomorphology and palaeoseismology, may not have been resolved by the geological maps

230   in cases where the thickness of the Meso-Cenozoic units is larger than the fault offset, and

231   therefore there is no evidence of offset of geological units on the fault. We took this into

232   account during our analysis.

233

234   We have also collated measurements of the throw accumulated since the demise of the Last

235   Glacial Maximum (15 ±3 ka; LGM throw) from published values and our own field

236   measurements (Figures 6, 7 and Table 1). The LGM was a time of high erosion and

237   sedimentation due to the cold climate and freeze-thaw activity (Tucker et al. 2011). This

238   means that slip in the LGM has not been preserved, and only slip after the climate changed

239   during the demise of the LGM has been preserved as fault scarps. In particular we used the

240   throw values for periglacial slopes from the LGM offset across the faults (see Roberts and

241   Michetti 2004 for a review). Thus, to gain values for the throw-rates on the active fault scarps

242   we have combined (1) measurements of fault scarp offsets (Roberts and Michetti, 2004;

243   Papanikolaou et al., 2005; Faure Walker et al., 2010; Galli et al., 2011), (2)

244   palaeoseismological analysis (Galli et al., 2010; Galli et al., 2011; Cinti et al., 2011),

245   assuming that the throw-rate measured in the trench is constant during the last 15±3 ka, and

246   (3) our own new field measurements (Figure 7) to get slip-rates that apply over all or parts of

247 the Holocene. We have assumed constant fault slip-rates since 15 ±3 ka because *in situ* ^{36}Cl

248 cosmogenic exposure dating shows that this is a good approximation of the time when scarps

249 began to be preserved (Cowie et al., 2017). Our post-LGM throw values have only been

250 collected from locations free of significant Holocene erosion and sedimentation, following

251 the approach of Cowie et al. (2017), where the periglacial surfaces in the footwall and

252 hangingwall are planar and undisturbed by post-Holocene erosion, evidenced by parallel

253 hangingwall and footwall cut-offs (Figure 7c). With these characteristics, we can reasonably

254 assume that the fault scarp has been exhumed only by repeated coseismic surface ruptures,

255 and therefore its height represents a measurement of the throw accumulated since 15±3 ka.

256

257 We have also studied the along-strike arrangements of faults, and we have constructed strike

258 lines for the principal fault segments in order to understand how the fault strike varies along

259 the fault system (Figure 8). Strike lines are horizontal lines joining points of the same

260 elevation on a structure such as the hangingwall cut-off.

261

262 To compare all the above data, we have constructed along-strike profiles for the long-term

263 throw from offsets of pre-rift strata (Figure 9a), and offsets since the LGM (Figure 9b). These

264 profiles, together with the analysis of the fault traces arrangement, the topographic relief

265 associated with the Aterno Valley Fault System (Figure 9c) and the presence of N-S striking

266 cross faults (e.g. Pizzi and Galadini, 2009; Figure 5), allow us to identify the tips of the fault

267 system and to reconstruct the segmentation of the main faults of the system (Figure 9f). We

268 have also compared the long-term activity of the Aterno Valley Fault System with the

269 coseismic activity following the 6th April M_w 6.3 L'Aquila earthquake and 7th April Mw 5.6

270 aftershock, herein referred to as (1) the coseismic surface deformation derived from DiNSAR

271 analysis (Figure 9d; Papanikolaou et al., 2010), and (2) five different published geodetic and

272   seismological models of the coseismic slip distribution at depth of the earthquake (Figure 9e;

273   Atzori et al., 2009; Walters et al., 2009; Cheloni et al., 2010; Cirella et al., 2010; D'Agostino

274   et al., 2012).

275

276   **4. Results**

277

278   4.1 Analysis of the geometry of the Aterno valley fault system

279

280   The Aterno valley fault system is composed of several fault segments of variable length, with

281   both en-echelon and end-on arrangements (Figure 8). Overall, the south-eastern part of the

282   fault system is highly segmented, characterized by relatively short fault traces. The north-

283   western part is characterized by relatively more continuous fault traces, with significant

284   overlaps between fault segments. The distance between the tips of neighbouring faults is

285   relatively small, and in most instances is less than 5 km.

286

287   Strike-lines drawn along the fault system show that the fault system contains a bend in its

288   strike (Figure 8). While the fault segments outside the bend (outer faults) have an average

289   strike of N131º, with values ranging between N130º and N133º, across the bend the strike

290   gradually change, with values ranging between N083º and N122º, with an average strike of

291   N106º. This along-strike bend, resulting from a variation of fault strike of ~25º, produces an

292   overall left en-echelon arrangement of the fault system (Figure 8).

293

294   4.2 Analysis of the throw profiles of the Aterno valley fault system

295

296 By combining the measured along-strike throw distributions and the fault trace arrangements,

297 we have reconstructed the segmentation and the length of the four main faults of the Aterno

298 valley fault system: the Barisciano fault, the Paganica-San Demetrio fault, the Pettino fault

299 and the Barete fault (Figure 9). The Barisciano and the Paganica-San Demetrio faults at the

300 surface appear to be characterised by many relatively short, discontinuous fault segments

301 (Figure 9d), organised with en-echelon arrangements and the presence of mostly synthetic

302 faults with a few short antithetic strands. However, the lengths of individual faults are in

303 places hard to determine due to limited exposure; it may be that faults are more connected

304 than we have shown in Figure 9e. The multi-humped throw profiles, with numerous maxima

305 and minima along strike, are consistent with the notion that the faults grew by linkage of

306 relatively short segments (green and pale blue lines in Figure 9a; see Cowie and Roberts,

307 2001). The Pettino and Barete faults are characterized by what appear to be longer and more

308 continuous fault segments, although again this may be due to more continuous exposure

309 rather than any difference in fault connectivity compared to faults to the SE (Figure 9e).

310 However, greater connectivity may be reflected in their long-term throw profiles, which show

311 a single maximum and a decrease of values towards the fault terminations (purple and orange

312 lines in Figure 9a).

313

314 The cumulative long-term throw profile across all the faults in the Aterno Valley Fault

315 System (dark blue line in Figure 9a) shows that the overall throw is asymmetric, with

316 maximum throw located in the NW half of the overall fault trace, within the along-strike

317 bend of the Aterno Valley Fault System defined by strike lines (Figure 8).

318

319 The throw that has accumulated since the demise of the LGM (dark blue line in Figure 9b),

320 constructed using measurements from fault scarp heights (squares in Figure 9b) and

321 palaeoseismology (triangles in Figure 9b), shows that the cumulative post-LGM throw is

322 again asymmetric, with the post-LGM maximum throw located in the NW half of the overall

323 fault trace, within the along-strike bend of the Aterno Valley Fault System defined by strike

324 lines (Figure 8).

325

326 The topographic relief associated with the Aterno Valley Fault System agrees with the

327 findings obtained with the study of the longer-term offsets (Figure 9c). The relief achieves a

328 maximum within the bend (~1000 m) and decreases towards zero at the tips of the fault

329 system (Figure 9c). A local minimum within the fault bend is produced by a prominent

330 incised drainage system that cuts through the fault system (see Figure 2).

331

332 Overall, the similarity between the long-term and post-LGM throw profiles (Figures 9a and

333 9b), together with the study of the topographic relief (Figure 9c), indicates that this group of

334 faults behave as a single interacting fault segment over multiple earthquake cycles, and that

335 the repetition of slip during several earthquake cycles, like that occurred since the demise of

336 the LGM, built the long-term throw. This is also suggested by the observation of the slip

337 vector azimuths measured along the fault system (from Roberts and Michetti, 2004;

338 Papanikolaou et al., 2005; Faure Walker et al., 2010), which show a convergent pattern

339 towards the hangingwall, with dip-slip kinematic in the central part and oblique slip towards

340 the tips of the fault system (Figure 9f). Converging slip-vector azimuths like this have been

341 used as a criterion to define the length of single interacting segments because they form due

342 to the lateral continuity of differential uplift between the hangingwall and footwall, which

343 causes asymmetry between the extensional strains in both hangingwall and footwall (Ma and

344 Kusznir, 1995; Roberts 1996a, Roberts and Ganas 2000, Roberts and Michetti 2004, Roberts

345 2007; Ampel et al., 2013).

346

4.3 Comparison between the longer-term activity of the Aterno Valley Fault System and the

M_w 6.3 L'Aquila Earthquake

349

The key question is whether the single interacting segment defined above ruptures in its

entirety or partially in single earthquakes. When we compare the long-term and the post-

LGM throw profiles with the coseismic slip profiles of the 6th April 2009 M_w 6.3 L'Aquila

earthquake, it is clear that the earthquake only ruptured a relatively small portion of the

Aterno Valley Fault System (~20 km; compares Figures 9a-c and 9d-f), comprising only ~

40% of its overall ~50 km along strike length. This is consistent with the mapped traces of

the coseismic ruptures, which are localized in a small part of the fault system (Figure 9e-f).

Note that the surface rupture formed mostly outside of the overall fault bend in the Aterno

Valley Fault System, where the maximum cumulative post LGM throw and longer-term

throw was observed (Figure 9f).

360

4.4 Comparison between the long-term and post-LGM throw rates along the Aterno Valley

Fault System

363

To understand how the post-LGM throw rates compare with the long-term history of the fault

system, we have calculated the predicted long-term throw profile of the Aterno Valley Fault

System assuming constant post-LGM throw rates during the entire fault activity (last 3 Ma;

Roberts et al., 2002), and compared it with the long-term throw profile derived from the

geological cross-sections (Figure 10). The comparison shows that the predicted long-term

throw is overall consistent with the measured long-term throw profile given the above

assumptions, and reveals how the post-LGM fault throw rates are working in a way that

371 mimics the long-term behaviour of the fault system. In fact, local discrepancies between the

372 predicted and the measured throw profiles suggest that faults are working in order to produce

373 a throw profile consistent with one for a single interacting fault segment, with relatively low

374 post-LGM throw-rates localized where the long-term throw profile presents local maxima

375 (for example at ~40 km distance along strike, Figure 10) and relatively fast post-LGM throw

376 rates localized where the long-term throw profile presents minima (at ~33km distance along

377 strike, Figure 10).

378

379 Thus, our overall finding from this and the previous section is that faults studied herein

380 behave as a single interacting fault segment over time periods containing multiple earthquake

381 cycles (e.g. over 15 ±3ka or 2-3 Ma), with the position of the maximum offset controlled by a

382 bend in the strike of the system, producing an asymmetric throw profile. Individual ruptures

383 float within the fault system, at times rupturing only part of the along strike extent of the

384 system, with other ruptures, such as those in 1703 AD, having a greater along strike extent.

385 Rupture locations since the demise of the LGM may exhibit a propensity to fill displacement

386 deficits that have developed over 2-3 Ma. Palaeoseismic results from Galli et al. (2011)

387 suggest that in some earthquakes multiple faults may be ruptured with rupture extent

388 approaching that of the length of the entire fault system.

389

390   **5. Discussion**

391

392 Our observations show that the 2009 L'Aquila M_w 6.3 earthquake shared several of the

393 attributes that we observed for the 2016 Mt. Vettore M_w 6.0 and M_w 6.5 earthquakes: the

394 overall long-term throw profile is asymmetric, as is the post-LGM throw profile, and

395 numerous across-strike fault strands combine to produce these asymmetries. However, the

396 coseismic throws in 2009 L'Aquila earthquake occurred mostly outside of the overall fault

397 bend, in contrast to the Mt. Vettore earthquakes. Overall, these three earthquakes show that

398 the locations of coseismic offsets can define either complete or partial rupture of the overall

399 fault system. The "partial" earthquakes float within the structure in the way described for

400 other earthquakes on normal faults (e.g. Roberts, 1996b; Roberts and Koukovelas, 1996;

401 DuRoss et al., 2016). Given these observations, we recommend that the along strike extents

402 of single coseismic ruptures are not a good guide to describe the lengths of fault segments

403 that develop over multiple seismic cycles, or the potential rupture lengths and earthquake

404 magnitudes for future events.

405

406 The relative short distance between fault segments of the Aterno Valley Fault System (mostly

407 <5 km across strike) is interesting to compare with maximum distance for the definition of

408 multi-faulting earthquakes on other fault systems such as the San Andreas fault system in

409 California (e.g. UCERF 3 model, Field et al., 2014; 2015; 2017). Empirical studies have also

410 shown that normal faulting earthquakes are capable of rupturing steps in the fault strike that

411 can reach up to 5-7 km (Wesnousky, 2008), and that in dip slip ruptures the 30% of the

412 observed ruptured steps are larger than 5 km (Biasi and Wesnousky, 2016). Moreover, there

413 are examples of normal faulting earthquakes that ruptured simultaneously parallel faults

414 spaced about 5 km (e.g. the M 7.2-6.8 1954 Fairview Peak-Dixie Valley and the M 7.5 1959

415 Hebgen Lake earthquakes; dePolo et al., 1991). Therefore, the relatively small across strike

416 spacing within the Aterno Valley Fault System may indicate that ruptures can cross between

417 fault strands. Given these considerations, we suggest that for the Aterno Valley Fault System,

418 seismic ruptures appear to be able to jump from one fault to another, rupturing more than one

419 fault during the same seismic event and producing multi-fault earthquakes, as it is suggested

420 from palaeoseismological studies (Galli et al., 2011; see Figure 4a), although data for the

421 Barisciano fault is lacking. Ruptures within the bend may lead to relatively large throws, for

422 example related to larger coseismic throw, as was the case for the 2016 Mt. Vettore ruptures

423 (Iezzi et al., 2018; Figure 1). If ruptures join along strike linking separate faults, earthquake

424 magnitudes larger than the M_w 6.3 of the 2009 L'Aquila earthquake may occur (e.g. the 1703

425 earthquake). The worst-case scenario, in which the fault system ruptures for its entire length

426 of about 50 km, would imply that the fault system has the potential to release a M_w 7

427 earthquake, according to empirical M_w/surface rupture length scaling relationship (Figure 11;

428 Wells and Coppersmith, 1994). More work is needed to assess whether the above is true of

429 other parts of the overall Central Apennines Fault System, but we note that the faults are

430 commonly interconnected and close to each other (Roberts and Michetti 2004). We suggest

431 that the occurrence of multi-fault earthquakes should be investigated for other localities along

432 the fault system, and that study of the structural geology of active faults, as demonstrated in

433 this paper, should form part of future studies aimed at ascertaining the propensity for multi-

434 fault earthquakes.

435

436 Our results for the 2016 Mt. Vettore earthquakes and the 2009 L'Aquila earthquake also have

437 implications for how to interpret palaeoseismic results. We show that maximum throw values

438 are found within the bends in both fault systems: for the 2009 L'Aquila earthquake in both

439 the long-term throw and the post-LGM throw profiles, and for the 2016 Mt. Vettore

440 earthquakes in both the long-term and coseismic throw profiles. This is similar to results from

441 other studies which show that anomalously large throws are located within along-strike fault

442 bends on single fault segments (Faure Walker et al., 2009; Wilkinson et al., 2015; Mildon et

443 al., 2016; Iezzi et al., 2018). If high values for throw-rates in the long-term are produced by

444 large values of coseismic throw, rather than more frequent earthquakes, as suggested by the

445 Mt. Vettore example, then palaeoseismic throws reported from trench sites within bends may

446 overestimate the palaeoearthquake magnitude if that value of coseismic throw is used within

447 the scaling relationships between maximum displacement and magnitude, such as that in

448 Wells and Coppersmith (1994), and Manighetti et al. (2007) (Iezzi et al. 2018). In fact, this

449 may well be a common feature for normal fault systems because we note that consistency of

450 the locations of the maxima in both the long-term and LGM throw profiles may indicate that

451 the effect of the along-strike fault bend persists through time (see Faure Walker et al., 2009).

452

453 Overall, our results suggest that the 2009 M_w 6.3 L'Aquila earthquake represents a partial

454 rupture of a more complex fault system. Therefore, we recommend that future studies of the

455 Aterno Valley Fault System should investigate whether it has the potential to release larger

456 earthquakes. If this typifies other active normal faults, the occurrence of partial and complete

457 rupture of the overall fault length will produce ambiguity in the outputs of palaeoseismology

458 for seismic hazard. Detailed palaeoseismological studies within segmented fault systems,

459 concentrating on whether multiple faults rupture simultaneously, should be given high

460 priority.

461

462 **6. Conclusions**

463

464 We have studied the fault geometry and the slip history of the Aterno Valley Fault System

465 (Central Apennines), ruptured during the 6th April 2009 M_w 6.3 L'Aquila earthquake, in order

466 to understand 1) how coseismic slip magnitudes in one earthquake relate to the summed slip

467 across all the faults of the fault system that have developed over the entire history of faulting

468 and 2) if prominent along-strike bends within a fault system has consistently halted

469 earthquake ruptures or promoted high values of slip.

470

471 The comparison between the offset measured since initiation of faulting at 2-3 Ma, since the

472 Last Glacial Maximum at ~15±3 ka and during the 2009 M_w 6.3 L'Aquila earthquake,

473 together with the analysis of the geometry of the fault system and the comparison between

474 long-term and post-LGM throw rates, suggest that: 1) faults within a segmented fault system

475 can behave as a single interacting fault segment over time periods containing multiple

476 earthquake cycles (e.g. over 15 ±3ka or 2-3 Ma), with maxima values of throw within a bend

477 in the strike of the fault system, across which the strike shifts of ~25º; 2) single earthquakes

478 can float within the fault system, rupturing either part or all the along strike extent of the

479 system; 3) the along-strike bend seems to exert a persistent control on the distribution of

480 throw within the fault system, promoting high values of throw and throw-rates within the

481 bend; 4) the close proximity between mapped fault segments indicates that for the Aterno

482 Valley Fault System seismic ruptures may be able to jump from one fault to another,

483 producing multi-fault earthquakes, which can release earthquakes with magnitudes up to M_w

484 7.

485

486 Given the structure of the Central Apennines Fault System, where faults are commonly

487 interconnected and close to each other, we suggest that the occurrence of multi-fault

488 earthquakes should be investigated for other parts of the fault system. Hence, we suggest that

489 study of the structural geology of active faults should be included in assessments of the

490 propensity for the occurrence of multi-fault earthquakes.

491

492 **Acknowledgments**

493

498

499 **References**

500

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772

773 **Figures caption**

774

775 Figure 1 – Attributes of the 2016 M_w 6.0 and M_w 6.5 Mt. Vettore earthquakes, Central Italy.

776 a) Partial and complete rupture of the Mt. Vettore fault during the 2016 seismic sequence.

777 Two earthquakes have occurred on the same fault system, producing a partial (i; 24th August

778 2016 M_w 6.0 earthquake), and a complete rupture of the fault (ii; 30th October 2016 M_w 6.5

779 earthquake). Fault traces are adapted from Pierantoni et al. (2013). Digital elevation model is

780 from Tarquini et al. (2012). Distribution of surface ruptures are adapted from Livio et al.,

781 2016 for the 24th August 2016 M_w 6.0 earthquake and from Civico et al., 2018, and Villani et

782 al., 2018, for the 30th October 2016 M_w 6.5 earthquake. b) Comparison between the i)

783 geological throw, derived from geological cross-sections across pre-rift strata, the ii)

784 coseismic throw following the 30th October M_w 6.5 earthquake (from Iezzi et al., 2018) and

785 the iii) coseismic throw following the 24th August M_w 6.0 earthquake (from Iezzi et al., 2018)

786 with the trace of the main Holocene fault scarp of the Mt. Vettore fault (panel iv)). Both

787 coseismic throws and geological throw profiles are asymmetric, with maxima values across

788 an along-strike fault bend within the main Holocene fault trace of the Mt. Vettore fault,

789 which is identified by the construction of strike lines (in red in panel iv). (modified from Iezzi

790 et al., 2018).

791

792 Figure 2 – Location map of the Aterno Valley Fault System, central Apennines, Italy. Thick

793 red lines are normal fault segments part of the Aterno Valley Fault System, thin red lines are

794 other active normal faults part of the Central Apennines Fault System. Black lines are traces

795 of the geological cross sections. Black triangles are locations of measurements of post 15±3

796 ka fault throw obtained from fault scarp measurements (from Roberts and Michetti, 2004;

797 Papanikolaou et al., 2005; Galli et al., 2011; our own fieldwork); blue triangles are locations

798 of measurements of post 15±3 ka fault throw derived from throw rates obtained with

799 palaeoseismological analysis, assuming these throw rates constant within the last 15±3 ka

800 (from Galli et al., 2010; 2011; Cinti et al., 2011). Red stars are the epicentres of the 6th April

801 2009 M_w 6.3 L'Aquila earthquake mainshock and of the 7th April 2009 M_w 5.6 aftershock.

802 Pale blue lines are the traces of the coseismic surface ruptures following the 6th April 2009

803 M_w 6.3 L'Aquila earthquake (modified from Vittori et al., 2011). Blue and pink dashed lines

804 define the areas of subsidence and uplift, respectively, derived from DiNSAR analysis

805 (Papanikolaou et al., 2010). a-a' and b-b' are traces of profiles across the deformed areas (see

806 Figure 9). Yellow lines are topographic profiles used to derive the topographic relief

807 associated with the Aterno Valley Fault System (showed in Figure 9c).

808

809 Figure 3 – Coseismic ruptures following the 2009 L'Aquila earthquake. a) Coseismic scarp in

810 eluvial-colluvial deposits, with vertical offset of ~10 cm. b) Opening cracks on the ground

811 surface. c) Surface rupture on concrete, with vertical offset of ~10 cm. d) Location map of the

812 surface ruptures showed in a), b) and c).

813

814   Figure 4– Palaeoseismological hypothesis of the occurrence of multi-fault earthquakes across

815   the Aterno Valley Fault System. (a) shows in blue fault segments inferred to have ruptured

816   during the 1703 M_w 6.7 earthquake, following Galli et al., 2011. Yellow polygons are

817   locations of palaeoseismological studies with evidences of rupture ascribable to the 1703

818   earthquake (from Galli et al., 2011). (b) shows in blue surface ruptures following the 6th April

819   2009 M_w 6.3 earthquake, modified after Vittori et al., 2011. It is shown that

820   palaeoseismological studies suggest that the 1703 M_w 6.7 earthquake have ruptured at the

821   same time several fault segments across the total extension of the fault system, suggesting the

822   occurrence of multi-fault earthquakes.

823

824   Figures 5 –Geological cross-sections built across the Aterno valley fault system. (a)

825   Geological map of the Aterno Valley Fault System, modified from Vezzani and Ghisetti,

826   1998. In red are faults part of the Aterno Valley Fault System, in black traces of the cross-

827   sections. The stratigraphy is derived from Vezzani and Ghiseeti, 1998, map; colours are in

828   agreement with the ones reported in the map, and used in the cross-sections to highlight the

829   offset on fault. Here are shown cross-sections from 1 to 13. b) Cross-sections from 14 to 39.

830   BRF: Barisciano fault; PSDF: Paganica-San Demetrio fault; BTF: Barete fault; PF: Pettino

831   fault. When it was not possible to establish the thickness of a formation, we assigned it the

832   maximum thickness provided by the legend of the map.

833

834   Figure 6 – Location map of the fault scarps and palaeoseismological studies used to constrain

835   the throw rates since the demise of the Last Glacial Maximum (15±3 ka) along the Aterno

836   Valley Fault System, comprehensive of published and newly collected data. Location

837   numbers are coded in agreement with the name of the fault to which they belong:

838   BRF=Barisciano fault; PSDF=Paganica-San Demetrio fault; PF=Pettino fault; BTF=Barete

839   fault.

840

841   Figure 7 – Newly collected field measurements of throw and throw-rates since the demise of

842   the Last Glacial Maximum (15±3 ka) from fault scarps located along the Aterno Valley Fault

843   System. a) Interpreted scarp profiles showing the measured throw associated with the fault

844   scarp. Scarp profiles have been built through chain surveying techniques using a 1 m ruler

845   and a clinometer. Location numbers are coded in agreement with the database shown in

846   Figure 6b. b) Location map of the field locations in a). c) Sketch of a fault scarp to show the

847   criteria we have followed to select the site of measurement. Measurements of scarp height are

848   collected only in locations where upper and lower slopes and hangingwall and footwall cut-

849   offs are preserved since the demise of the LGM (15±3 ka), so to represent the throw

850   accumulated during the last 15±3 ka.

851

852   Figure 8 – Analysis of the geometry of the Aterno Valley Fault System. In black are reported

853   strike lines built on the main fault segments of the fault system. Strike lines are lines joining

854   locations at the same elevation, and therefore they provide a good representation of the

855   overall strike of the fault segments. It is shown that the fault system presents a wide along-

856   strike bend, across which the strike of different fault segments changes, with an overall shift

857   of ~25º from the strike of the fault segments outside the fault bend (outer faults).

858

859   Figure 9 – Throw profiles of the Aterno Valley Fault System. a) Long-term throw profiles of

860   the main faults of the fault system. Values of throw are derived from geological cross-

861   sections shown in Figures 5a-5b. In blue is reported the cumulative throw profile of the fault

862   system, calculated by summing up the throw values across each fault segment. b) Profiles of

863   the throw accumulated since the demise of the Last Glacial Maximum (15±3 ka) across the

864   fault system. Squares are values of throw derived from fault scarp measurements (Roberts

865   and Michetti, 2004; Papanikolaou et al., 2005; Galli et al., 2011; our own fieldwork),

866   triangles are values of throw derived from palaeoseismological analysis (palaeoseismological

867   throw rate times 15±3 ka; Galli et al., 2010; 2011; Cinti et al., 2011). In blue is the

868   cumulative LGM throw profile of the entire fault system. Throw rates, reported on the left-

869   hand side, are calculated assuming a constant throw rate within the last 15ka. c) Topographic

870   relief associated with the footwall escarpment of the Aterno Valley Fault System. In orange is

871   the topographic profile of the footwall, in blue of the hangingwall, derived from 10m DEM.

872   d) Profiles of coseismic deformation areas of uplift and subsidence following the 6th April

873   2009 M_w 6.3 mainshock and the 7th April 2009 M_w 5.6 aftershock, derived from DInSAR

874   analysis (profile traces a-a' and b-b' in Figure 2; adapted from Papanikolaou et al., 2010). e)

875   Along-strike profiles of the coseismic slip of the 6th April 2009 M_w 6.3 L'Aquila earthquake,

876   derived from different geodetic and seismological fault models (Atzori et al., 2009; Walters

877   et al., 2009; Cheloni et al., 2010; Cirella et al., 2010; D'Agostino et al., 2012). Profiles have

878   been drawn at 7.5 km depth. f) Reconstruction of the segmentation of the principal faults

879   forming the Aterno Valley Fault System. This figure shows that 1) the 2009 earthquake

880   ruptured only a small part of a complex fault system, 2) faults within the Aterno Valley Fault

881   System are interacting over several earthquake cycles, with potential to release multi-fault

882   earthquakes, 3) maximum throws are localized within a fault bend, which is a persistent

883   feature influencing the throw distribution over the history of the fault system.

884

885   Figure 10 – Comparison between the measured long-term throw profile (blue line) and the

886   predicted long-term throw profile (red line), assuming constant post-LGM throw rates during

887   the last 3 Ma. It shows that the two profiles are overall consistent, which suggest that the

888   post-LGM throw rates can be representative of the throw rates averaged over the entire faults

889   activity. Local discrepancies prompt the idea that post-LGM throw rates are working in order

890   to produce a throw profile which reflect the long-term throw profile.

891

892   Figure 11 – Complete and partial ruptures of the Aterno Valley Fault System. a) Fault map of

893   the Aterno Valley Fault System showing that it can experience complete ruptures, involving

894   all its fault segments (red bar), and partial ruptures, as is the case of the 2009 M_w 6.3

895   L'Aquila earthquake (green bar). b) Moment Magnitude versus Surface Rupture Length

896   scaling relationship (Wells and Coppersmith, 1994), with reported partial and total ruptures

897   of the Aterno Valley Fault System.

898

899   **Table Caption**

900

901   Table 1 – Database of measurements of throw and throw rates showed in Figure 6 and 7.