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Coseismic ground deformation of the 6 April 2009 L'Aquila earthquake (central Italy, M_w6.3)

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[1] We provide field data of coseismic ground deformation related to the 6 April Mw 6.3 L'Aquila normal faulting earthquake. Three narrow fracture zones were mapped: Paganica-Colle Enzano (P-E), Mt. Castellano-Mt. Stabiata (C-S) and San Gregorio (SG). These zones define 13 km of surface ruptures that strike at 130–140°. We mapped four main types of ground deformation (free faces on bedrock fault scarps, faulting along synthetic splays and fissures with or without slip) that are probably due to the near-surface lithology of the fault walls and the amount of slip that approached the surface coseismically. The P-E and C-S zones are characterized by downthrow to the SW (up to 10 cm) and opening (up to 12 cm), while the SG zone is characterized only by opening. Afterslip throw rates of 0.5–0.6 mm/day were measured along the Paganica fault, where paleoseismic evidence reveals recurring paleo-earthquakes and post-24.8 kyr slip-rate ≥ 0.24 mm/yr. **Citation:** Boncio, P., A. Pizzi, F. Brozzetti, G. Pomposo, G. Lavecchia, D. Di Naccio, and F. Ferrarini (2010), Coseismic ground deformation of the 6 April 2009 L'Aquila earthquake (central Italy, M_w6.3), *Geophys. Res. Lett.*, *37*, L06308, doi:10.1029/2010GL042807.

1. Introduction

[2] On 6 April 2009 (01:32 UTC), a M_w 6.3 earthquake struck the town of L'Aquila in the central Apennines of Italy. It was preceded by foreshocks (4 with $3.5 \leq Ml \leq 4.0$ in the previous week) and was followed by aftershocks, including two strong shocks on 7 (M_w 5.6) and 9 (M_w 5.4) April. The focal mechanisms indicate normal faulting, with T-axes trending from ENE to NE (www.ingv.it, Figure 1). The hypocenters are mostly shallower than 10–11 km, with a main shock depth of ~9 km, and define normal faults dipping to the SW at ~50°; a depth of 15 km was calculated for the 7 April shock [*Chiarabba et al.*, 2009].

[3] The seismic sequence is located within a system of nearly parallel SW-dipping active normal faults [*Pizzi et al.*, 2002; *Boncio et al.*, 2004, and references therein]. Offsets of deposits and morphologies of late Quaternary age, as well as paleoseismic activity, are widely documented along the faults [*Galli et al.*, 2008, and references therein]. In particular, the 6 April epicentral area is located on the hanging wall of the Mt. Stabiata and Paganica–San Demetrio normal fault systems (Figure 1). The 5 km-long Mt. Stabiata fault dips to the SSW and strikes E-W in the western sector and NW–SE in the eastern part. The Paganica–San Demetrio system is 13–15 km-long, dips SW, strikes 130° and bounds the NE side of a tectonic depression filled by Quaternary continental deposits (Figure 1) [e.g., *Bagnaia et al.*, 1992; *Vezzani and Ghisetti*, 1998; *Agency for Environmental Protection and Technical Services* (*APAT*), 2005].

[4] After the main shock, we started a detailed field survey to detect evidence of coseismic ground deformation. Although other field reports exist [*EMERGEO Working Group*, 2009; *Falcucci et al.*, 2009] (see also ISPRA at www.apat.gov.it), we first document important fracture zones (e.g., Mt. Stabiata, San Gregorio), providing a more complete picture of the ground deformation.

[5] Our purpose is to combine i) the descriptive/quantitative data about the coseismic and early postseismic deformation at the surface and ii) the paleoseismic record, with iii) the evidence of late Quaternary faulting along previously known and newly mapped faults, in order to improve the regional seismotectonic model. We also synthesize our key structural observations to provide insights on how seismogenic slip propagates upward and deforms the ground surface during moderate magnitude earthquakes. This provides a guide as to how similar active faults might behave in the future. Moreover, the presented data offer constraints to seismic source modelers about the displacement field at the ground surface. This parameter, indeed, seems poorly constrained from seismologic or geodetic data alone, as indicated by the different results from, e.g., DInSAR data. In fact, *Atzori et al.* [2009] suggest that the fault does not offset the ground surface, while, *Walters et al.* [2009] indicate a 10-cm offset of the ground surface at Paganica.

2. Coseismic Faulting and Fracturing

[6] Coseismic deformation manifests at the surface in cm-sized free faces along bedrock fault scarps (the term free face is restricted here to the rejuvenated part of the fault plane originating at the base of a preexisting fault scarp), échelon cracks and open fractures that cut the ground surface and human structures. Three main narrow zones of coseismic deformation were mapped: Paganica–Colle Enzano, Mt. Castellano-Mt. Stabiata and, San Gregorio (Figure 1, see also details in Figures S1, S2a, S2b, and Data Set S1 of the auxiliary material).[2] Gaps along the trace of the fracture zones are mostly due to vegetation cover.

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[2]Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2010gl042807/. Other auxiliary material files are in the HTML.

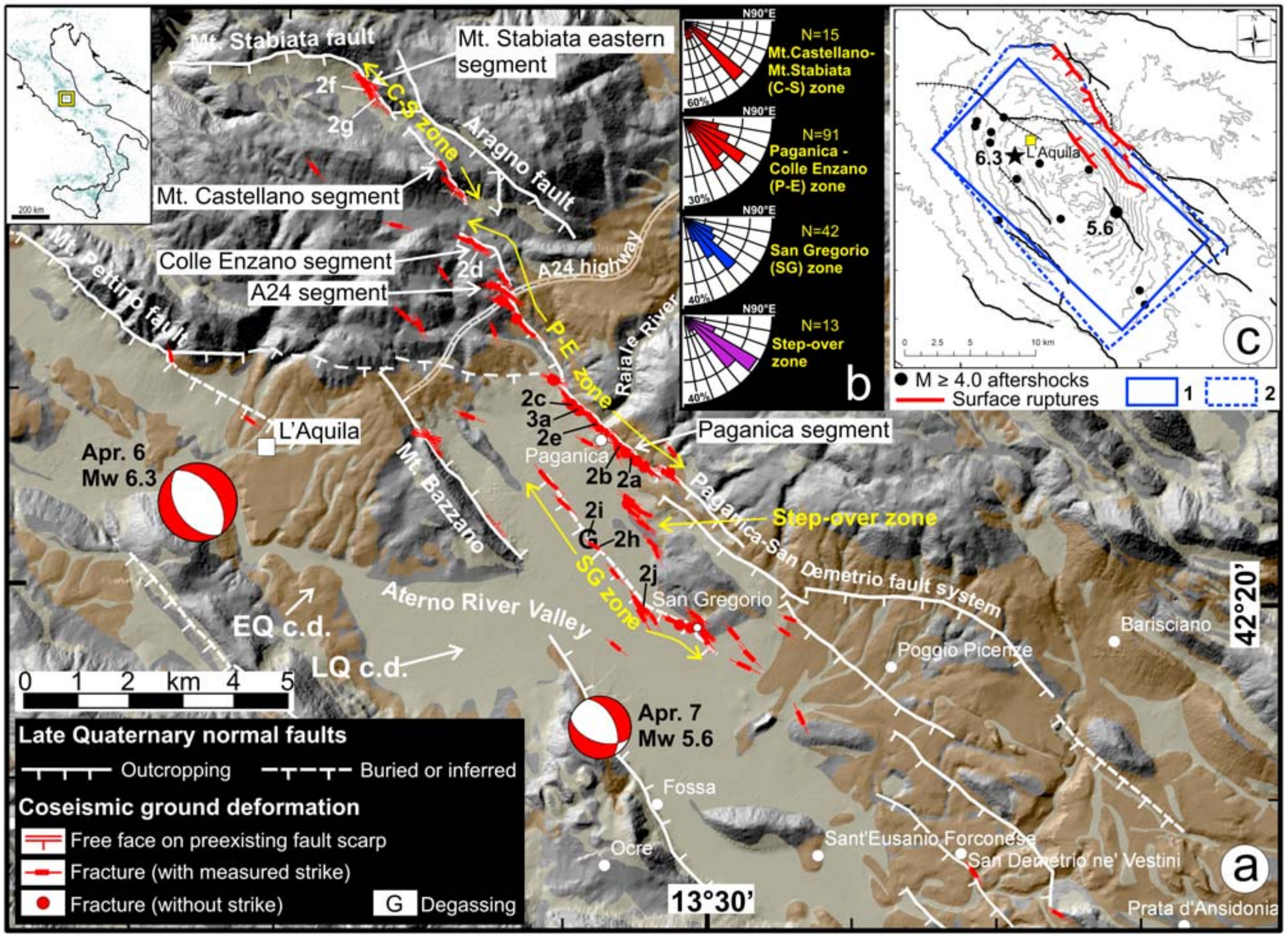

Figure 1. (a) Map of the L'Aquila 2009 epicentral area with active (late Quaternary) normal faults (modified from *Pizzi et al.* [2002] and *Boncio et al.* [2004]) and point measurements of coseismic ground deformation; EQ c.d. (brown color) and LQ c.d. (light brown) are early and late Quaternary continental deposits, respectively (from *APAT* [2005]); the CMT solutions of the main shock (6 April) and largest aftershock are shown; (b) strike rose-diagrams of structures in the main zones of coseismic deformation; (c) comparison among COSMO-SkyMed DInSAR fringes (gray curves, redrawn from *Atzori et al.* [2009]), surface ruptures (red), surface projections of model faults (1 = variable-slip source model from *Atzori et al.* [2009], 2 = geological fault from this paper) and, epicenters (star and dots) [from *Chiarabba et al.*, 2009] (see Figure S1 for a more detailed view of (c)).

2.1. Paganica–Colle Enzano (P-E) Zone

[7] The P-E zone, 6.3 km-long, is the longest and most continuous zone of mapped faults and fractures (Figure 1). In the central-southern part, the P-E zone strikes at 130° on average along the previously mapped Paganica fault segment, that forms a fault scarp on Middle Pleistocene conglomerates up to 35 m tall. In the northern part, the P-E zone displays two right-stepping échelon segments along two normal faults that strike at 100°–140°. The first segment crosses the A24 highway and strikes along a minor SW-dipping normal fault (A24 segment). The second segment strikes along a SSW-dipping normal fault characterized by a prominent limestone fault scarp up to 30 m tall (Colle Enzano segment).

[8] Along the Paganica segment, we observed a free face 6 to 8 cm tall at the base of a fault scarp well-preserved on conglomerates (Figure 2a). Elsewhere, we observed systems of fractures along the fault trace and in the hanging wall. The hanging wall fractures generally strike parallel to the fault trace and do not extend more than 35–40 m from the fault trace. Sporadically, long fractures with cm-size opening and dip-slip occur at larger distances from the fault trace (120–140 m; sites P31–34 in Figure S2b). Fractures are characterized by cm-size apertures and vertical slip to the SW, or only by apertures without slip (Figures 2b and 2c).

[9] In the northern part of the town of Paganica, the fractures cross the Gran Sasso water pipeline, which was broken during the main shock. High-pressure water eroded a NE-trending trench that exposed the Paganica fault zone (Figure 3a). Detailed mapping of lithologic and soil units in the trench, constrained by ^{14}C dating, permitted a geologic interpretation. At least six steeply dipping normal faults offset the Quaternary sequence, with a throw perhaps as great as several meters. With the exception of F3 and F3′, which are very close to each other and probably join at a shallow depth, fault strands are spaced 10–12 m apart. Unfortunately, in many cases, the occurrence of multiple erosional events and the related angular unconformities prevent the estimation of the cumulative offset and the paleoseismic history.

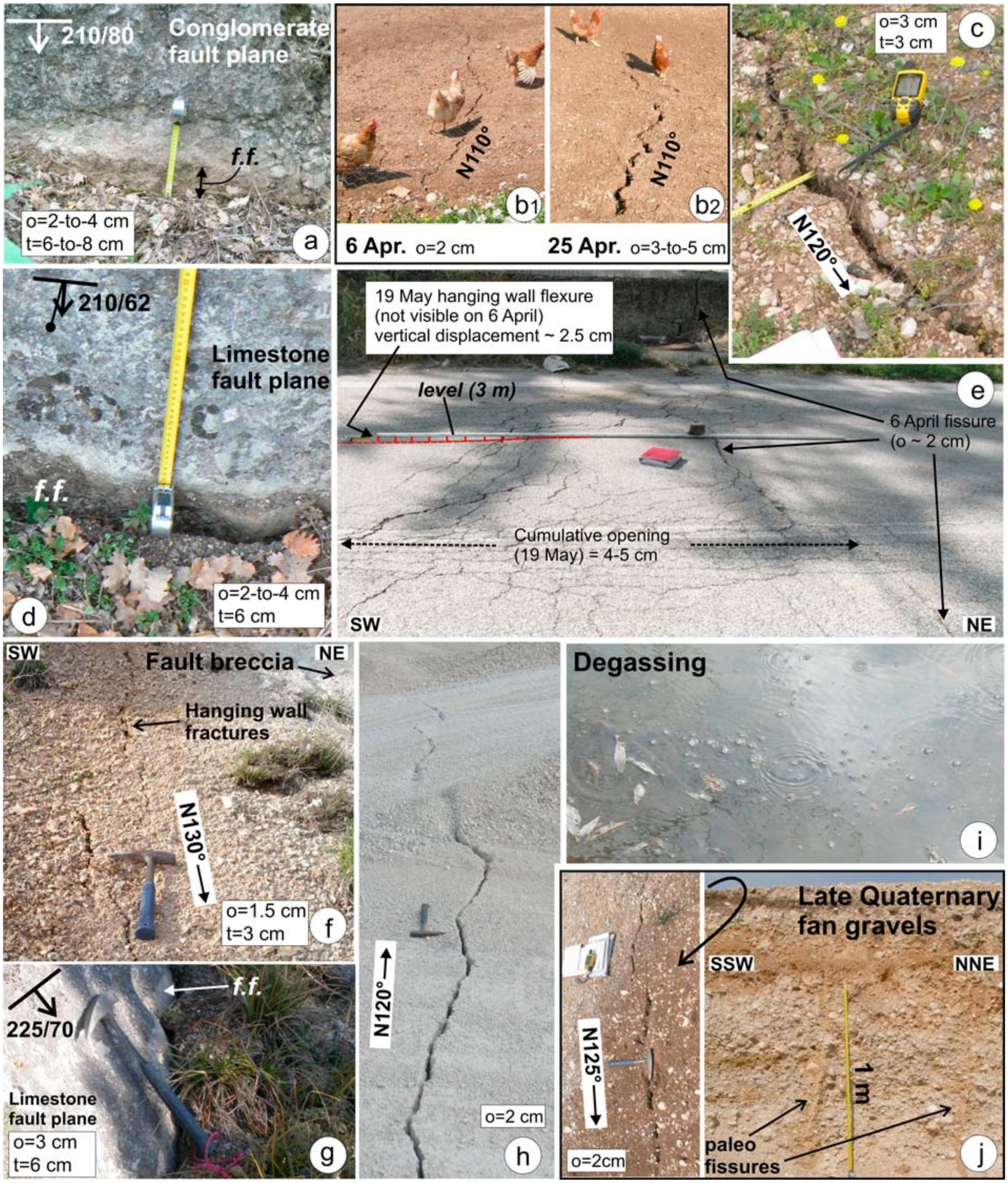

Figure 2. Examples of coseismic and early postseismic deformation along the (a–e) Paganica-Colle Enzano, (f and g) Mt. Castellano-Mt. Stabiata and (h–j) San Gregorio zones (location in Figure 1a, see also Figure S2); f.f. = free face; o = opening; t = throw. Attitude of faults give dip-direction/dip; b1 and b2 refer to the same fissure measured at different times after the main shock and show afterslip opening.

[10] Evidence of repeated offsets during the Late Pleistocene-Holocene was observed along the F3, F3′, F5 and possibly F4 strands (Figure 3a). A minimum dip-slip of 3 m characterizes the F3; the two scarp-derived colluvial wedges (U7) overlaying the soil dated as 24890 ± 140 yr BP (AQ1 sample), indicates that at least 1.5 m of dip-slip postdates this age. Scarp-derived orange colluvium (U6), sealing the F3, points out a younger age of faulting for the F3′ strand, which shows a minimum dip-slip of 2.5 m. A ^{14}C age of ~5 kyr for the U5 orange-brown colluvium [*Falcucci et al.*, 2009] also supports this evidence. The occurrence of the orange colluvium and debris (U6) in contact with the alluvial gravels (U9) provides a minimum 1.4 m of dip-slip for F4. Above the orange colluvium (U6), there is a subtle

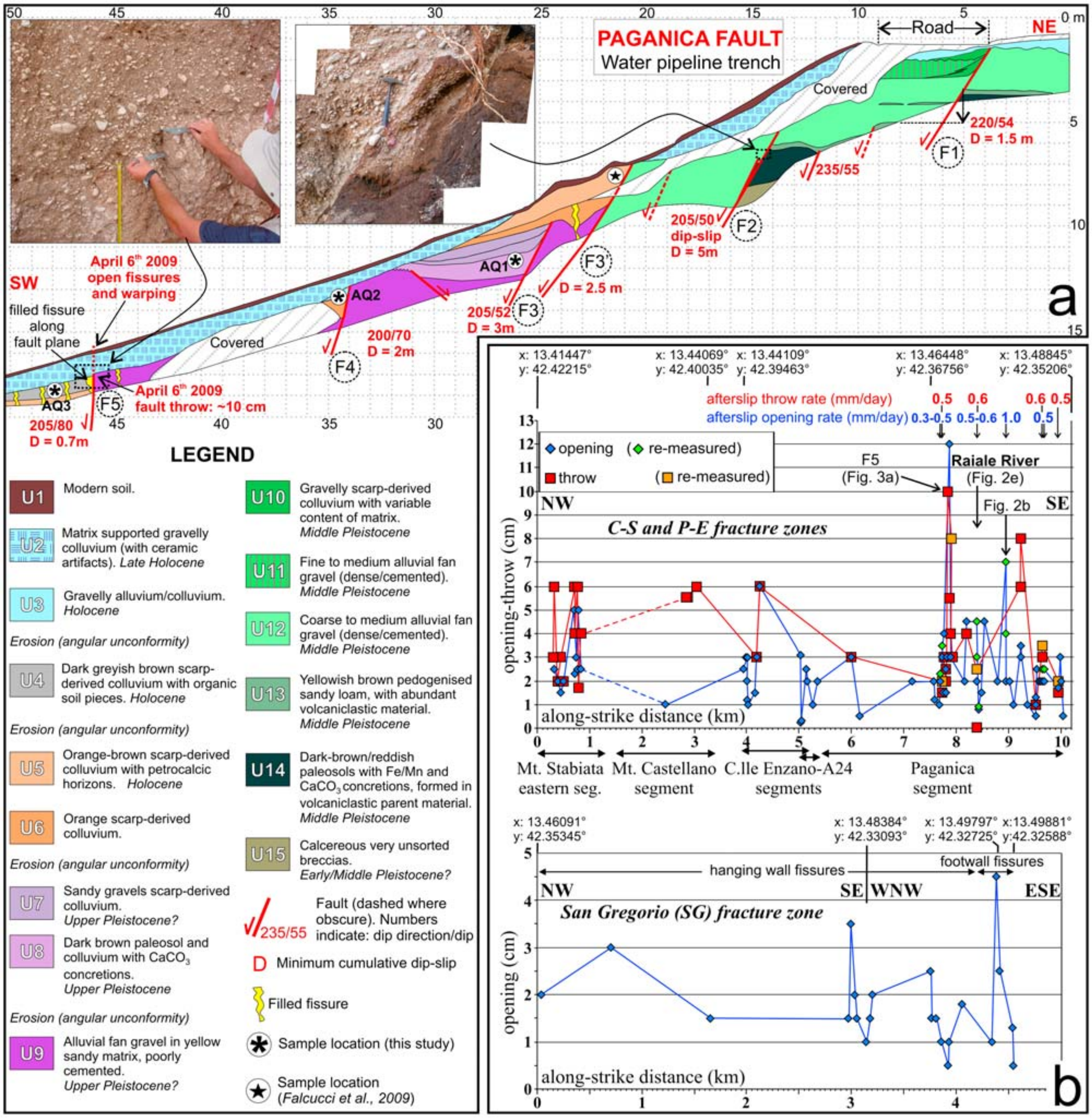

Figure 3. (a) Log of the Paganica water pipeline trench showing the fault zone (location in Figure 1a); shear fabric along the F2 normal fault is evidenced by smeared cohesive material (paleosol) and pebbles rotated parallel to the fault plane; the close-up of the F5 fault shows 10 cm of throw which affects the base of the Late Holocene colluvium and open fissures associated to the 6 April earthquake. (b) Along-strike variation of the coseismic and early postseismic throw and opening along the P-E and C-S zones (top graph) and SG zone (bottom graph); data from overlapping fractures are summed; afterslip throw and opening rates are obtained by re-measurements during the first 45 days after the main shock (see also Figure S2 and Data Set S1).

scarp-derived colluvium ~0.4 m thick. A thin organic horizon at the base of this wedge has a ^{14}C age of 1850 ± 40 yr BP (sample AQ2). However, because of the coverage and great disturbance due to human excavation, we are not completely confident with this historical event on F4. At the hanging wall of F5, dating of organic soil pieces reworked within the ~0.5 m thick scarp-derived colluvium (U4, sample AQ3) provided a ^{14}C age of 33440 ± 260 yr BP, indicating at least one important slip event after this age. Since the underlying orange-brown colluvium is very similar to the 5 kyr-old U5 unit, we suggest a possible Holocene age for this slip event.

[11] Figure 3a shows about 10 cm of throw on the F5 strand at the boundary between the dark grayish-brown colluvium U4 and the overlying historical colluvium and modern soil U2. Following the main shock, a fracture was mapped along the F5 fault trace. At the trench, the surface is gently warped near this fracture. About 30 m ESE of the

trench, the same fracture dislocates the ground surface ~10 cm vertically and ~4 cm horizontally. About 30 m NW of the trench, the deformation is more broadly distributed along 3 parallel fractures spaced 2–3 m apart: one along the F5 trace, and the others in the footwall. Thus, the near-surface 10 cm of throw measured in trench at the F5, coupled with the bending of the ground surface over the fault tip, clearly represents the 6 April coseismic deformation.

[12] Summarizing, the post-24.8 kyr activity of the dip-slip Paganica normal fault seems distributed among the F3, F3′, F5 (and possibly F4) strands, where a minimum cumulative dip-slip of ~6.0 m yields a minimum slip-rate of 0.24 mm/yr. Moreover, the recognition of scarp-derived colluvial wedges with a thickness of ~0.5 m, suggests that the Paganica fault is a seismogenic structure capable of surface faulting during earthquakes with M probably larger than 6.3.

[13] The 0.4 km-long A24 fault is a SW-dipping normal fault that dislocates both limestone bedrock and Quaternary debris (Figure 1a). Its coseismic reactivation is indicated by the opening of two preexisting faults within the fault zone (A24 outcrop, apertures of 0.5–1 cm; see Figure S2a) and by right-stepping fissures along the fault trace (apertures of 1–2.5 cm) without vertical displacement.

[14] The reactivation of the 1.5 km-long Colle Enzano segment is indicated by a continuous coseismic free face at the base of the preexisting fault scarp (Figures 1a and 2d). The free face was mapped along the entire central part of the segment, where the fault is well preserved on limestone rocks of the footwall. There, we measured 4 to 6 cm of coseismic throw and apertures of 4 to 8 cm.

[15] The openings and throws measured at several sites are plotted in Figure 3b. The throw is systematically down to the SW and ranges from 1 to 10 cm; the opening ranges from 0.5 to 12 cm. In the days following the main shock, we observed an increase of the opening and throw along the fractures. In order to estimate the rate of widening, we re-sampled 7 sites along the Paganica segment (Figure 3b). At the site shown in Figure 2b, for example, we observed about 2 cm of widening of the fracture between 6 and 25 April. On 6 April, we observed a fissure along the fault trace close to the Raiale river (Figure 2e) with aperture of ~2 cm, without appreciable vertical displacement. On 19 May, we mapped a hanging wall flexure 2.5–3 m wide. The cumulative opening across the deformation zone was 4–5 cm. The vertical displacement across the flexure was ~2.5 cm. A very similar deformation was observed close to the southern end of the Paganica segment (site P7 in Figure S2b).

2.2. Mt. Castellano-Mt. Stabiata (C-S) Zone

[16] Along the C-S zone, two preexisting normal faults were reactivated: the eastern Mt. Stabiata segment and the Mt. Castellano segment (Figure 1). The eastern Mt. Stabiata segment is 1.2 km long, dips SW, and was mapped before the 2009 earthquake. The Mt. Castellano segment is 1.8 km long, dips SW, and was previously unknown. Both segments are characterized by continuous, well-preserved fault scarps on limestone rocks of the footwall. We observed free faces 2 to 6 cm tall at the base of the fault scarps and hanging wall right-stepping fractures on late Quaternary debris located a few meters from the fault trace (Figures 2f and 2g; see also Figures S1 and S2). A couple of favorable exposures show that those fractures are synthetic structures splaying from the fault and partitioning the horizontal and vertical displacements in the hanging wall.

2.3. San Gregorio (SG) Zone

[17] The SG zone extends for a total length of ~4.5 km (Figure 1). It contains a southern segment that strikes 130–140°, a central segment that strikes 110° and a northern segment that strikes 130–140°. The northern segment and the Paganica segment form a right-stepping pair, with a separation of 1.4–1.7 km and an overlap of ~1.3 km. Deformation along the SG zone is manifested by linear fissures with cm-size apertures and échelon cracks, without appreciable slip (Figures 2h–2j and 3b). Close to the northern bend, the fractures strike near and parallel to a set of paleo-fissures dipping steeply to the SSW. The paleo-fissures cut late Quaternary gravels and are filled by sandy material (Figure 2j). This suggests that a preexisting fracture zone was reactivated during the main shock. In the central part of the northern segment, a long fissure (Figure 2h) crosses an irrigation channel where we observed a vigorous degassing on 10 April (Figure 2i).

[18] Geological, geophysical and well investigations performed after the earthquake (Working Group for L'Aquila Seismic Microzoning - Macroarea 3 at www.protezionecivile.it), indicate that the SG zone strikes parallel to a normal fault, buried by a thin cover of late Quaternary gravels, synthetic to the Paganica fault (San Gregorio fault). In particular, two boreholes located in the footwall of the SG fault penetrated the limestone bedrock at 20–30 m depths below a cover of alluvial gravels. A borehole located in the hanging wall penetrated the limestone bedrock at 190 m depth, indicating an abrupt deepening of the bedrock across the SW-dipping SG normal fault. The central and northern segments of the SG fracture zone are located in the hanging wall of the normal fault, at a distance of 60–90 m from the fault trace (Figures S1 and S2). The southern segment is located in the footwall, at a distance of 140–150 m from the fault trace.

[19] Three right-stepping alignments of ground fissures (200–450 m long) were observed in the step-over zone between the P-E and SG zones (Figure 1). Other evidence of coseismic reactivation was mapped along the Bazzano fault, which dips NE and is antithetic to the Paganica fault (Figures S1 and S2).

3. Discussion and Conclusions

[20] We observed three main right-stepping zones of coseismic ground faulting and fracturing: the P-E, C-S and SG zones. The P-E and C-S zones strike along preexisting SW-dipping normal faults with late Quaternary activity. They are the Paganica, A24 and Colle Enzano faults (P-E), and the Mt. Castellano and eastern Mt. Stabiata faults (C-S). The SG zone strikes parallel to a subsurface SW-dipping normal fault in right-stepping relation with the P-E (San Gregorio fault). The average strikes are 130° for P-E and 135° for C-S. The SG strikes from 130–140° to 110° (Figures 1a and 1b). Paleoseismic evidence indicates that the Paganica fault is capable of surface faulting during earthquakes with M probably larger than 6.3 and provides post-24.8 kyr minimum slip-rates of 0.24 mm/yr (Figure 3a).

[21] We observed four main types of coseismic ground deformation. Their differences are probably due to the near-

surface lithology of the fault walls and the amount of slip that approached the surface coseismically:

[22] 1. Free faces at the base of well-preserved fault scarps on lithified rocks, such as conglomerates or limestone (P-E and C-S zones). This suggests that the coseismic slip propagated upward along the main fault, breaching the ground surface;

[23] 2. Open fractures with dip-slip along synthetic splays of the master fault that cut poorly consolidated deposits (colluvium, gravels; P-E zone, Figure 3a). Fracturing results in a more irregular distribution of the displacement, such as: i) surface offset along a single fracture; ii) offset distributed among parallel fractures spaced few meters apart; or iii) open fissures with a warped ground surface;

[24] 3. Open fissures along the fault trace, on unconsolidated alluvium or colluvium (P-E zone). These open fissures are accompanied by flexure of the ground surface, which may have occurred during the early postseismic phase. This suggests that the slip stopped below the ground surface, very close to it, and deformed the surface in a way similar to that described by *Kaven and Martel* [2007] for a blind normal fault. Tensional stresses above the fault tip produced fissuring. Dip-slip at depth produced a flexure of the ground surface. The up-propagation of slip during the early postseismic phase (afterslip) amplified the flexure and locally offset the surface. The short wavelength of the flexure (e.g., 2.5–3 m in Figure 2e) suggests a very shallow fault tip, perhaps as shallow as few meters;

[25] 4. Hanging wall or footwall open fissures without slip (SG zone). These might be due to near-surface tensional stresses above the tip of a blind coseismic fault [*Kaven and Martel*, 2007]. Hanging wall fissures might also be interpreted as sub-vertical mode-I cracks coseismically propagated upward from the tip of the activated fault. For the latter case, we infer a depth of 100-to-250 m for the tip of the SG coseismic fault.

[26] Types (1) and (2) are evidence of coseismic surface faulting in a strict sense (i.e., offset of the ground surface). In both cases, the dip-slip is systematically associated with aperture of the fault and the ratio between throw and opening ranges from ~1 to 2.5. This suggests non-planar faults with dips ranging from 40–50° at depth to 60–80° near the surface, which allowed the fault walls to lose contact during slip in the near-surface.

[27] Our field data support a tectonic model in which the seismogenic master fault strikes 130–140° along the Mt. Stabiata - Paganica - San Demetrio normal fault system. The master fault dips SW and has a sub-surface length of ~20 km, in agreement with seismologic and geodetic data (Figures 1c and S1) [*Chiarabba et al.*, 2009; *Cirella et al.*, 2009; *Atzori et al.*, 2009; *Walters et al.*, 2009]. Faulting of the ground surface occurred only in the central-northern part of the seismogenic source, for a length of 10 km (C-S and P-E zones). The surface displacement varies along-strike, with maximum throw (10 cm) and opening (12 cm) along the Paganica segment (Figure 3b). The along-strike variation of surface displacement seems to reflect the inherited fault segmentation, although the right-stepping segments mapped at the surface are probably linked to each other at seismogenic depths. The deformation observed after the main shock is likely due to afterslip along the shallow portion of the fault. We estimated, along the Paganica segment, an afterslip throw rate ranging from 0.5 to 0.6 mm/day and an opening rate ranging from 0.3 to 1 mm/day (Figure 3b). The SG normal fault was activated during the main shock, but the coseismic slip stopped below the ground surface, perhaps at depths of a few hundred meters. The SG fault is interpreted as a synthetic splay of the deep master fault. The Bazzano antithetic fault was also probably activated up to the surface during the seismic sequence. The total length of the ground ruptures zone, including SG, is 13 km.

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