The Paganica fault and surface co-seismic ruptures caused by the April 6, 2009 earthquake (L'Aquila, central Italy)

E. Falcucci (1,2), S. Gori (1,4), E. Peronace (3), G. Fubelli (4), M. Moro (5), M. Saroli (6), B. Giaccio (7), P. Messina (7), G. Naso (3), G. Scardia (1), A. Sposato (7), M. Voltaggio (7), P. Galli (3), F. Galadini (1).

1 Istituto Nazionale di Geofisica e Vulcanologia, sezione Milano-Pavia
2 Dipartimento di Scienze della Terra, Università degli Studi "La Sapienza", Roma
3 Dipartimento della Protezione Civile Nazionale
4 Dipartimento di Scienze Geologiche, Università degli Studi "Roma Tre", Roma
5 Istituto Nazionale di Geofisica e Vulcanologia, sezione CNT
6 Dipartimento di Meccanica, Strutture, Ambiente e Territorio, Università degli Studi di Cassino, Cassino
7 Consiglio Nazionale delle Ricerche, Istituto di Geologia Ambientale e Geoingegneria

Corresponding author: Dr. Emanuela Falcucci
Istituto Nazionale di Geofisica e Vulcanologia, sezione Milano-Pavia
Via Bassini, 15
20133 Milan
Italy
e-mail: falcucci@mi.ingv.it

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

In the central Apennines, active faulting and earthquakes result from the ongoing extensional tectonics. The strongest earthquakes in the CPTI04 seismic catalogue (Working Group CPTI, 2004) occurred on September 9, 1349 (Mw 6.5), and February 2, 1703 (Mw 6.7). While the origin of the former is still debated with regard to its source, the latter event was associated with the Upper Aterno Valley fault system (UAVFS; Fig. 1), an ensemble of 7-to-10-km-long normal-oblique fault segments (Galadini and Galli, 2000; Galadini and Messina, 2001). The 1703 earthquake induced heavy damage in L'Aquila (Is 9, MCS scale; Stucchi et al., 2007), and the association of this earthquake with the UAVFS has been demonstrated by paleoseismological investigations (Moro et al., 2002) and by the distribution of the damage along the Upper Aterno River valley. Moreover, the recent activity of the UAVFS is demonstrated by displacement of Late Pleistocene-Holocene colluvial and alluvial deposits along the different segments of the system (Galadini and Galli, 2000; Moro et al., 2002).

Other damaging earthquakes that have affected the L'Aquila region in the past (i.e., 1461, Mw 6.4; 1762, Mw 5.9; 1916, Mw 5.2; 1958, Mw 5.2; see also Rossi et al., 2005) are more comparable to the April 6 damage distribution than to the damage from the 1349 and 1703 events. In particular, the 1461 event caused damage in Onna, Sant'Eusanio Forconese, Poggio Picenze, Castelnuovo and L'Aquila (10, 10, 10, 10 and 9, MCS scale, respectively; Stucchi et al., 2007), which is comparable to that of the April 6 earthquake (Galli and Camassi, 2009). Moreover, the magnitude calculated on the basis of 1461 earthquake macroseismic data point is evidently close to that of the April 6 shock. The most evident characteristic of all of these events is that, as in the case of the April 6 shock, most of the damage affected L'Aquila and villages south of L'Aquila, while little damage was recorded in the villages north of L'Aquila.

The UAVFS aside, other faults that could have been responsible for Mw >6 earthquakes have been reported in the literature, with slightly different interpretations regarding their geometry (Fig. 1). In particular, the Ovindoli-Pezza and Campo Felice-Colle Cerasitto faults (OPF-CFCF; Fig. 1) have normal or normal-oblique kinematics, and delineate a 28- to 30 km-long, NNW-SSE to NW-SE trending fault system south of L'Aquila that has Late Pleistocene-Holocene displacements, as indicated by paleoseismological investigations (Pantosti et al., 1996; Salvi et al., 2003). The 20-km-long, NW-SE trending Laga Mts. fault (LMF; Fig. 1) north of L'Aquila shows evidence of Holocene activity with normal kinematics, as indicated by displacement of 8ka deposits (Galadini and Galli, 2003). NE of L'Aquila, Holocene displacements have also been detected on the Campo Imperatore fault system (CIFS; Fig. 1) (Galli et al., 2002; Galadini et al., 2003) where trenches across secondary normal faults exposed evidence of surface faulting that occurred since about 3,4 ka. The different segments have a total length on the order of 33 km. Also, an impressive fault system exists between San Demetrio ne' Vestini and Molina Aterno, and further south, between Castelvecchio Subequo and Goriano Sicoli (Bosi and Bertini, 1970; Bagnaia et al., 1992; Galadini and Galli, 2000; Boncio et al., 2004) that were partly described as the Middle Aterno Valley fault system (MAVFS; Fig. 1) (Galadini and Galli, 2000). Paleoseismological investigations that were ongoing when the earthquake of April 6 occurred have revealed late Holocene activity of the segment between Castelvecchio Subequo and Goriano Sicoli (SVF; Fig. 1) (Falcucci et al., in preparation).

The location of the main shock, the aftershocks, and the distribution of the April 6 damage (Istituto Nazionale di Geofisica e Vulcanologia, 2009; Analisi dati di sismicità, http://www.ingv.it), however, are not consistent with the activation of the above-described faults (Fig. 2).

To identify the causative fault of this April 6 earthquake, we consider the structural framework of the area E and SE of L'Aquila, for where different structural patterns have been proposed in the past (Fig. 3). Indeed, since the 1970s, this sector has been repeatedly investigated regarding its neotectonic and active tectonic frameworks (Bosi and Bertini, 1970; Bosi, 1989;

Bagnaia et al., 1992; Bertini and Bosi, 1993). In particular, the two most recent studies present substantially different structural frameworks regarding the Quaternary activity. Bagnaia et al. (1992) reported a normal fault in the zone of Paganica that connects it with another normal fault in the area of San Demetrio ne' Vestini, providing a simple structural image of this area (Fig. 3a) that is affected by a ca. 20-km-long fault that partly affects Quaternary deposits. In contrast, Bertini and Bosi (1993) summarised a complicated structural framework of Quaternary faults in this area. The scheme proposed excludes a link between the Paganica fault and that in the area of San Demetrio ne' Vestini. The information on the Quaternary faults was summarised in a map by Vezzani and Ghisetti (1998), where the Paganica fault is mapped as a 9-km-long segment independent of the San Demetrio ne' Vestini fault (Fig. 3b).

Finally, these data have been included in different ways in seismotectonic studies at a regional scale. When mapping the surficial expression of sources that could potentially be responsible for M $\geq$6.5 earthquakes, Galadini and Galli (2000) did not include the short Paganica fault segment at the NW end of the MAVFS. In contrast, Boncio et al. (2004) linked one segment of the UAVFS mapped by Galadini and Galli (2000), i.e. the southeastern-most one (the Mt. Pettino fault), to the Paganica fault, defining a single 13-km-long fault segment in the area of L'Aquila that is not linked to the San Demetrio ne' Vestini fault (Fig. 3c). Roberts and Michetti (2004) and Papanikolaou et al. (2005) reported a segment of more than 30 km in this area , not including, however, the Paganica fault.

The geological surveys carried out *ad-hoc* after the earthquake along the Paganica fault (which is presently considered the surface expression of the seismogenic source of the earthquake of April 6) provide a different picture from that in the published literature before this earthquake.

3. The Paganica fault

Our geological surveys and analyses of aerial photographs taken after the earthquake define the surficial geometry of the long-term expression of this fault. We define three NW-SE trending segments that have a dextral en-echelon relationship (Fig. 4). The northernmost segment (segment 1, 3 km long) is located between the area east of Collebrincioni and Vallone delle Grotte (NE of Tempèra). The central segment is detected in the area of Paganica (segment 2; 3 km long) and terminates towards the SE along the road that connects Paganica and Pescomaggiore. The southernmost segment (segment 3; 2 km long) extends to the NW from the village of San Gregorio.

The surficial expression of the northern fault segment is marked by a prominent fault scarp in carbonate bedrock, at the base of which the slickenside surface is exposed (Fig. 5a). In the central part of the segment, next to Colle Cocurello and Colle Enzano, the fault splits into two splays (Fig. 4). Here, unconsolidated slope deposits (i.e., not older than the Last Glacial Maximum period; see Castiglioni et al. 1979; Dramis, 1983; Coltorti and Dramis, 1988, for more on this topic) are exposed at the base of the fault scarp and seems to be displaced along the eastern fault splay, where the "Vigne Basse" viaduct of the A24 motorway crosses the fault zone (Fig. 5b). Moreover, a small hand-made excavation (few tens of centimetres deep) performed along the fault scarp slightly to the north exposed post-Last Glacial Maximum debris dragged along the fault scarp, due to the fault movement. Hence, overall, these findings confirm the Late Pleistocene-Holocene activity of the Paganica fault.

The scarp on the central segment of the Paganica fault is present at the base of the slopes between Tempèra and Paganica. The fault scarp is formed both in the carbonate bedrock – in the northernmost part of the branch – and in fluvial deposits (Fig. 5c) – in the central and southern portions of the segment. Here, according to Sheet 359 "L'Aquila" of the Geologic Map of Italy at 1:50,000 (Foglio CARG 1:50,000, 2009. Cartografia geologica ufficiale Foglio CARG 1:50,000 N. 359, L'Aquila), the tectonic structure places Pliocene/Middle Pleistocene continental deposits in contact with Late Pleistocene sediments.

Many outcrops in the fault zone show displaced middle Pleistocene-Holocene fluvial and slope deposits (Fig. 6a) along several synthetic fault planes (about N140° trending).

The oldest fluvial sediments displaced along the fault contain partially-to-strongly reworked and/or weathered ash layers. Locally, ash deposits occur as primary air-fall deposits, as centimetre-thick, tephra layers (Fig. 6b). Chemical, lithological and isotope analyses on three of the thickest, best-preserved ashes have allowed us to assign them to the eruptions of "Tufo Pisolitico di Trigoria", "Pozzolane Rosse" and "Tufo Rosso a Scorie Nere" (authors' unpublished data) from the Colli Albani and Sabatini volcanic districts (central Italy); these ashes have been dated to about 560, 456 and 450 ka, respectively (Marra et al., 2009, and references therein). These data provide the oldest chronological point-control for the dating of the activity of the Paganica fault.

More recent activity on the central segment of the Paganica fault is documented by displaced colluvial and fluvial deposits along at least three shear planes that are exposed in the walls of a deep trench (up to 5 m high) that is perpendicular to the fault. The trench, which is in north of Paganica, was dug out by a strong jet of water from a leak in an aqueduct that ruptured during the earthquake (Fig.6c). In the uppermost part of the trench, one fault plane places carbonate breccia in contact with fluvial gravel, colluvial and soil levels that are displaced by some metres (Fig. 6c). Other shear planes exposed in the trench displace fluvial and slope deposits (Fig. 6d). Organic-rich material in the colluvium yielded radiocarbon ages of 5,718 BC/5,467 B.C. to 5,403 BC/5,387 B.C. (calibrated, 2σ) (Fig. 6c) and 34,970 ±470 BP. The latter age is supported by U/Th dating of a calcareous tufa that is embedded in the dated organic-rich deposit that gave an age of 33,000 ±4100 BP. These data support the Late Pleistocene-Holocene activity of the Paganica fault.

The southern end of the central segment of the Paganica fault ends against a N-S trending tectonic structure that dips about 80° to the E. This fault is visible along the road that connects Paganica to Pescomaggiore and shows normal-to-transtensive kinematics (Fig. 6e). Here, alluvial-fan and colluvial deposits are displaced on the Paganica fault and the N-S fault. The sediments contain the above-described Middle Pleistocene tephra layers, thus indicating a post-Middle

Pleistocene activity of the N-S fault.

The central and the southern branches of the Paganica fault are separated by a transfer zone (e.g. Peacock, 2002) that is here marked by a wide landsurface that gently dips towards the NW.

The southern segment of the Paganica fault is located SE of Paganica from the area E of the San Vittorino to the village of San Gregorio. Its surficial expression is defined by a scarp in carbonate bedrock, at the base of which the slickenside surface is often exposed (Fig. 7a, b). At its northern end, the fault branch intersects a fault plane trending about N20° and dipping steeply eastward, which affects the carbonate bedrock (Fig. 7c). This fault and the above-mentioned N-S trending tectonic structure are probably part of to the same fault system.

4. Coseismic surface deformation along the Paganica fault zone

The field surveys performed in the days subsequent to the main shock allowed us to identify coseismic surface deformation along the Paganica fault that produced sets of NW-SE trending ground cracks aligned along the fault zone, and parallel the fault segments, and which comprise a belt not wider than a few tens of metres. These fractures were up to a few centimetres wide and several tens of metres long (with no solution of continuity), and they commonly had an en-echelon (mainly dextral step-over) arrangement.

These ground cracks were almost continuous 1) through fields and urban areas, where roads and buildings were affected by newly formed ruptures and damage; 2) along slopes and plain areas; 3) across any morphological features of the landscape, such as small ridges, valleys and landsurfaces; and 4) affecting both natural and man-made terrain.

Moreover, most cracks along the central fault segment had vertical and horizontal offset between the sides (with the downslope side lowered) of a few centimetres; the displacement increased during the days subsequent to the April 6 shock, reaching a maximum of about 15 cm. In contrast, cracks along the northern and the southern branches did not have readily observable vertical offsets rather the ground was gently flexed, with an amplitude of less than 10 to 15 cm.

4.1 Northern fault segment

Along the northern segment of the Paganica fault, discontinuous ground ruptures, no more than about 20 m long and 1 cm wide, were observed at the base of the fault scarp (Fig. 8a, b, c, d). In particular, in the central part of the segment, the cracks are located where the fault splits into two splays (i.e. between Colle Cocurello and the Vigne Basse locality, see previous section), with different sets that trend roughly 120° to 170°. We observed cracks on both splays. A crack was also present where the above-described Late Pleistocene-Holocene slope debris was perhaps displaced on the tectonic structure (Fig. 8e).

Here, the "Vigne Basse" viaduct of the A24 motorway that crosses the Paganica fault zone (see previous section) suffered damage during the shock of April 6. This damage to the viaduct, mainly consisting in the re-opening of pre-existing "injuries" due to aging (i.e. old cracks with traces of water percolation), occurred where it crosses the Paganica fault. Hence, the damage might have been mostly caused by the strong ground motion caused by the earthquake, combined (subordinately) with the coseismic ground deformation (which is marked by cracks) at the fault zone (where piers of the viaduct are positioned) .

Moreover, evidence of reactivation of the fault plane is visible along the northern part of the segment where a fresh-looking free-face up to 8-10 cm high is present at the base of the slickenside surface. This free-face extends continuously for several metres, and marks the contact between the carbonate bedrock and the slope scree at the base of the scarp (Fig. 8f). In some places, the free-face was marked by the remnants of soil that coats the base of the scarplet. Moreover, the slope scree was separated from the bedrock scarp surface by an about 1-3-cm-wide fissure.

4.2 Central fault segment

We found ground cracks in the area between Tempèra and Paganica that parallel the fault branch where synthetic shear planes affect the Late Pleistocene-Holocene deposits (Fig. 9). Cracks are present continuously along the entire segment. In the village of Paganica village, these ground ruptures intersected the trench at the aqueduct (Fig. 9c), so we can reasonably hypothesise that the damage to the aqueduct can be attributed to the coseismic surface displacement along the tectonic structure.

To the southeast, we found ground ruptures as far as the southern end of the central segment. Along the transfer zone that separates the central segment and southern of the Paganica fault, we found two intersecting sets of ground fractures, one set trending about roughly N20° and the other trending about NW-SE (about 150°) (Fig. 10a). The former set was aligned with the aforementioned N-S fault, while the latter has a direction similar to the Paganica fault trend. Some of these intersecting ground cracks appeared in the days subsequent to the mainshock, probably related to the occurrence of afterslip (Fig. 10b).

Rare and discontinuous E-W trending fractures extend for less than 1 km in length in the area of Tempèra. These secondary features might result from local, surficial craking due to passive movement caused by ground shaking along secondary E-W striking tectonic structures, which have been mapped in this area (e.g. Bagnaia et al., 1992; Vezzani and Ghisetti, 1998; Foglio CARG 1:50,000, 2009. Cartografia geologica ufficiale Foglio CARG 1:50,000 N. 359, L'Aquila); the Late Quaternary activity of these E-W tectonic structures has never been demonstrated by thorough geological studies.

4.3 Southern fault segment

A few tens of metres south-eastwards, we found NW-SE trending ground cracks at the northern end of the southern fault segment that extend towards the SE and parallel the carbonate bedrock fault scarp (Fig. 10c). The width of the fractures increased in the days subsequent to the mainshock. This confirmed the occurrence of a certain amount of afterslip.

Further south, we found several ground ruptures close to the southern end of the fault branch, in the area of San Gregorio (Fig. 10d, e, f), with some cracks being tens of metres long. According to eye witnesses, some of these fracture formed during the aftershock of April 7 (Mw 5.6; Istituto Nazionale di Geofisica e Vulcanologia, 2009; MedNet, http://mednet.rm.ingv.it/procedure/events/QRCMT/090406_013322/qrcmt.html).

Here, the cracks were arranged in two sets trending between N120° and N150°. We also found, a fresh fracture with N350° trend that affected the carbonate bedrock (Fig. 10g). A fresh-looking crack on the ground occurred where the fracture intersected the surface (Fig. 10g, inset).

5. Investigation along the Mt. Bazzano antithetic normal fault

We also examined a previously mapped normal fault (e.g. Vezzani and Ghisetti, 1998) on the eastern slopes of Mt. Bazzano, and that is an antithetic fault to the Paganica fault. The surficial expression of this structure is a preminent fault scarp at the base of which the fault plane is exposed.

We identify local evidence of fault-plane reactivation that consists of a free face of up to 15 cm high, at the base of the slickenside and which, in places, had remnants of the soil coating the scree deposited at the base of the fault plane. This new free face was discontinuous as it was typically observable for no more than a few metres in length (Fig. 10h). Many sectors of the fault, indeed, showed no evidence of rejuvenation along the bedrock scarp.

Taken together with 1) the remarkable steepness of the slopes, and 2) the absence of evident ground cracks along the fault, – comparably to the Paganica fault – this suggests that the formation of the free face along the Bazzano normal faults was probably mainly due to non-tectonic gravitational processes and/or compaction of the unconsolidated scree at the base of the fault planes. Nevertheless, we cannot preclude a coseismic tectonic component to the new free face because, the fault is antithetic to the Paganica fault.

6. Concluding remarks

Our field surveys and studies of aerial photographs in the L'Aquila area (central Apennines) after the April 6 seismic event (Mw 6.3) permitted us to identify evidence of coseismic surface faulting on the Paganica fault, a NW-SE striking and SW dipping Quaternary normal fault located E of L'Aquila.

This structure had been mapped by previous studies (Bagnaia et al., 1992, Vezzani and Ghisetti, 1998; Boncio et al., 2004; Foglio CARG 1:50,000, 2009) but none of the previous works had documented its latest Pleistocene and Holocene activity.

Our data define three en-echelon segments of the Paganica fault, based on its surficial expression, each one 3-4 km long. The total length of the structure is about 10 km.

Apart from the obvious association with the April 6 earthquake, recent activity of the Paganica fault is defined by the displacement of ^{14}C- and U-series-dated Late Pleistocene-Holocene deposits along the tectonic structure. In particular, a trench eroded along a ruptured aqueduct exposed several tens of centimetres of offset in Late Holocene deposits along the Paganica fault, which suggests that the fault has probably generated stronger earthquakes in the past.

We identified evidence of surface faulting along the Paganica fault due to the April 6 shock including set of continuous aligned ground cracks along the central segment of the fault; some cracks had both vertical and horizontal offset up to about 15 cm. The offset of some cracks increased as much as a few centimetres in the days subsequent to the mainshock. This is probably evidence of a small amount of afterslip related to the aftershocks. The presence of ground cracks, although discontinuous and with no vertical offset along the northern and the southern fault segments suggest that also these branches of the Paganica fault were probably activated during the April 6 shock.

Overall, our observations show to relatively little coseismic surficial movements on the Paganica fault, which probably was less than a few centimetres. Further evidence that supports the occurrence of surface faulting on the Paganica fault includes the rejuvenation of the fault plane, i.e. the free-face observed at the base of the slickenside, along the northern and central segments of the tectonic structure. It is worth noting that base on empirical relationships between moment magnitude and the surface rupture length (Wells and Coppersmith, 1994), the length of the Paganica fault rupture is consistent (taking into account the uncertainty range proposed by Wells and Coppersmith) with the reported magnitude (Mw=6.3; Istituto Nazionale di Geofisica e Vulcanologica, 2009; MedNet, http://mednet.rm.ingv.it/procedure/events/QRCMT/090406_013322/qrcmt.html).

Finally, our evidence of surface rupture combined with the location and the length of the Paganica fault is consistent with it being the source of the April 6 earthquake. This conclusion is also consistent with the results from studies of 1) interferometric SAR observations (Atzori et al., in press); 2) the location and geometry of the fault modelled using the coseismic ground deformation patterns from GPS data (Anzidei et al., in press); and 3) seismological data, that is the location and focal mechanism of the main shock and the aftershock distribution (Istituto Nazionale di Geofisica e Vulcanologia, 2009; Analisi dati di sismicità, http://www.ingv.it).

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Figure captions

Figure 1 – Seismotectonic framework of the central Apennines (modified after Galadini and Galli, 2000). MVEF - Mt. Vettore fault; NFS – Norcia fault system; LMF - Laga Mts. fault; UAVFS - Upper Aterno Valley fault system; CIFS – Campo Imperatore fault system; CFCF - Campo Felice-Colle Cerasitto fault; OPF - Ovindoli-Pezza fault; MAVFS - Middle Aterno Valley fault system; SVF – Subequana Valley fault; MMF - Mt. Morrone fault; FF - Fucino fault; MPFS – Maiella-

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

Figure 2 – Digital terrain model of the study area. Black lines with bars on downthrown side mark the Paganica fault segments as defined in the present study; the black dotted line encircles the area that suffered intensities (MCS scale) ≥VIII from the April 6 shock; epicentres of the aftershocks that occurred in the area are marked by white circles (for Mw up to 4) and white squares (i.e., Mw comprised between 4 and 5), and the white stars indicate the epicentres of *i*) the Mw 6.3 April 6 shock (with the focal mechanism) and *ii*) the Mw 5.7 aftershock of April 7.

Figure 3 – Tectonic structures (white lines) affecting the area of Paganica, as reported in a) Bagnaia et al. (1992), b) Vezzani and Ghisetti (1998) and c) Boncio et al. (2004).

Figure 4 – Satellite image on which the segments of the Paganica fault (as defined by the study) are shown (white lines; white bars and points mark the possible southern prolongation of the coseismic surface displacement), together with the approximately N-S trending fault plane (white dashed line) detected between the central and the southern branches of the Paganica fault; the black and the white squares mark sites where *i*) the Paganica fault and *ii*) the evidence of surface faulting/ rupturing (i.e. ground cracks and free-faces) have been observed, respectively (left panel). The location of the figures showing the Paganica fault segments and the evidence of co-seismic ground deformation along the tectonic structure is reported on the right panel.

Figure 5 – a) Fault scarp formed on the carbonate bedrock, along the northern segment of the Paganica fault; b) slope deposits, the attitude of which is highlighted by the white dashed line, probably placed in contact (marked by the black arrows) with the carbonate bedrock by the northern

fault branch (black dashed lines mark secondary shear planes); c) fault scarp on the northern fault branch formed on alluvial deposits, near to the southern end of the segment.

Figure 6 – a) Fluvial gravels (the black dashed line marks the attitude) displaced along a synthetic fault plane (indicated by the black arrows) related to the Paganica fault, characterised by rotated clasts in the shear zone (inset); b) fluvial and slope deposits containing Middle Pleistocene tephra layers displaced along a synthetic fault plane (indicated by the white arrows) of the Paganica fault; c) synthetic fault plane, detected along the walls of the trench of the aqueduct, displacing alluvial, pedogenic and colluvial deposits; d) synthetic shear plane, detected along the wall of the trench, placing fluvial gravels in contact with colluvial deposits dated to the Late Holocene.

Figure 7 – a) Fault plane of the southern fault branch, exposed at the base of the carbonate bedrock fault scarp; b) Paganica fault plane in the area of San Gregorio. c) Fault plane roughly N20° trending, seen at the northern end of the southern branch of the Paganica fault;

Figure 8 – Ground cracks along the northern fault branch near the “Vigne Basse” viaduct of the A24 motorway (a, b, c, d) and next to the slope deposits shown in Figure 5b (e); free-face exposed at the base of the slickenside surface along the northern fault segment (f);

Figure 9 – Ground cracks (marked by black and white arrows) along the central segment of the Paganica fault affected paved courtyards, walls, fields, and dirt roads (a, b, c, d, e, f, g); some fractures have vertical and horizontal offsets between their sides (h, inset). Some ground cracks are located close to the trench of the aqueduct (c).

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

the black ones indicate the NW-SE (150°) trending set) in the transfer zone between the central and southern segments of the Paganica fault (a, b); Ground fractures formed in the days subsequent to the mainshock, in fields close to the northern end of the northern fault branch (c); ground cracks at San Gregorio along paved and dirt roads, courtyards and building walls (d, e, f); fracture affecting the carbonate bedrock near the southern termination of the southern segment of the Paganica fault (g); free-face (white band at the base of the slickenside, indicated by the black arrows) exposed in places at the base of the bedrock of the Bazzano fault (h).