1 **The Paganica fault and surface co-seismic ruptures caused by the April 6, 2009 earthquake**

2 **(L'Aquila, central Italy)**

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1. Introduction

On April 6, 2009, at 01:32 GMT, a Mw 6.3 seismic event (Istituto Nazionale di Geofisica e Vulcanologia, 2009; MedNet, http://mednet.rm.ingv.it/procedure/events/QRCMT/090406_013322/qrcmt.html) hit the central Apennines, severely damaging the town of L'Aquila and dozens of neighbouring villages, resulting in almost 300 casualties. This earthquake was the strongest in central Italy since the devastating 1915 Fucino event (Mw 7.0). The INGV national seismic network located the hypocentre 5 km SW of L'Aquila, 8-9 km deep. Based on this information and on the seismotectonic framework of the region, earthquake geologists travelled to the field to identify possible surface faulting (Emergeo, Working Group, 2009; Rilievi geologici di terreno effettuati nell'area epicentrale della sequenza sismica dell'Aquilano del 6 Aprile 2009; http://www.ingv.it; Emergeo, Working Group, 2009, submitted to Terra Nova).

The most convincing evidence of primary surface rupture is along the Paganica fault, the geometry of which is consistent with seismological, synthetic aperture radar (SAR) and GPS data.

Investigation of other known normal faults of the area, i.e. the Mt. Pettino, Mt. San Franco and Mt Stabiata normal faults, (Emergeo, Working Group, 2009; Rilievi geologici di terreno effettuati nell'area epicentrale della sequenza sismica dell'Aquilano del 6 Aprile 2009; http://www.ingv.it; Emergeo, Working Group, 2009, submitted to Terra Nova) suggested that these structures were not activated during the April 6 shock.

In this report, we first describe the seismotectonic framework of the area and then we present the field information that supports the occurrence of surficial displacement on the Paganica fault.

2. Seismotectonic framework

The shock of April 6, 2009, occurred in a region that has been struck by past earthquakes (Working Group CPTI, 2004; Fig. 1) and is in an Apennine sector which contains a complex array of active

51 normal faults (e.g. Barchi et al., 2000; Galadini and Galli, 2000; Boncio et al., 2004; Roberts and

52 Michetti, 2004).

53   In the central Apennines, active faulting and earthquakes result from the ongoing extensional

54 tectonics. The strongest earthquakes in the CPTI04 seismic catalogue (Working Group CPTI, 2004)

55 occurred on September 9, 1349 (Mw 6.5), and February 2, 1703 (Mw 6.7). While the origin of the

56 former is still debated with regard to its source, the latter event was associated with the Upper

57 Aterno Valley fault system (UAVFS; Fig. 1), an ensemble of 7-to-10-km-long normal-oblique fault

58 segments (Galadini and Galli, 2000; Galadini and Messina, 2001). The 1703 earthquake induced

59 heavy damage in L'Aquila (Is 9, MCS scale; Stucchi et al., 2007), and the association of this

60 earthquake with the UAVFS has been demonstrated by paleoseismological investigations (Moro et

61 al., 2002) and by the distribution of the damage along the Upper Aterno River valley. Moreover, the

62 recent activity of the UAVFS is demonstrated by displacement of Late Pleistocene-Holocene

63 colluvial and alluvial deposits along the different segments of the system (Galadini and Galli, 2000;

64 Moro et al., 2002).

65   Other damaging earthquakes that have affected the L'Aquila region in the past (i.e., 1461,

66 Mw 6.4; 1762, Mw 5.9; 1916, Mw 5.2; 1958, Mw 5.2; see also Rossi et al., 2005) are more

67 comparable to the April 6 damage distribution than to the damage from the 1349 and 1703 events.

68 In particular, the 1461 event caused damage in Onna, Sant'Eusanio Forconese, Poggio Picenze,

69 Castelnuovo and L'Aquila (10, 10, 10, 10 and 9, MCS scale, respectively; Stucchi et al., 2007),

70 which is comparable to that of the April 6 earthquake (Galli and Camassi, 2009). Moreover, the

71 magnitude calculated on the basis of 1461 earthquake macroseismic data point is evidently close to

72 that of the April 6 shock. The most evident characteristic of all of these events is that, as in the case

73 of the April 6 shock, most of the damage affected L'Aquila and villages south of L'Aquila, while

74 little damage was recorded in the villages north of L'Aquila.

75   The UAVFS aside, other faults that could have been responsible for Mw >6 earthquakes

76   have been reported in the literature, with slightly different interpretations regarding their geometry

77   (Fig. 1). In particular, the Ovindoli-Pezza and Campo Felice-Colle Cerasitto faults (OPF-CFCF;

78   Fig. 1) have normal or normal-oblique kinematics, and delineate a 28- to 30 km-long, NNW-SSE to

79   NW-SE trending fault system south of L'Aquila that has Late Pleistocene-Holocene displacements,

80   as indicated by paleoseismological investigations (Pantosti et al., 1996; Salvi et al., 2003). The 20-

81   km-long, NW-SE trending Laga Mts. fault (LMF; Fig. 1) north of L'Aquila shows evidence of

82   Holocene activity with normal kinematics, as indicated by displacement of 8ka deposits (Galadini

83   and Galli, 2003). NE of L'Aquila, Holocene displacements have also been detected on the Campo

84   Imperatore fault system (CIFS; Fig. 1) (Galli et al., 2002; Galadini et al., 2003) where trenches

85   across secondary normal faults exposed evidence of surface faulting that occurred since about 3,4

86   ka. The different segments have a total length on the order of 33 km. Also, an impressive fault

87   system exists between San Demetrio ne' Vestini and Molina Aterno, and further south, between

88   Castelvecchio Subequo and Goriano Sicoli (Bosi and Bertini, 1970; Bagnaia et al., 1992; Galadini

89   and Galli, 2000; Boncio et al., 2004) that were partly described as the Middle Aterno Valley fault

90   system (MAVFS; Fig. 1) (Galadini and Galli, 2000). Paleoseismological investigations that were

91   ongoing when the earthquake of April 6 occurred have revealed late Holocene activity of the

92   segment between Castelvecchio Subequo and Goriano Sicoli (SVF; Fig. 1) (Falcucci et al., in

93   preparation).

94   The location of the main shock, the aftershocks, and the distribution of the April 6 damage

95   (Istituto Nazionale di Geofisica e Vulcanologia, 2009; Analisi dati di sismicità, http://www.ingv.it),

96   however, are not consistent with the activation of the above-described faults (Fig. 2).

97   To identify the causative fault of this April 6 earthquake, we consider the structural

98   framework of the area E and SE of L'Aquila, for where different structural patterns have been

99   proposed in the past (Fig. 3). Indeed, since the 1970s, this sector has been repeatedly investigated

100   regarding its neotectonic and active tectonic frameworks (Bosi and Bertini, 1970; Bosi, 1989;

101 Bagnaia et al., 1992; Bertini and Bosi, 1993). In particular, the two most recent studies present

102 substantially different structural frameworks regarding the Quaternary activity. Bagnaia et al.

103 (1992) reported a normal fault in the zone of Paganica that connects it with another normal fault in

104 the area of San Demetrio ne' Vestini, providing a simple structural image of this area (Fig. 3a) that

105 is affected by a ca. 20-km-long fault that partly affects Quaternary deposits. In contrast, Bertini and

106 Bosi (1993) summarised a complicated structural framework of Quaternary faults in this area. The

107 scheme proposed excludes a link between the Paganica fault and that in the area of San Demetrio

108 ne' Vestini. The information on the Quaternary faults was summarised in a map by Vezzani and

109 Ghisetti (1998), where the Paganica fault is mapped as a 9-km-long segment independent of the San

110 Demetrio ne' Vestini fault (Fig. 3b).

111 Finally, these data have been included in different ways in seismotectonic studies at a

112 regional scale. When mapping the surficial expression of sources that could potentially be

113 responsible for M ≥6.5 earthquakes, Galadini and Galli (2000) did not include the short Paganica

114 fault segment at the NW end of the MAVFS. In contrast, Boncio et al. (2004) linked one segment of

115 the UAVFS mapped by Galadini and Galli (2000), i.e. the southeastern-most one (the Mt. Pettino

116 fault), to the Paganica fault, defining a single 13-km-long fault segment in the area of L'Aquila that

117 is not linked to the San Demetrio ne' Vestini fault (Fig. 3c). Roberts and Michetti (2004) and

118 Papanikolaou et al. (2005) reported a segment of more than 30 km in this area , not including,

119 however, the Paganica fault.

120 The geological surveys carried out *ad-hoc* after the earthquake along the Paganica fault

121 (which is presently considered the surface expression of the seismogenic source of the earthquake

122 of April 6) provide a different picture from that in the published literature before this earthquake.

123

124 **3. The Paganica fault**

125 Our geological surveys and analyses of aerial photographs taken after the earthquake define the

126   surficial geometry of the long-term expression of this fault. We define three NW-SE trending

127   segments that have a dextral en-echelon relationship (Fig. 4). The northernmost segment (segment

128   1, 3 km long) is located between the area east of Collebrincioni and Vallone delle Grotte (NE of

129   Tempèra). The central segment is detected in the area of Paganica (segment 2; 3 km long) and

130   terminates towards the SE along the road that connects Paganica and Pescomaggiore. The

131   southernmost segment (segment 3; 2 km long) extends to the NW from the village of San Gregorio.

132   The surficial expression of the northern fault segment is marked by a prominent fault scarp

133   in carbonate bedrock, at the base of which the slickenside surface is exposed (Fig. 5a). In the central

134   part of the segment, next to Colle Cocurello and Colle Enzano, the fault splits into two splays (Fig.

135   4). Here, unconsolidated slope deposits (i.e., not older than the Last Glacial Maximum period; see

136   Castiglioni et al. 1979; Dramis, 1983; Coltorti and Dramis, 1988, for more on this topic) are

137   exposed at the base of the fault scarp and seems to be displaced along the eastern fault splay, where

138   the "Vigne Basse" viaduct of the A24 motorway crosses the fault zone (Fig. 5b). Moreover, a small

139   hand-made excavation (few tens of centimetres deep) performed along the fault scarp slightly to the

140   north exposed post-Last Glacial Maximum debris dragged along the fault scarp, due to the fault

141   movement. Hence, overall, these findings confirm the Late Pleistocene-Holocene activity of the

142   Paganica fault.

143   The scarp on the central segment of the Paganica fault is present at the base of the slopes

144   between Tempèra and Paganica. The fault scarp is formed both in the carbonate bedrock – in the

145   northernmost part of the branch – and in fluvial deposits (Fig. 5c) – in the central and southern

146   portions of the segment. Here, according to Sheet 359 "L'Aquila" of the Geologic Map of Italy at

147   1:50,000 (Foglio CARG 1:50,000, 2009. Cartografia geologica ufficiale Foglio CARG 1:50,000 N.

148   359, L'Aquila), the tectonic structure places Pliocene/Middle Pleistocene continental deposits in

149   contact with Late Pleistocene sediments.

150   Many outcrops in the fault zone show displaced middle Pleistocene-Holocene fluvial and

151   slope deposits (Fig. 6a) along several synthetic fault planes (about N140° trending).

152   The oldest fluvial sediments displaced along the fault contain partially-to-strongly reworked

153   and/or weathered ash layers. Locally, ash deposits occur as primary air-fall deposits, as centimetre-

154   thick, tephra layers (Fig. 6b). Chemical, lithological and isotope analyses on three of the thickest,

155   best-preserved ashes have allowed us to assign them to the eruptions of "Tufo Pisolitico di

156   Trigoria", "Pozzolane Rosse" and "Tufo Rosso a Scorie Nere" (authors' unpublished data) from the

157   Colli Albani and Sabatini volcanic districts (central Italy); these ashes have been dated to about 560,

158   456 and 450 ka, respectively (Marra et al., 2009, and references therein). These data provide the

159   oldest chronological point-control for the dating of the activity of the Paganica fault.

160   More recent activity on the central segment of the Paganica fault is documented by displaced

161   colluvial and fluvial deposits along at least three shear planes that are exposed in the walls of a deep

162   trench (up to 5 m high) that is perpendicular to the fault. The trench, which is in north of Paganica,

163   was dug out by a strong jet of water from a leak in an aqueduct that ruptured during the earthquake

164   (Fig.6c). In the uppermost part of the trench, one fault plane places carbonate breccia in contact

165   with fluvial gravel, colluvial and soil levels that are displaced by some metres (Fig. 6c). Other shear

166   planes exposed in the trench displace fluvial and slope deposits (Fig. 6d). Organic-rich material in

167   the colluvium yielded radiocarbon ages of 5,718 BC/5,467 B.C. to 5,403 BC/5,387 B.C. (calibrated,

168   2σ) (Fig. 6c) and 34,970 ±470 BP. The latter age is supported by U/Th dating of a calcareous tufa

169   that is embedded in the dated organic-rich deposit that gave an age of 33,000 ±4100 BP. These data

170   support the Late Pleistocene-Holocene activity of the Paganica fault.

171   The southern end of the central segment of the Paganica fault ends against a N-S trending

172   tectonic structure that dips about 80° to the E. This fault is visible along the road that connects

173   Paganica to Pescomaggiore and shows normal-to-transtensive kinematics (Fig. 6e). Here, alluvial-

174   fan and colluvial deposits are displaced on the Paganica fault and the N-S fault. The sediments

175   contain the above-described Middle Pleistocene tephra layers, thus indicating a post-Middle

176 Pleistocene activity of the N-S fault.

177 The central and the southern branches of the Paganica fault are separated by a transfer zone (e.g.

178 Peacock, 2002) that is here marked by a wide landsurface that gently dips towards the NW.

179 The southern segment of the Paganica fault is located SE of Paganica from the area E of the San

180 Vittorino to the village of San Gregorio. Its surficial expression is defined by a scarp in carbonate

181 bedrock, at the base of which the slickenside surface is often exposed (Fig. 7a, b). At its northern

182 end, the fault branch intersects a fault plane trending about N20° and dipping steeply eastward,

183 which affects the carbonate bedrock (Fig. 7c). This fault and the above-mentioned N-S trending

184 tectonic structure are probably part of to the same fault system.

185

186 **4. Coseismic surface deformation along the Paganica fault zone**

187 The field surveys performed in the days subsequent to the main shock allowed us to identify

188 coseismic surface deformation along the Paganica fault that produced sets of NW-SE trending

189 ground cracks aligned along the fault zone, and parallel the fault segments, and which comprise a

190 belt not wider than a few tens of metres. These fractures were up to a few centimetres wide and

191 several tens of metres long (with no solution of continuity), and they commonly had an en-echelon

192 (mainly dextral step-over) arrangement.

193 These ground cracks were almost continuous 1) through fields and urban areas, where roads and

194 buildings were affected by newly formed ruptures and damage; 2) along slopes and plain areas; 3)

195 across any morphological features of the landscape, such as small ridges, valleys and landsurfaces;

196 and 4) affecting both natural and man-made terrain.

197 Moreover, most cracks along the central fault segment had vertical and horizontal offset between

198 the sides (with the downslope side lowered) of a few centimetres; the displacement increased during

199 the days subsequent to the April 6 shock, reaching a maximum of about 15 cm. In contrast, cracks

200 along the northern and the southern branches did not have readily observable vertical offsets rather

201   the ground was gently flexed, with an amplitude of less than 10 to 15 cm.

202

203   4.1 Northern fault segment

204   Along the northern segment of the Paganica fault, discontinuous ground ruptures, no more than

205   about 20 m long and 1 cm wide, were observed at the base of the fault scarp (Fig. 8a, b, c, d). In

206   particular, in the central part of the segment, the cracks are located where the fault splits into two

207   splays (i.e. between Colle Cocurello and the Vigne Basse locality, see previous section), with

208   different sets that trend roughly 120° to 170°. We observed cracks on both splays. A crack was also

209   present where the above-described Late Pleistocene-Holocene slope debris was perhaps displaced

210   on the tectonic structure (Fig. 8e).

211   Here, the "Vigne Basse" viaduct of the A24 motorway that crosses the Paganica fault zone (see

212   previous section) suffered damage during the shock of April 6. This damage to the viaduct, mainly

213   consisting in the re-opening of pre-existing "injuries" due to aging (i.e. old cracks with traces of

214   water percolation), occurred where it crosses the Paganica fault. Hence, the damage might have

215   been mostly caused by the strong ground motion caused by the earthquake, combined

216   (subordinately) with the coseismic ground deformation (which is marked by cracks) at the fault

217   zone (where piers of the viaduct are positioned) .

218   Moreover, evidence of reactivation of the fault plane is visible along the northern part of the

219   segment where a fresh-looking free-face up to 8-10 cm high is present at the base of the slickenside

220   surface. This free-face extends continuously for several metres, and marks the contact between the

221   carbonate bedrock and the slope scree at the base of the scarp (Fig. 8f). In some places, the free-face

222   was marked by the remnants of soil that coats the base of the scarplet. Moreover, the slope scree

223   was separated from the bedrock scarp surface by an about 1-3-cm-wide fissure.

224

225   4.2 Central fault segment

226　We found ground cracks in the area between Tempèra and Paganica that parallel the fault branch

227　where synthetic shear planes affect the Late Pleistocene-Holocene deposits (Fig. 9). Cracks are

228　present continuously along the entire segment. In the village of Paganica village, these ground

229　ruptures intersected the trench at the aqueduct (Fig. 9c), so we can reasonably hypothesise that the

230　damage to the aqueduct can be attributed to the coseismic surface displacement along the tectonic

231　structure.

232　　To the southeast, we found ground ruptures as far as the southern end of the central

233　segment. Along the transfer zone that separates the central segment and southern of the Paganica

234　fault, we found two intersecting sets of ground fractures, one set trending about roughly N20° and

235　the other trending about NW-SE (about 150°) (Fig. 10a). The former set was aligned with the

236　aforementioned N-S fault, while the latter has a direction similar to the Paganica fault trend. Some

237　of these intersecting ground cracks appeared in the days subsequent to the mainshock, probably

238　related to the occurrence of afterslip (Fig. 10b).

239　　Rare and discontinuous E-W trending fractures extend for less than 1 km in length in the

240　area of Tempèra. These secondary features might result from local, surficial craking due to passive

241　movement caused by ground shaking along secondary E-W striking tectonic structures, which have

242　been mapped in this area (e.g. Bagnaia et al., 1992; Vezzani and Ghisetti, 1998; Foglio CARG

243　1:50,000, 2009. Cartografia geologica ufficiale Foglio CARG 1:50,000 N. 359, L'Aquila); the Late

244　Quaternary activity of these E-W tectonic structures has never been demonstrated by thorough

245　geological studies.

246

247　4.3 Southern fault segment

248　A few tens of metres south-eastwards, we found NW-SE trending ground cracks at the northern end

249　of the southern fault segment that extend towards the SE and parallel the carbonate bedrock fault

250　scarp (Fig. 10c). The width of the fractures increased in the days subsequent to the mainshock. This

251   confirmed the occurrence of a certain amount of afterslip.

252   Further south, we found several ground ruptures close to the southern end of the fault branch, in the

253   area of San Gregorio (Fig. 10d, e, f), with some cracks being tens of metres long. According to eye

254   witnesses, some of these fracture formed during the aftershock of April 7 (Mw 5.6; Istituto

255   Nazionale di Geofisica e Vulcanologia, 2009; MedNet,

256   http://mednet.rm.ingv.it/procedure/events/QRCMT/090406_013322/qrcmt.html).

257   Here, the cracks were arranged in two sets trending between N120° and N150°. We also found, a

258   fresh fracture with N350° trend that affected the carbonate bedrock (Fig. 10g). A fresh-looking

259   crack on the ground occurred where the fracture intersected the surface (Fig. 10g, inset).

260

261   **5. Investigation along the Mt. Bazzano antithetic normal fault**

262   We also examined a previously mapped normal fault (e.g. Vezzani and Ghisetti, 1998) on the

263   eastern slopes of Mt. Bazzano, and that is an antithetic fault to the Paganica fault. The surficial

264   expression of this structure is a preminent fault scarp at the base of which the fault plane is exposed.

265   We identify local evidence of fault-plane reactivation that consists of a free face of up to 15

266   cm high, at the base of the slickenside and which, in places, had remnants of the soil coating the

267   scree deposited at the base of the fault plane. This new free face was discontinuous as it was

268   typically observable for no more than a few metres in length (Fig. 10h). Many sectors of the fault,

269   indeed, showed no evidence of rejuvenation along the bedrock scarp.

270   Taken together with 1) the remarkable steepness of the slopes, and 2) the absence of evident ground

271   cracks along the fault, – comparably to the Paganica fault – this suggests that the formation of the

272   free face along the Bazzano normal faults was probably mainly due to non-tectonic gravitational

273   processes and/or compaction of the unconsolidated scree at the base of the fault planes.

274   Nevertheless, we cannot preclude a coseismic tectonic component to the new free face because, the

275   fault is antithetic to the Paganica fault.

276

6. Concluding remarks

277

278 Our field surveys and studies of aerial photographs in the L'Aquila area (central Apennines) after

279 the April 6 seismic event (Mw 6.3) permitted us to identify evidence of coseismic surface faulting

280 on the Paganica fault, a NW-SE striking and SW dipping Quaternary normal fault located E of

281 L'Aquila.

282 This structure had been mapped by previous studies (Bagnaia et al., 1992, Vezzani and

283 Ghisetti, 1998; Boncio et al., 2004; Foglio CARG 1:50,000, 2009) but none of the previous works

284 had documented its latest Pleistocene and Holocene activity.

285 Our data define three en-echelon segments of the Paganica fault, based on its surficial

286 expression, each one 3-4 km long. The total length of the structure is about 10 km.

287 Apart from the obvious association with the April 6 earthquake, recent activity of the

288 Paganica fault is defined by the displacement of ^{14}C- and U-series-dated Late Pleistocene-Holocene

289 deposits along the tectonic structure. In particular, a trench eroded along a ruptured aqueduct

290 exposed several tens of centimetres of offset in Late Holocene deposits along the Paganica fault,

291 which suggests that the fault has probably generated stronger earthquakes in the past.

292 We identified evidence of surface faulting along the Paganica fault due to the April 6 shock

293 including set of continuous aligned ground cracks along the central segment of the fault; some

294 cracks had both vertical and horizontal offset up to about 15 cm. The offset of some cracks

295 increased as much as a few centimetres in the days subsequent to the mainshock. This is probably

296 evidence of a small amount of afterslip related to the aftershocks. The presence of ground cracks,

297 although discontinuous and with no vertical offset along the northern and the southern fault

298 segments suggest that also these branches of the Paganica fault were probably activated during the

299 April 6 shock.

300 Overall, our observations show to relatively little coseismic surficial movements on the Paganica

301 fault, which probably was less than a few centimetres. Further evidence that supports the occurrence

302 of surface faulting on the Paganica fault includes the rejuvenation of the fault plane, i.e. the free-

303 face observed at the base of the slickenside, along the northern and central segments of the tectonic

304 structure. It is worth noting that base on empirical relationships between moment magnitude and the

305 surface rupture length (Wells and Coppersmith, 1994), the length of the Paganica fault rupture is

306 consistent (taking into account the uncertainty range proposed by Wells and Coppersmith) with the

307 reported magnitude (Mw=6.3; Istituto Nazionale di Geofisica e Vulcanologica, 2009; MedNet,

308 http://mednet.rm.ingv.it/procedure/events/QRCMT/090406_013322/qrcmt.html).

309 Finally, our evidence of surface rupture combined with the location and the length of the Paganica

310 fault is consistent with it being the source of the April 6 earthquake. This conclusion is also

311 consistent with the results from studies of 1) interferometric SAR observations (Atzori et al., in

312 press); 2) the location and geometry of the fault modelled using the coseismic ground deformation

313 patterns from GPS data (Anzidei et al., in press); and 3) seismological data, that is the location and

314 focal mechanism of the main shock and the aftershock distribution (Istituto Nazionale di Geofisica e

315 Vulcanologia, 2009; Analisi dati di sismicità, http://www.ingv.it).

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448

449   **Figure captions**

450   Figure 1 – Seismotectonic framework of the central Apennines (modified after Galadini and Galli,

451   2000). MVEF - Mt. Vettore fault; NFS – Norcia fault system; LMF - Laga Mts. fault; UAVFS -

452   Upper Aterno Valley fault system; CIFS – Campo Imperatore fault system; CFCF - Campo Felice-

453   Colle Cerasitto fault; OPF - Ovindoli-Pezza fault; MAVFS - Middle Aterno Valley fault system;

454   SVF – Subequana Valley fault; MMF - Mt. Morrone fault; FF - Fucino fault; MPFS – Maiella-

455 Porrara fault system; ACF - Aremogna-Cinquemiglia fault; USFS - Upper Sangro Valley fault

456 system.

457

458 Figure 2 – Digital terrain model of the study area. Black lines with bars on downthrown side mark

459 the Paganica fault segments as defined in the present study; the black dotted line encircles the area

460 that suffered intensities (MCS scale) ≥VIII from the April 6 shock; epicentres of the aftershocks

461 that occurred in the area are marked by white circles (for Mw up to 4) and white squares (i.e., Mw

462 comprised between 4 and 5), and the white stars indicate the epicentres of *i*) the Mw 6.3 April 6

463 shock (with the focal mechanism) and *ii*) the Mw 5.7 aftershock of April 7.

464

465 Figure 3 – Tectonic structures (white lines) affecting the area of Paganica, as reported in a) Bagnaia

466 et al. (1992), b) Vezzani and Ghisetti (1998) and c) Boncio et al. (2004).

467

468 Figure 4 – Satellite image on which the segments of the Paganica fault (as defined by the study) are

469 shown (white lines; white bars and points mark the possible southern prolongation of the coseismic

470 surface displacement), together with the approximately N-S trending fault plane (white dashed line)

471 detected between the central and the southern branches of the Paganica fault; the black and the

472 white squares mark sites where *i*) the Paganica fault and *ii*) the evidence of surface faulting/

473 rupturing (i.e. ground cracks and free-faces) have been observed, respectively (left panel). The

474 location of the figures showing the Paganica fault segments and the evidence of co-seismic ground

475 deformation along the tectonic structure is reported on the right panel.

476

477 Figure 5 – a) Fault scarp formed on the carbonate bedrock, along the northern segment of the

478 Paganica fault; b) slope deposits, the attitude of which is highlighted by the white dashed line,

479 probably placed in contact (marked by the black arrows) with the carbonate bedrock by the northern

480   fault branch (black dashed lines mark secondary shear planes); c) fault scarp on the northern fault

481   branch formed on alluvial deposits, near to the southern end of the segment.

482

483   Figure 6 – a) Fluvial gravels (the black dashed line marks the attitude) displaced along a synthetic

484   fault plane (indicated by the black arrows) related to the Paganica fault, characterised by rotated

485   clasts in the shear zone (inset); b) fluvial and slope deposits containing Middle Pleistocene tephra

486   layers displaced along a synthetic fault plane (indicated by the white arrows) of the Paganica fault;

487   c) synthetic fault plane, detected along the walls of the trench of the aqueduct, displacing alluvial,

488   pedogenic and colluvial deposits; d) synthetic shear plane, detected along the wall of the trench,

489   placing fluvial gravels in contact with colluvial deposits dated to the Late Holocene.

490

491   Figure 7 – a) Fault plane of the southern fault branch, exposed at the base of the carbonate bedrock

492   fault scarp; b) Paganica fault plane in the area of San Gregorio. c) Fault plane roughly N20°

493   trending, seen at the northern end of the southern branch of the Paganica fault;

494

495   Figure 8 – Ground cracks along the northern fault branch near the "Vigne Basse" viaduct of the

496   A24 motorway (a, b, c, d) and next to the slope deposits shown in Figure 5b (e); free-face exposed

497   at the base of the slickenside surface along the northern fault segment (f);

498

499   Figure 9 – Ground cracks (marked by black and white arrows) along the central segment of the

500   Paganica fault affected paved courtyards, walls, fields, and dirt roads (a, b, c, d, e, f, g); some

501   fractures have vertical and horizontal offsets between their sides (h, inset). Some ground cracks are

502   located close to the trench of the aqueduct (c).

503

504   Figure 10 – Intersecting sets of ground cracks (the white arrows indicate the20°N trending set while

505 the black ones indicate the NW-SE (150°) trending set) in the transfer zone between the central and

506 southern segments of the Paganica fault (a, b); Ground fractures formed in the days subsequent to

507 the mainshock, in fields close to the northern end of the northern fault branch (c); ground cracks at

508 San Gregorio along paved and dirt roads, courtyards and building walls (d, e, f); fracture affecting

509 the carbonate bedrock near the southern termination of the southern segment of the Paganica fault

510 (g); free-face (white band at the base of the slickenside, indicated by the black arrows) exposed in

511 places at the base of the bedrock of the Bazzano fault (h).