The August 24, 2016, Amatrice earthquake (Mw 6.0): field evidence of on-fault effects

PRELIMINARY REPORT

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INDEX

1. Introduction

Immediately after the Mw 6.0 mainshock on the night of August 24, 2016, several teams of geologists from research institutes and universities reached the epicentral area in order to support the Civil Protection Department of Italy (DPC) through the characterization and mapping of earthquake environmental effects. The focus of the emergency survey was on effects related to the tectonic reactivation of the seismogenic fault (i.e. primary), as well as secondary effects mostly related to the seismic shaking (e.g. landslides, fracturing, hydrological anomalies, etc.).
A joint team of geologists from ISPRA, CNR, University of Insubria, University of Camerino, in strict contact with researchers from United Kingdom and Norway (Birkbeck and University College of London, Universities of Durham, Leeds and Sheffield) and Norway (University of Bergen), have carried out systematic field surveys in the areas surrounding the supposed surface exposure of the earthquake source, and in particular along the southern portion of the Mt. Vettore fault and the northern portion of the Laga fault.
These activities have been performed also with the objective of field validating the pattern of coseismic ground deformation from satellite monitoring (i.e., DInSAR), and to instrumentally assess by LIDAR and GPS the post-seismic evolution of the coseismic ruptures, especially along the Mt. Vettore fault.
These surveys were also coordinated with the INGV EMERGEO Working Group, that is in charge with regard to mapping and characterizing coseismic ground ruptures (cfr. EMERGEO Working Group 2016), and colleagues of DPC and other academic and research institutes.
In this report we describe preliminary results and conclusions of the observations collected so far. The ongoing activity will eventually build an integrated database portraying a more complete scenario of “on-fault” effects (coseismic and post-seismic), for a better understanding of earthquake impact on the natural environment and subsequent risk mitigation.

2. The Amatrice earthquake

2.1. Seismological and geological framework

On August 24, 2016, a M_W 6.0 earthquake hit Central Italy. The epicentral area was located between Norcia and Amatrice, at the boundaries among Lazio, Marche, Abruzzi and Umbria regions. The earthquake occurred just some tens of kilometers NW of L'Aquila (Abruzzo), hit by a slightly larger seismic event (M_W 6.3) on April 6, 2009.
The epicentre of the main shock was located a few kilometers north of the village of Accumoli (Rieti), and was followed about one hour later by an Mw 5.4 in the area of Norcia (Perugia). Thousands of aftershocks are continuing to shake the area since that time (Fig. 1). The focal mechanisms for the two main shocks show almost pure extension in an approximately NE-SW direction.

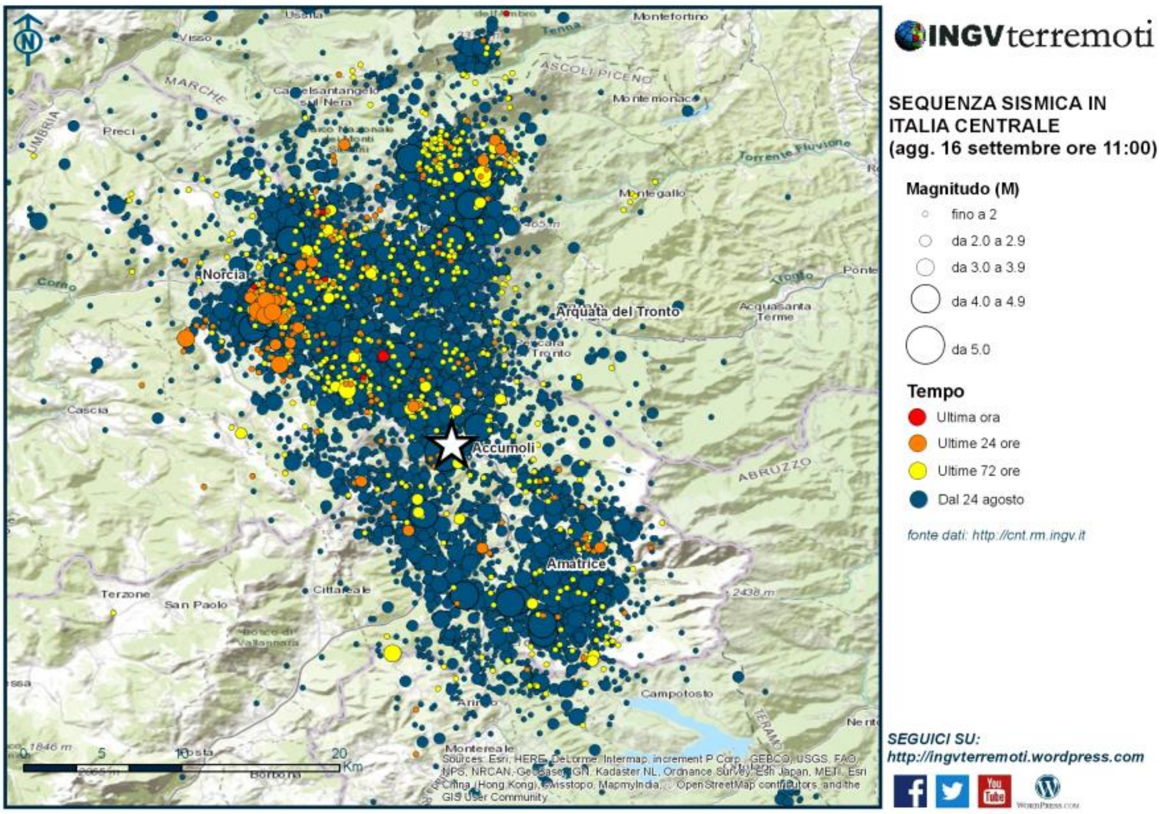

Fig. 1 – The seismic sequence started on 24 August in the Rieti, Ascoli and Perugia provinces (updated 16 September 2016). Source: INGV

In the official seismic hazard map of the Italian Civil Protection, the epicentral region is included in the highest probability of seismicity. The 2016 earthquake is consistent with the seismic history of the hit area, where the expected "worst scenario" is an earthquake of magnitude even larger than 6. Actually, the seismic history of the region reveals sequences of rather larger earthquakes, typified by the 1703 earthquake cluster with Mmax ca. 7. This last event also suggests that the L'Aquila 2009 earthquake has transferred tectonic stress to the NW, providing elements to assess possible future earthquake scenarios.
Despite the relatively low moment release, the August 24 event has been particularly devastating. The number of victims is almost equal to that seen for the 2009 L'Aquila event, which had greater

magnitude (Mw 6.3). A major cause for such loss of lives in 2016 is the occurrence of the mainshock in night-time (3:36 am local time) and in late August, when the Amatrice basin hosts approximately 30,000 people, mostly tourists in holiday houses, including those from other countries. In winter, the local population drops to less than 5,000 people.

The damage to buildings was truly severe because of their vulnerability, being mostly old masonry constructions lacking proper anti-seismic reinforcement measures. However, other effects, such as site amplification and directivity of the rupture, may have played a significant role, which is the subject of ongoing detailed seismological and engineering investigations. As a result, the estimated MCS epicentral intensity (X-XI) is comparable to that of the November 23, 1980, Mw 6.9 Irpinia event (Southern Italy). Not in L'Aquila (2009), nor in Colfiorito (September 1997, Mw 6.0) and in Norcia (1979, Mw 5.9), was such a severe effect on the historical building stock observed. This is a major warning to foster a better knowledge of these "moderate" events, the primary cause of earthquake loss in Italy in the past 25 years.

Two destructive historical earthquakes are known in the epicentral area (1639 and 1703, Table 1), causing local intensities greater than IX. The magnitudes, although not certain due to the age of these events, is widely agreed amongst the scientific community following study of the site effects.

Year Month Day	Epicentral Area	Mw		Epicentral intensity	Local Intensity (Amatrice)	Local Intensity (Accumoli)
1639 10 07	Monti della Laga	**6.2**		9-10	9-10	8-9
1703 01 14	Valnerina	**6.9**		11	9	10

Table 1 – Major historical earthquakes affecting the epicentral area (local intensity of 1639 for Amatrice takes into account also that of villages nearby). Source: DBMI15

This region hosts several major Quaternary normal faults with common seismic behaviour and arranged in a rather homogeneous structural pattern, which can be traced along the axis of the whole Apennines (e.g., Blumetti et al., 1993; Calamita et al., 1994; Blumetti, 1995; Piccardi et al., 1997; Cello et al., 1997; Piccardi et al., 1999; Di Domenica et al., 2012; Faure Walker et al. 2012) (Fig. 2).

The maximum magnitude (Mw) associated with this belt of capable normal faults is around 7, as shown during the historical sequence that hit Norcia, Montereale and L'Aquila in 1703, and during the January 13, 1915, Fucino earthquake (e.g., Serva et al., 1986; Michetti et al., 1996). The latter generated more than 23 km (most likely ca. 40 km) of surface faulting along the Serrone, Parasano, San Benedetto and Magnola Faults, with maximum displacement in the order of 1 m (Amoroso et al., 2016).

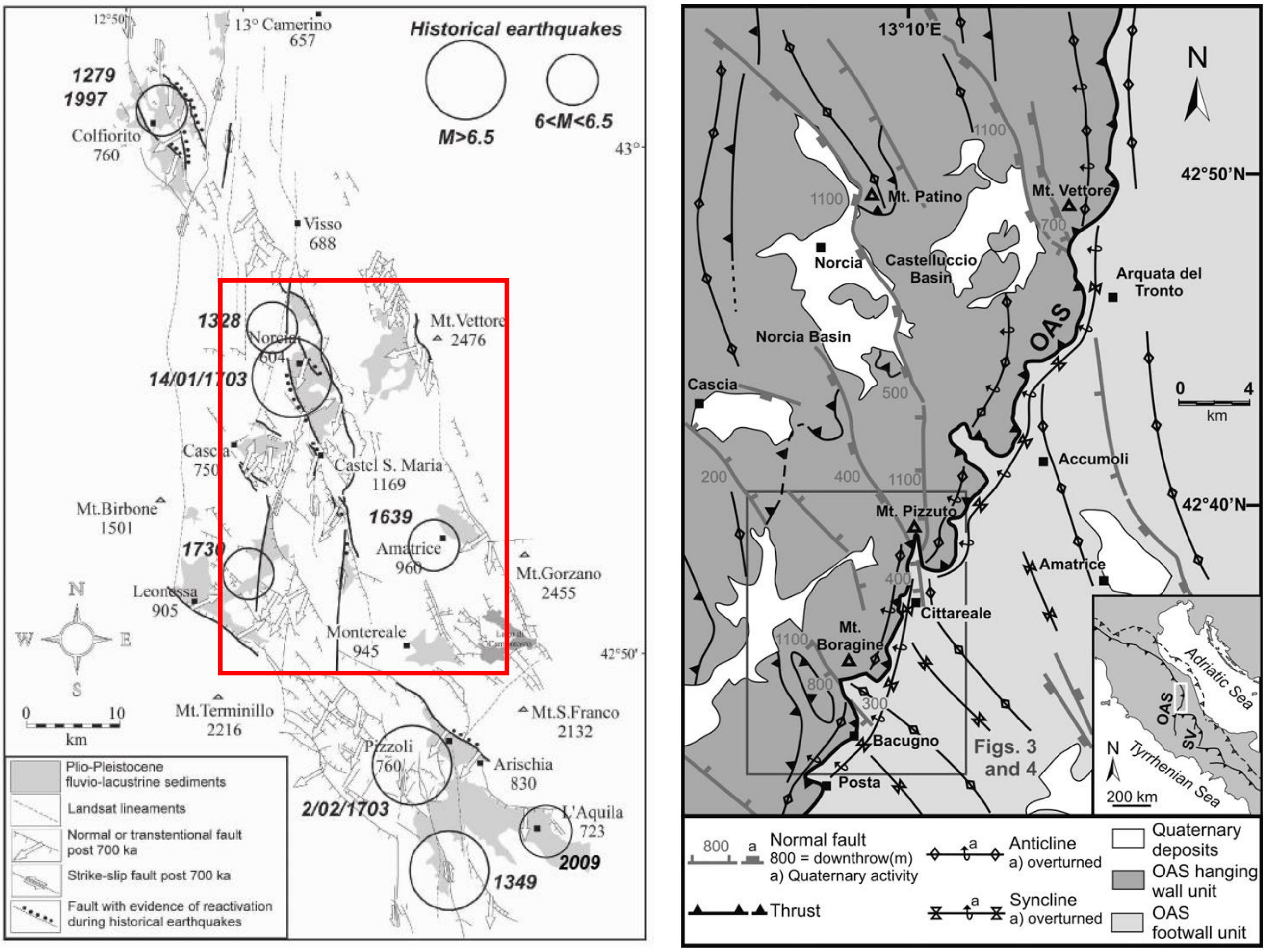

Fig. 2 – Examples of structural maps of the epicentral and surrounding areas. Left: Modified after Cello et al. (1997); Right: Di Domenica et al. (2012) (Location framed by the red box on left side figure).

Also the normal faults bordering the Laga Mt., the Vettore Mt., the Norcia basin and nearby Quaternary intermountain basins are well known as capable of producing surface faulting (e.g., Blumetti et al., 1993; Blumetti, 1995), and for this reason they are included in the ITHACA database, that is, the inventory of capable faults in Italy managed by ISPRA (Fig. 3).
During the last decades, in a large sector of this system different structures periodically activated (e.g., 1979 Norcia, 1997 Colfiorito, 2009 L'Aquila), so that the present seismic crisis fills at least in part what could be seen as a seismic gap (*sensu lato*) in the region (Fig. 4).

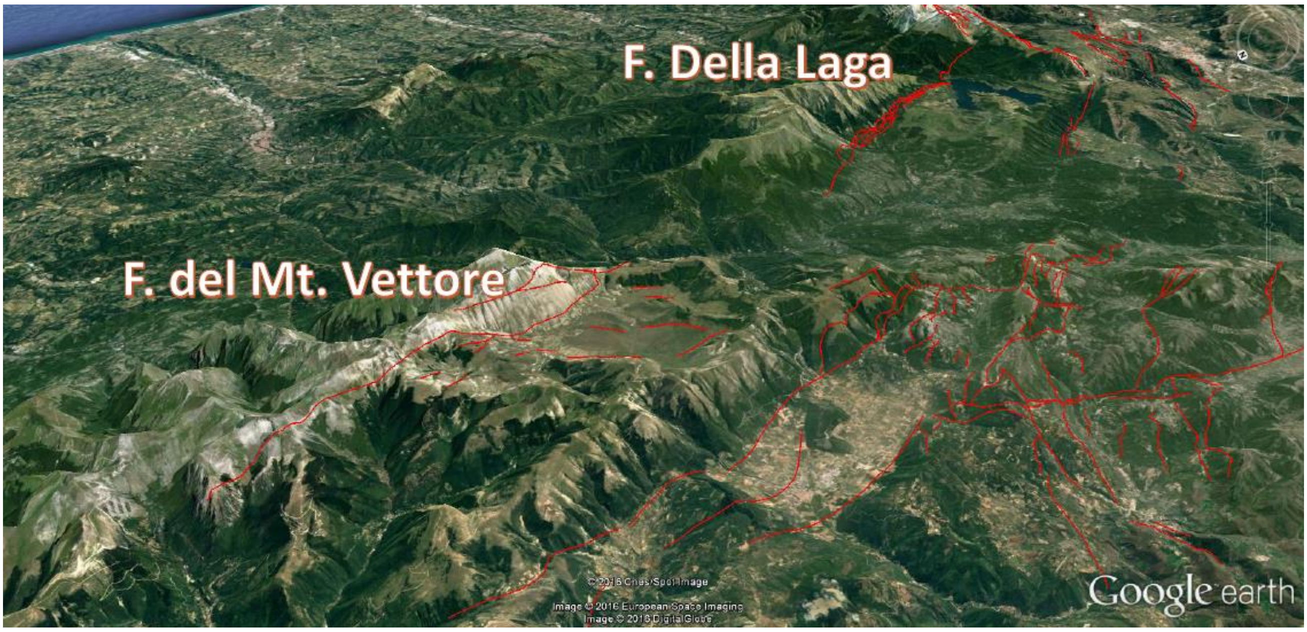

Fig. 3 – Capable faults in the epicentral and surrounding areas, according to ITHACA (source: ISPRA). View from northwest.

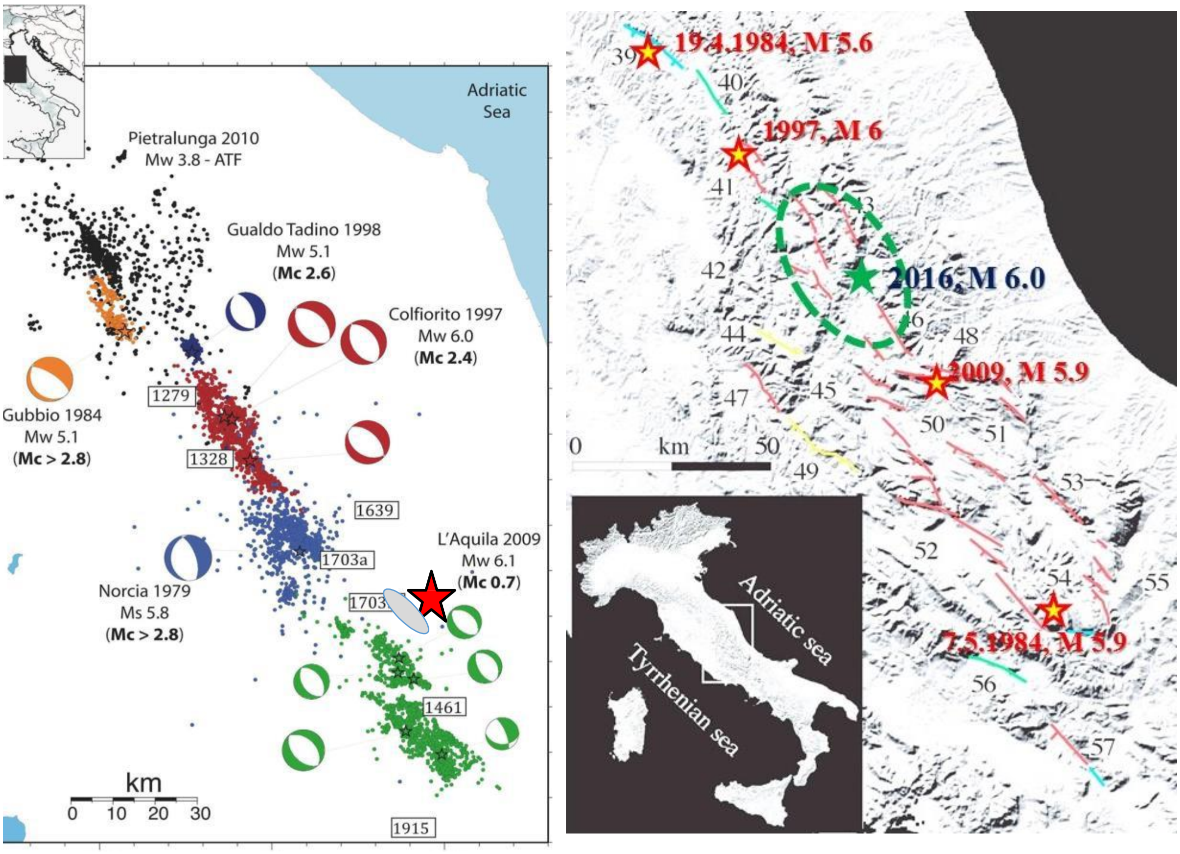

Fig. 4 - The 2016 Amatrice earthquake occurred in a seismic gap (sensu lato) along the inner sector of the Apenninic belt, in between the epicentral areas of 1997 Colfiorito and 2009 L'Aquila earthquakes (Gruppo di Lavoro INGV sul terremoto di Amatrice, 2016).

2.2. Coseismic ground deformation

According to preliminary seismological, geodetic and geologic data, the seismogenic structure appears to have a length of 25-30 km, a NNW-SSE orientation, a width of 10-12 km and a hypocentral depth of 10-12 km.

The preliminary model of the coseismic slip distribution (data ALOS2, Sentinel 1 and continuous GPS) and fault model from inversion of ground displacement (2 dataset SAR and 3 CGPS) has shown that most slip on the fault occurred in two areas, a deeper one beneath the Norcia and Castelluccio basins, and a shallower one (about 5 km) just under Accumoli: the maximum slip on the fault at depth, of more than 1.3 m, has been evaluated for this second area (*Gruppo di Lavoro INGV sul terremoto di Amatrice, 2016*) (Fig. 5). However, note that such studies are ongoing and the slip-distribution may be updated in the future.

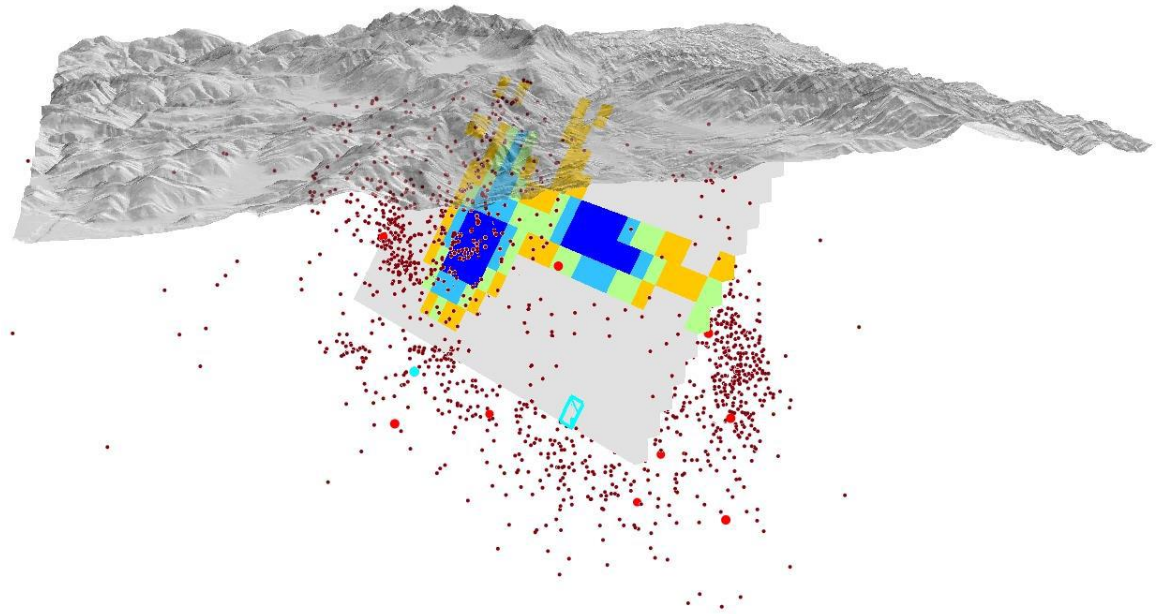

Fig. 5 - Preliminary 3D view of the seismogenic fault obtained by inversion of the static ground displacement (2 datasets SAR and 3 CGPS; Gruppo di Lavoro INGV sul terremoto di Amatrice, 2016).

The differential interferogram used for the inversion is shown in Fig. 6. It derives from a pair of ALOS-2 images covering the period 2015/09/09 – 2016/08/24.

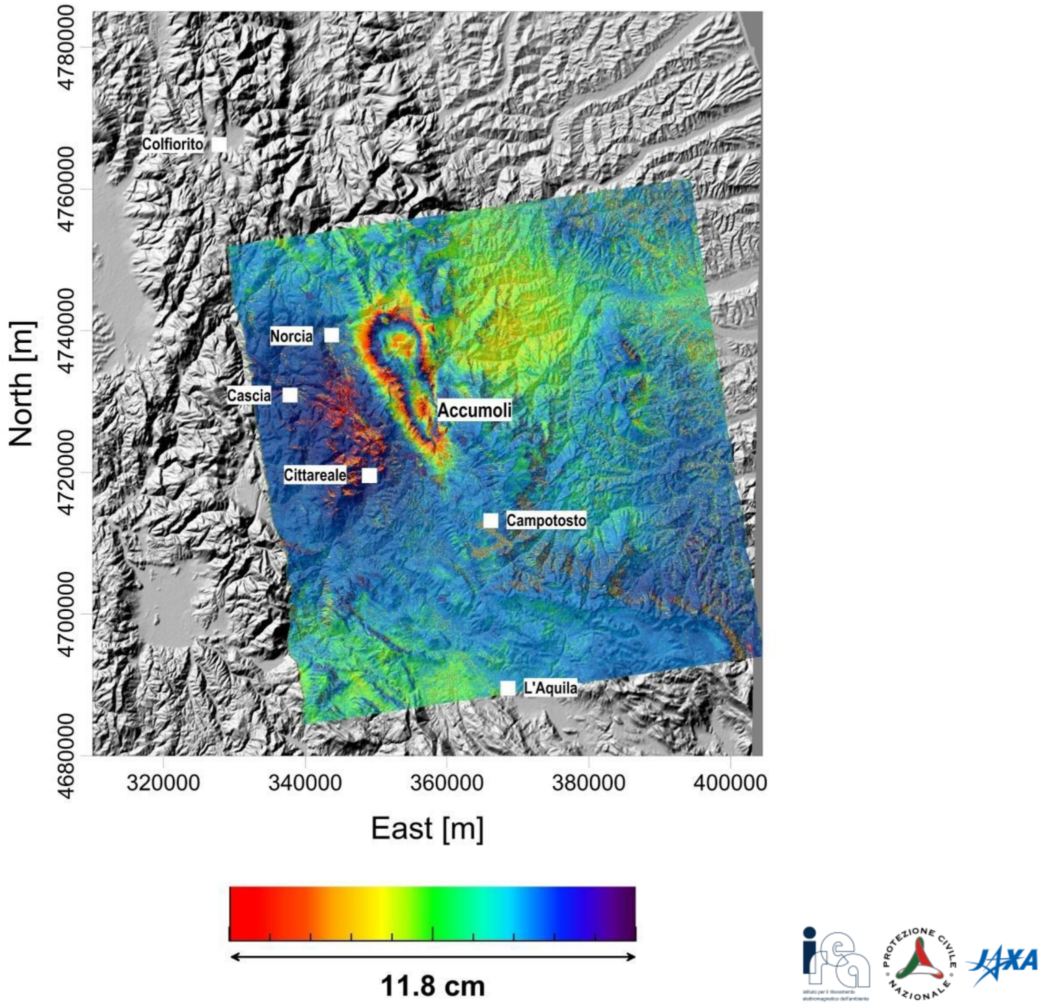

Fig. 6 - Differential interferogram obtained by the pair of ALOS-2 acquisitions, covering the time interval 2015/09/09 – 2016/08/24 (Gruppo di lavoro IREA-CNR & INGV, 2016).

Fig. 7 shows the ground deformation along the Line of Sight (LOS) in centimeters. The maximum lowering of about 20 cm was recorded in the Accumoli area. Northward, another wider depression, up to 18 cm deep, was perhaps generated by the M 5.3 aftershock.

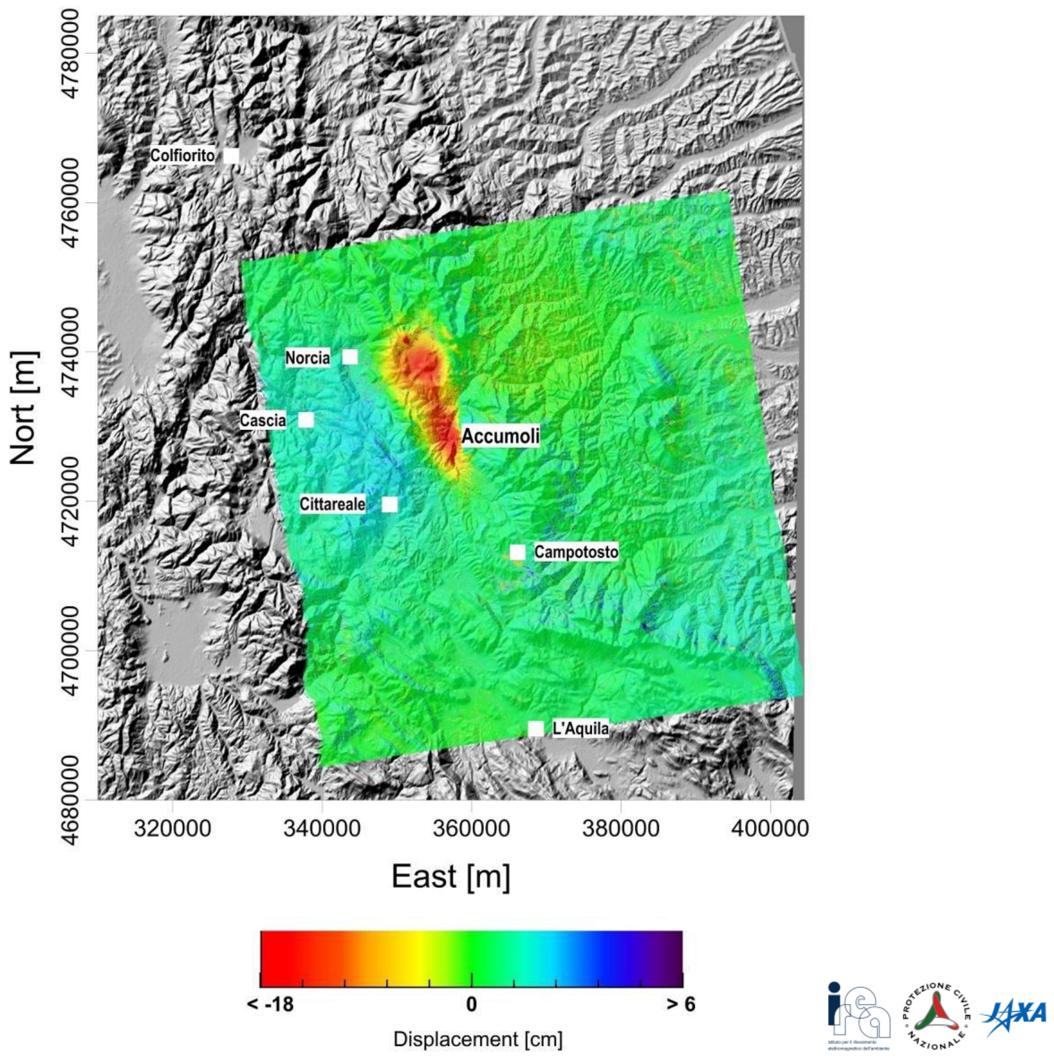

Fig. 7 - LOS ground motion map derived from the differential interferogram of Fig. 6 (Gruppo di lavoro IREA-CNR & INGV, 2016)

Data from Sentinel-1A and Sentinel-1B (operating in C band) and from COSMO-Sky-Med (operating in X band) acquired before (August 15) and after (August 27) the event have been studied by IREA-CNR and INGV (in collaboration with ASI). Fig. 8 shows the LOS, in ascending and descending mode, coseismic ground deformation maps (Figure 7) and the vertical component and east-west component of the ground motion (below). The results confirm a "spoon-shaped" lowering of the ground with a maximum sinking of 20 cm in the Accumoli area. Moreover, the E-W component of motion affects a wider area than does the vertical component, with a maximum deformation of 16 cm towards the west. The fault trace at surface based on the interpretation of these data is marked in blue (but with no more specific explanation).
Sentinel 1 InSAR images were processed also by COMET (NERC): the ascending (left side) and descending (right side) interferograms are shown in Fig. 9.

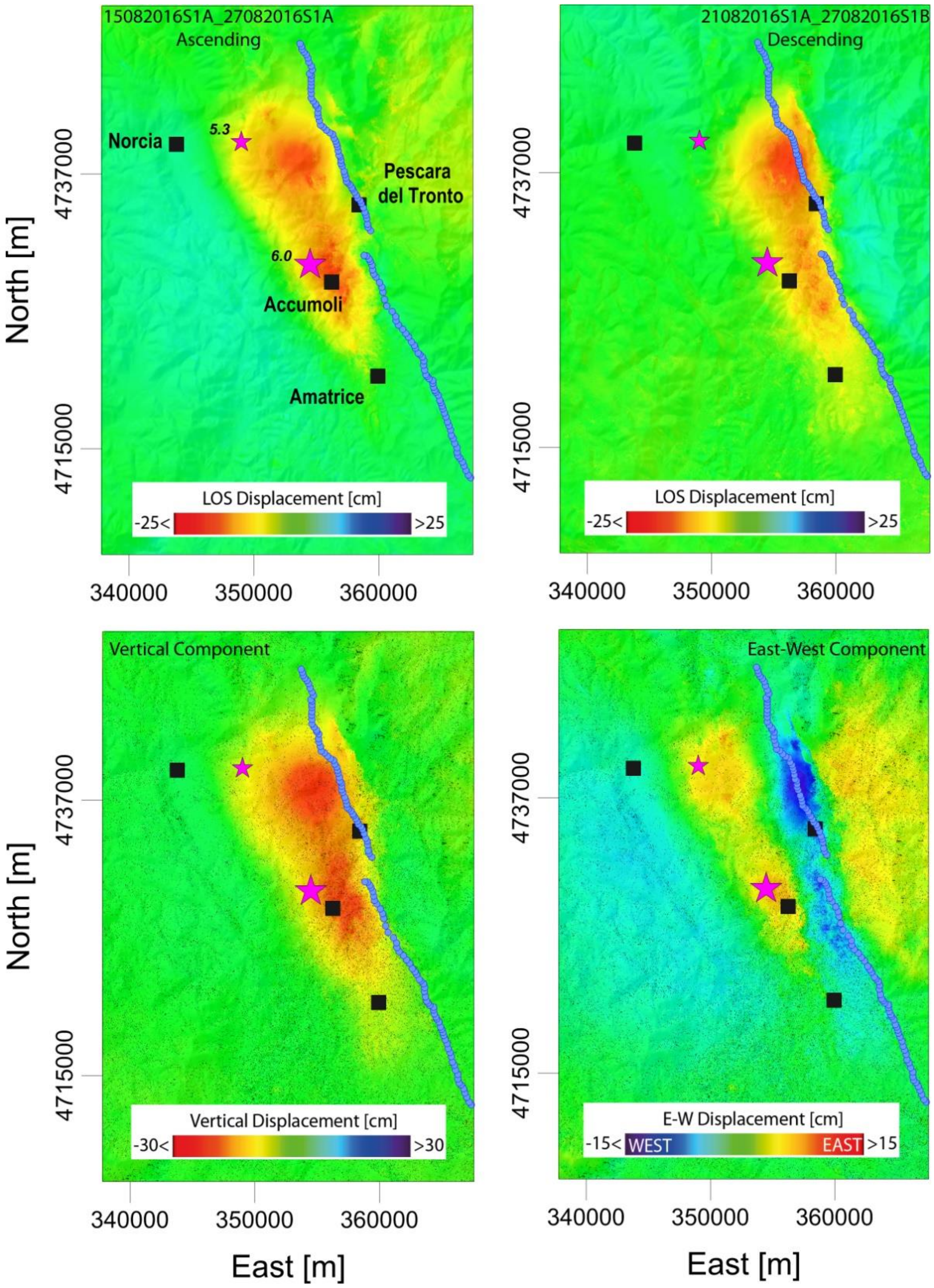

Fig. 8 - Upper part: Ascending and descending mode InSAR ground motion maps of the Sentinel 1A and Sentinel 1B images (along the LOS) related to the august 15 and 21, 2016 (before the event) and august 27, 2016 (after the event); Lower part: Vertical and E-W component of the ground motion derived from joined ascending and descending LOS images. In blue the interpreted fault trace on the surface (http://www.irea.cnr.it/index.php?option=com_k2&view=item&id=755:terremoto-di-amatrice).

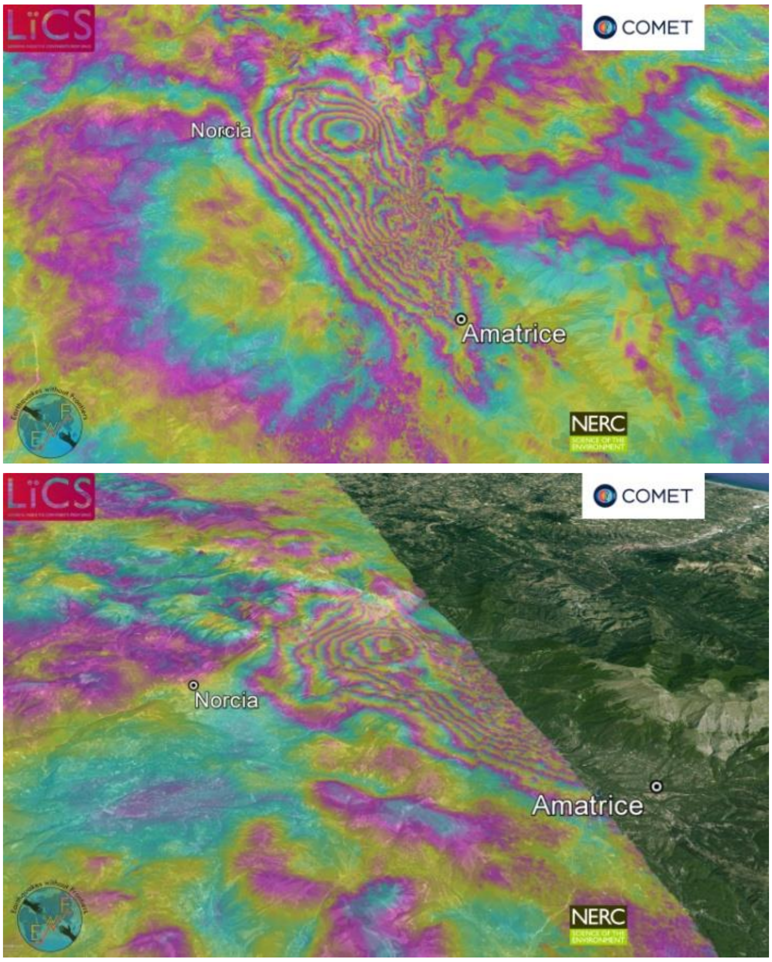

Fig. 9 - Interferograms of ascending (above) and descending (below) Sentinel-1 data (http://comet.nerc.ac.uk/)

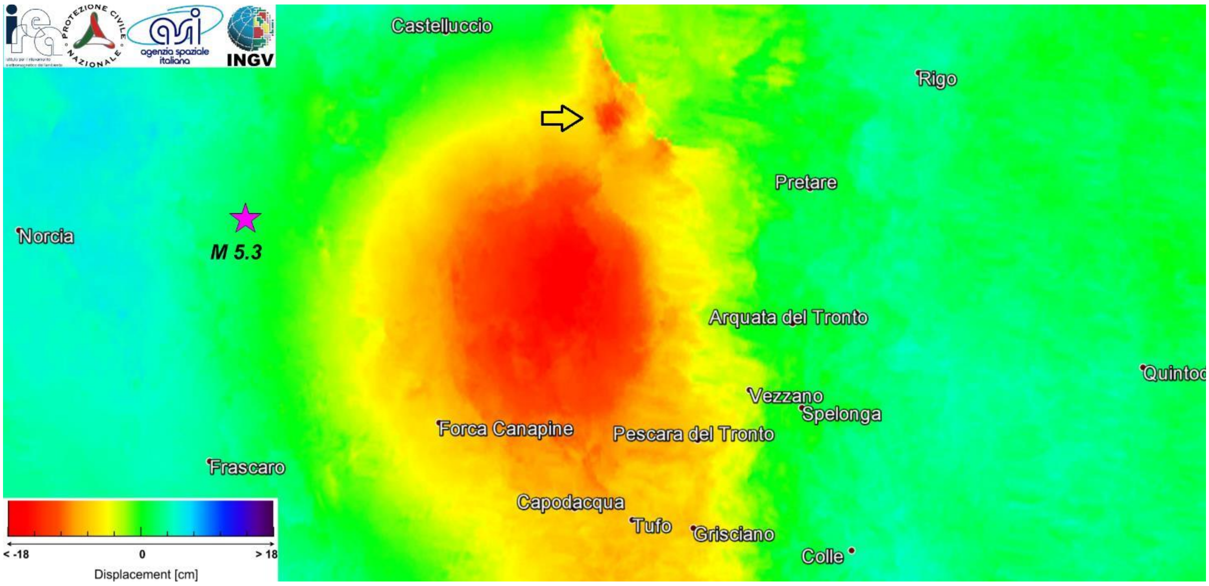

Fig. 10 - Coseismic ground deformation map obtained from InSAR analysis of COSMO-Sky-Med images (ASI) acquired along a descending orbit on August 20, 2016 (before the event) and on August 28, 2016 (after the event). The arrow indicates the deformation along the slope of Vettore Mt, suggested to be due the sliding of the slope debris cover (http://www.irea.cnr.it/index.php?option=com_k2&view=item&id=755:terremoto-di-amatrice).

High resolution COSMO-Sky-Med images (X band) were studied by INGV and CNR-IREA. The InSAR coseismic deformation map is shown in Fig. 10: the deformation along the western slope of the Mt. Vettore (indicated by an arrow) has been interpreted as the result of a minor gravitational mass movement by those authors.

3. Field surveys of on-fault effects

Since the day of the earthquake, field surveys in the epicentral area have been carried out by several geological teams from research and academic institutes with the aim of mapping and characterizing the Earthquake Environmental Effects (EEEs) induced by the earthquake.
This chapter provides a summary description of the so-called "on-fault effects". With this term we refer to the environmental effects mapped in proximity of the potential surface reactivation of the seismogenic fault, that includes primary effects (e.g. surface faulting, tectonic uplift, etc.), as well as likely secondary effects (e.g. gravitational phenomena) mainly triggered by the coseismic ground deformation along the seismogenic fault. The description of the "off fault effects" (i.e. seismically induced effects without any link with the tectonic reactivation of the seismogenic source) is the focus of another report still under preparation.

As indicated by the aftershocks distribution and interferometric data (see previous chapter) and in accordance with geological knowledge, the seismic source of this earthquake is organized in two main fault segments, separated by a right-step in the area of the epicentre (Pescara del Tronto, Grisciano), which correspond at surface to the Mt. Vettore fault (north) and to the northern portion of the Laga fault (namely the Amatrice fault, south). Figure 11 shows the two areas of on-fault field surveys along the Mt. Vettore fault and the Laga fault (up to September 3). More detailed maps are found in Figs. 14 and 22.

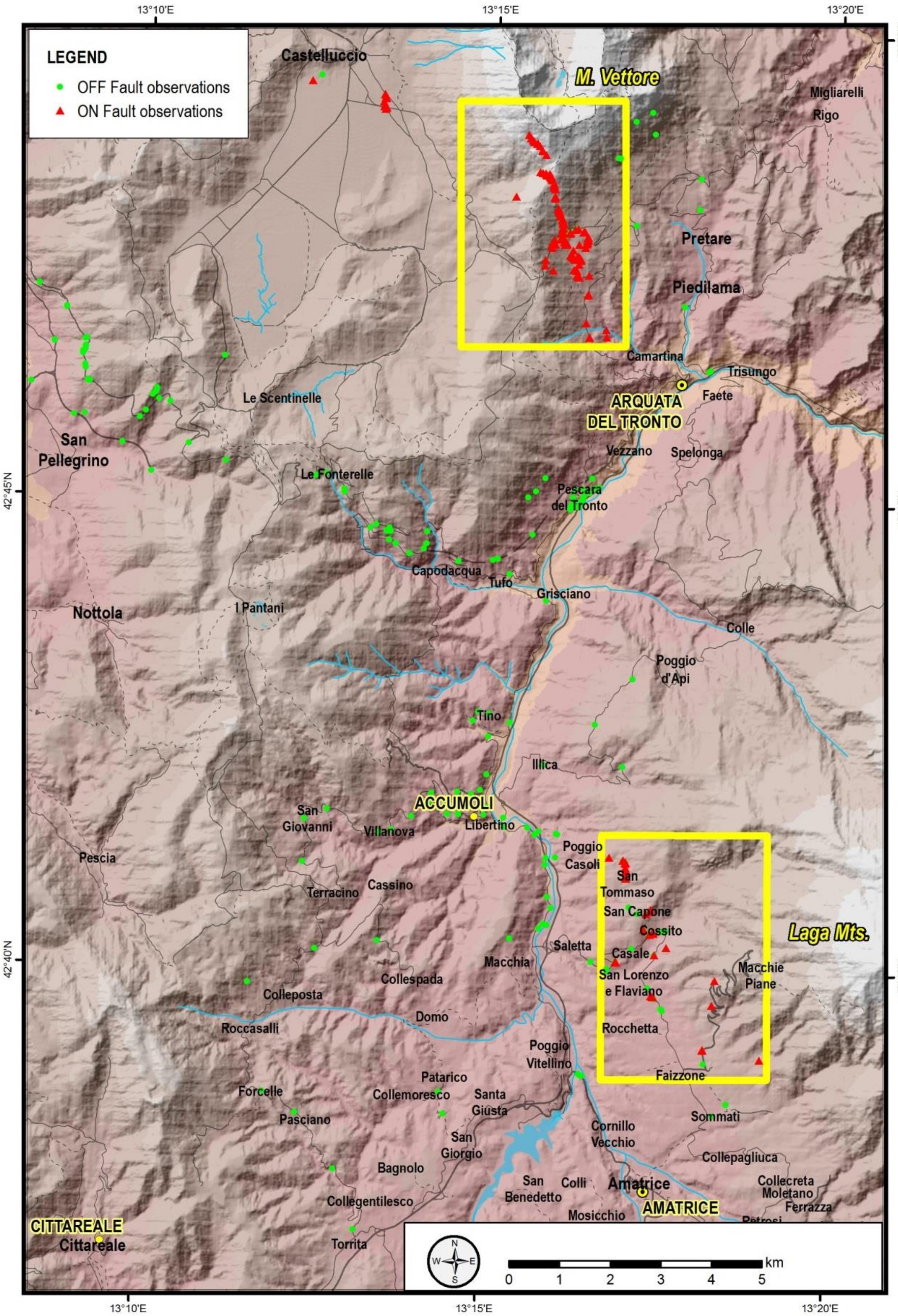

Fig. 11 – The two areas (in yellow) where field surveys of on-fault effects (red points have been performed. Green points are referred to off-fault observations (e.g. secondary effects) that are out of the scope of this report.

3.1. Mt. Vettore fault

The western slope of Mt. Vettore is the morphologic expression of a NNW-SSE trending SW dipping primary extensional tectonic element (total length 30 km) with northern termination at Mt. Bove. The total stratigraphic offset is in the order of one thousand meters.

The slope is marked by at least two major normal faults: the lower fault runs at the base of the Vettore escarpment and bounds the Castelluccio basin. The upper fault runs very close to the top of the Mt. Redentore, marked by a clearly visible fault scarplet in bedrock (commonly named "*Cordone del Vettore*"). A recent geological map (Pierantoni et al., 2013) provides a detailed trace of these faults (Fig. 12).

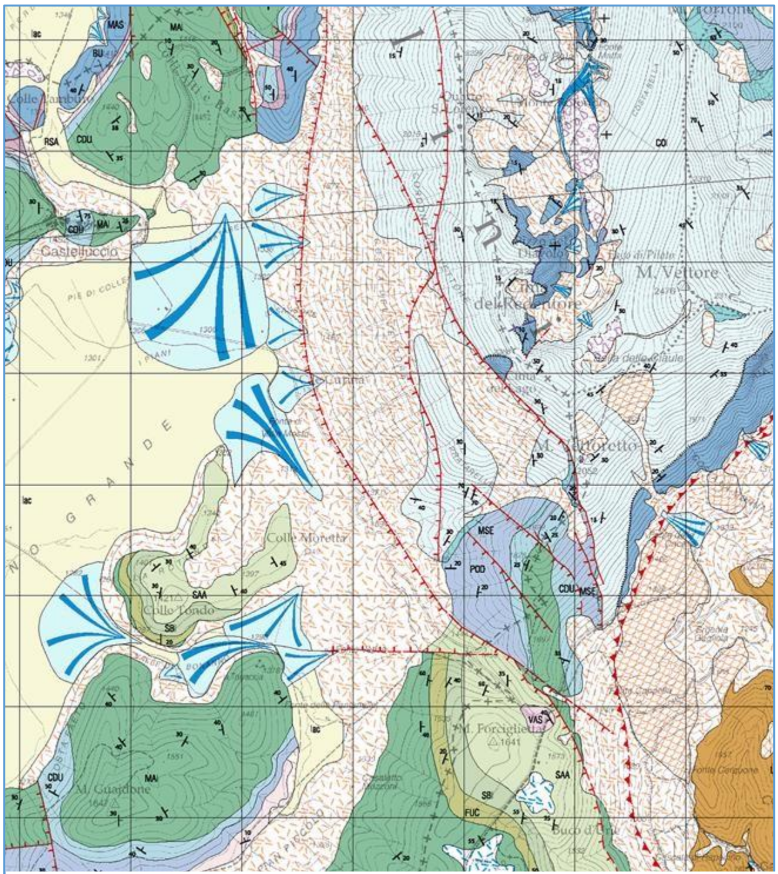

Fig. 12 – Geological map of the western slope of Mt. Vettore (source: Pierantoni et al., 2013).

The Mt. Vettore normal fault crosses and displaces the Sibillini thrust fault for some hundred meters. According to some authors, normal faulting may have locally reutilized some steeper shallow planes of the thrust zone (cfr. "tectonic inversion"; Cooper and Williams, 1989; Calamita et al., 1994; Di Domenica et al., 2012 and bibliography therein).

Recent activity on the normal faults was described by Scarsella (1947) and confirmed by several Authors in more recent times, who studied the geomorphic evolution of the Castelluccio Basin (e.g. Blumetti, 1991; Calamita et al., 1994; Coltorti and Farabollini, 1995), pointing out the occurrence of fault escarpments and scarplets. According to these Authors, the Castelluccio Basin (Fig. 13) is produced by extensional tectonics with slight left lateral component (cfr. ITHACA database). Paleoseismic investigations in the Castelluccio Basin (Galadini and Galli, 2003) provided stratigraphic evidence for three paleoearthquakes in the last 18 ka.

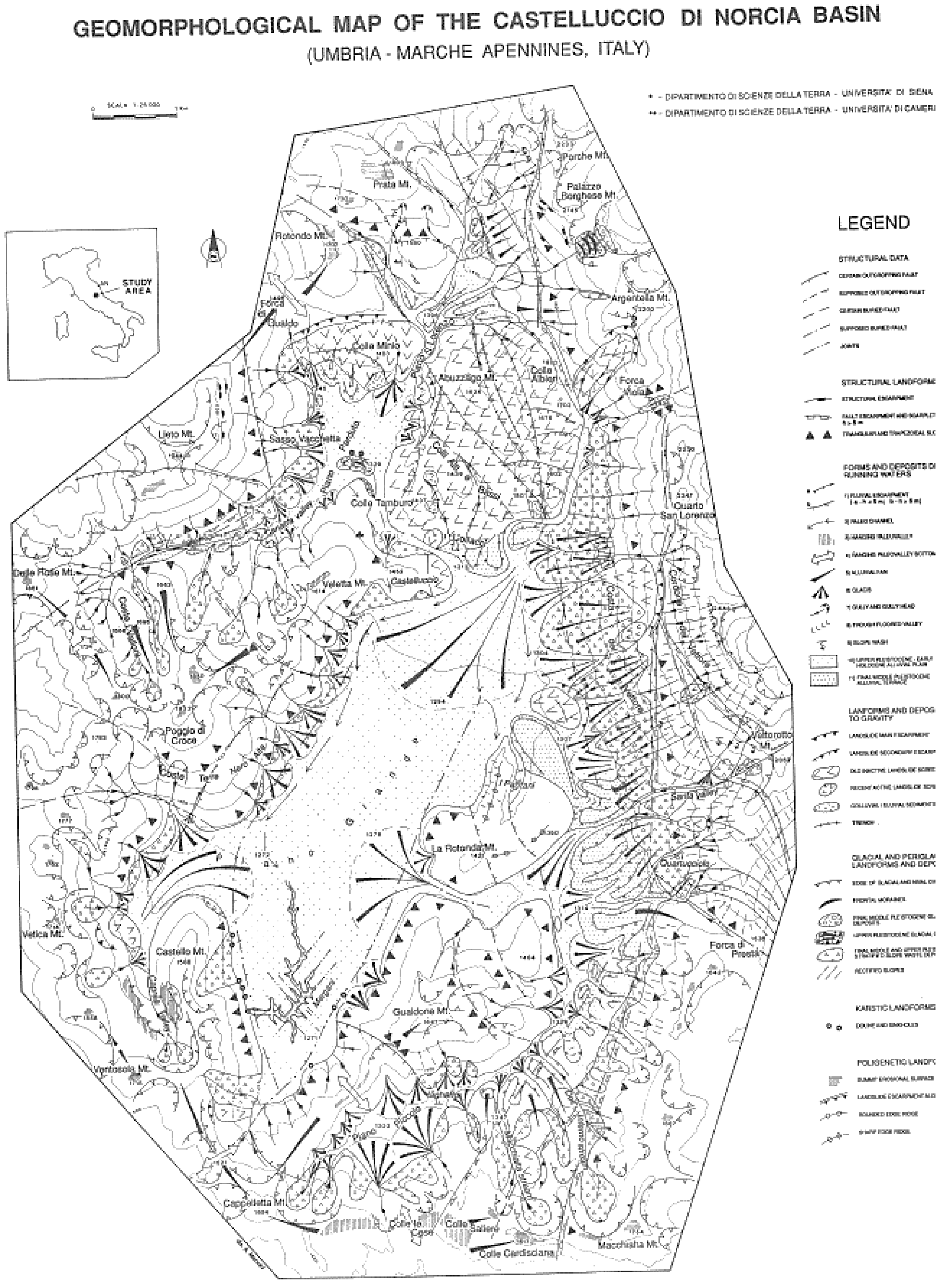

Fig. 13 – Geomorphological map of the Castelluccio di Norcia Basin (source: Coltorti and Farabollini, 1995).

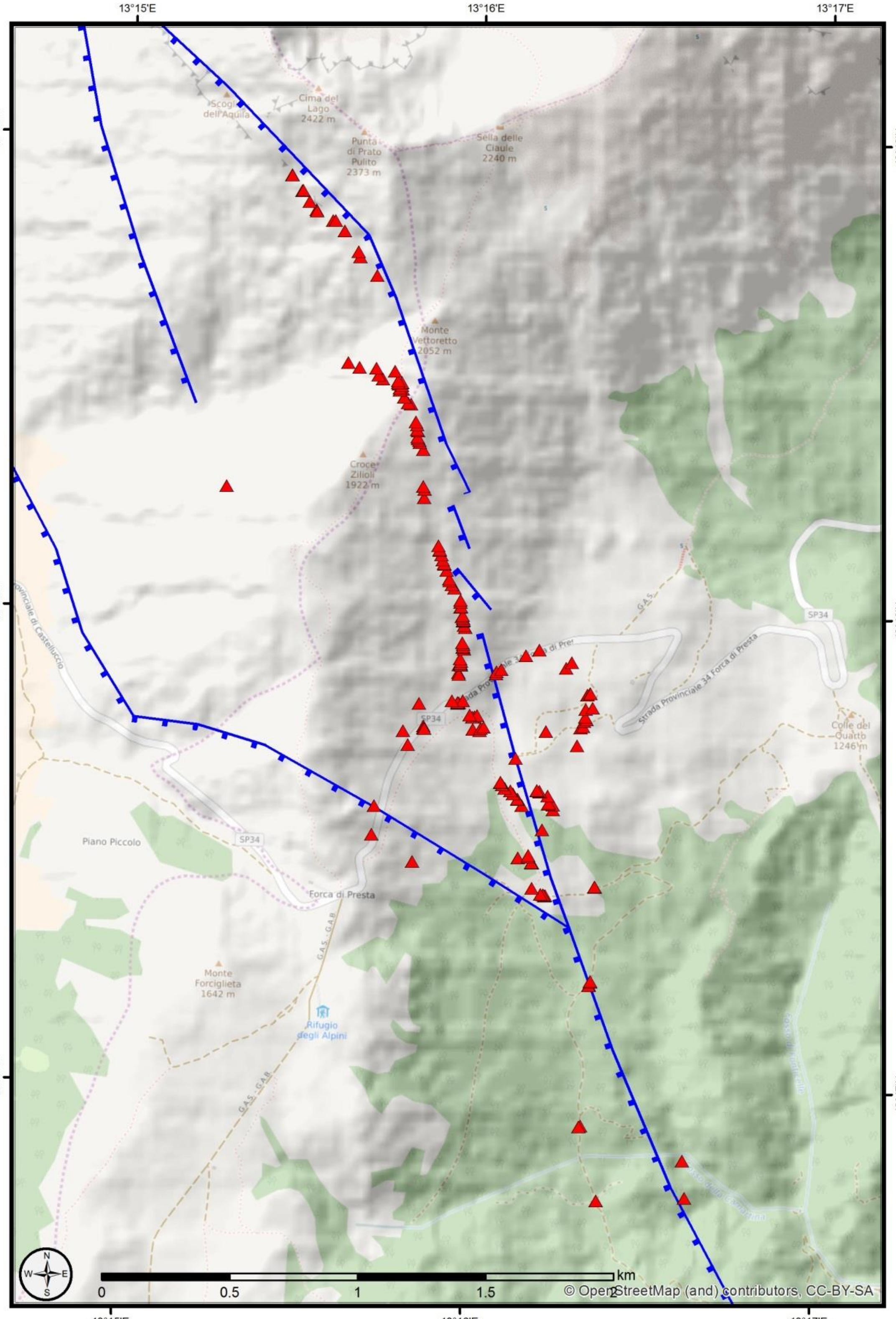

Fig. 14 – Observation points of on-fault effects along the Mt. Vettore fault.

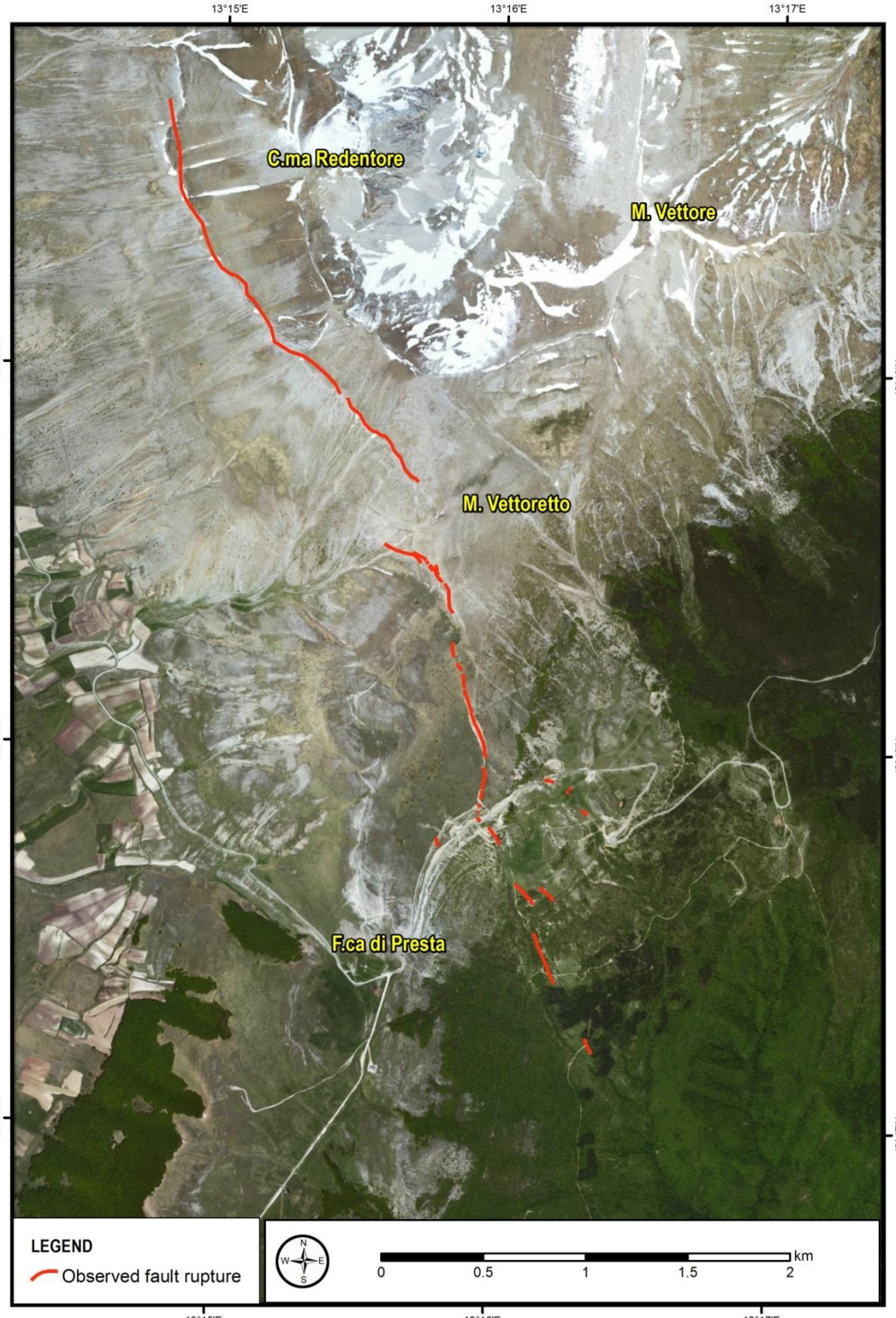

Fig. 15 – Pattern of ground ruptures observed along the Mt. Vettore fault. See text for details.

Figure 14 shows in detail the observation points related to on-fault effects along the Mt. Vettore fault. In Fig. 15 the pattern of coseismic surface faulting along the Mt. Vettore fault based on the results of our surveys is shown in detail.
In particular, a set of very clear ground ruptures was surveyed on the southern slope of Mt. Vettoretto in correspondence to the Mt. Vettore fault (Fig. 16). These ruptures mainly strike between NNW-SSE, with a slight left-lateral horizontal component. They generally affect colluvium and soil, often very close to the bedrock fault plane, but sometimes at a distance of several meters. In the first days, the observed throws were ranging from 2 to 25 cm, while opening reached 10 cm (see ahead for post-seismic evolution). These ruptures can be followed almost without interruptions from the SP34 (province road) to the end of Mt. Vettoretto slope, where the ruptures bend downslope to a ca. WNW direction. This portion of the rupture is continuous for about 1.7 km.

Fig. 16 – The ground ruptures cropping out on the southern slope of Mt. Vettoretto, above the SP34.

Continuing to uphill NW, even more evident ground ruptures are found in correspondence to the NW-SE trending fault segment running just below the top of Cima Redentore (namely the "Cordone del Vettore" fault). Here the ruptures (Fig. 17) have been surveyed in detail for about 2.4 km, but preliminary mapping shows that they continue northward, terminating somewhere before the end of the "cordone". The end-to-end length of this rupture zone is in excess of 4.5 km.

Fig. 17 – The ground ruptures along the "Cordone del Vettore" fault segment.

Other roughly north-south ground ruptures were found on the dirt road above the SP34 about 150 and 240 meters (east-facing) west of the main fault and south of the road SP34 toward Arquata (southern and lower portion of the Mt. Vettoretto slope) (Fig. 18). The former align with cracks on the road but are rather short and may connect to slide phenomena evident on the slope. The latter are quite well aligned with the major rupture but less continuous and not clearly associated to a bedrock fault plane. They mainly trend N120-150, with individual, single rupture lengths generally lower than a few tens of meters and opening of some centimeters. The end-to-end length of this rupture zone is about 1.2 km. Vertical offsets may exceed 20 cm, but in these cases a gravity component may be added to the tectonic displacement.
In summary, the total length of surveyed surface ruptures showing evidence of primary surface faulting along the Mt. Vettore fault is at least 5.3 km, likely longer because of the reported, but not yet surveyed by us, reactivation of the northern part of the "Cordone del Vettore" fault trace.

Repeated field surveys have clearly pointed out a post-seismic evolution of the rupture, whose vertical offset is continuing to increase with time. The phenomenon is clearly evident where the fault crosses the road SP34 (Fig. 19).

Fig. 19 - Evidence for afterslip at the Forca di Presta road. Above, reactivation of a pre-existing asphalt crack with virtually no displacement and a very thin new oblique crack, as observed on August 27; below, downwarping on the left side (west) and widening of the oblique crack (4 to 5 cm downthrow); new cracks have also appeared in the ground on both sides of the road (photograph taken on August 31).

In the Castelluccio basin, a NE-SW trending ground fracture (vertical throw≥ 10 cm, length in excess of 100 m, Fig. 20) appeared just south of the village of Castelluccio, possibly along an existing fault. If so, this might be a sympathetic rupture along an apparently secondary fault. Discontinuous cracks were also seen over a length of ca. 400 m in the plain at the foot of the Mt. Vettore, along the north-south subdued fault trace where a paleoseismological trench was excavated by Galadini and Galli (2000).

Fig. 20 – Ground rupture in correspondence to the NNE-SSW trending antithetic fault just below the village of Castelluccio.

3. 2. Laga fault

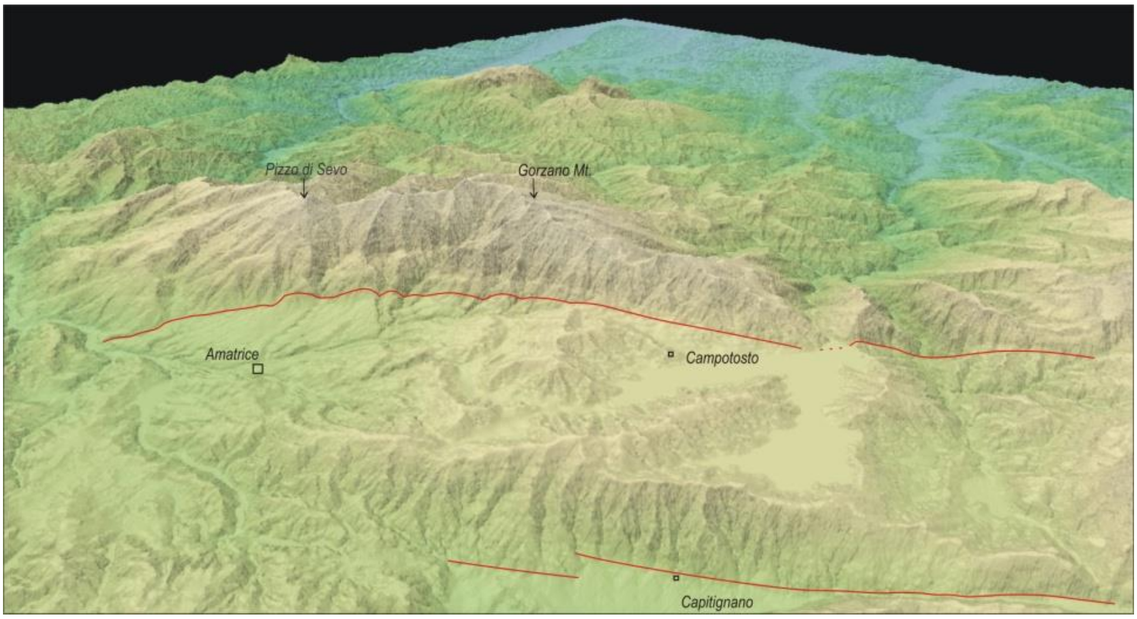

Fig. 21 – The main Laga fault and the associated Mt. Gorzano fault escarpment (source: Blumetti and Guerrieri, 2007)

The Laga fault is a N20W trending normal fault that bounds the Amatrice and Campotosto plateau and runs at the base of the Mt. Gorzano fault escarpment (Fig. 21).

This mountain front is mainly made of arenaceous-to-clay deposits of the Laga Formation (Messinian) resting on marls (Marne a Pteropodi Fm.) and marly limestones (Marne con Cerrogna Fm.). See Fig. 22 for more details.

The maximum stratigraphic offset of the Laga fault is in the order of 1500 m and progressively decreases to zero at the fault tips (Bachetti et al., 1991; Boncio et al., 2004).

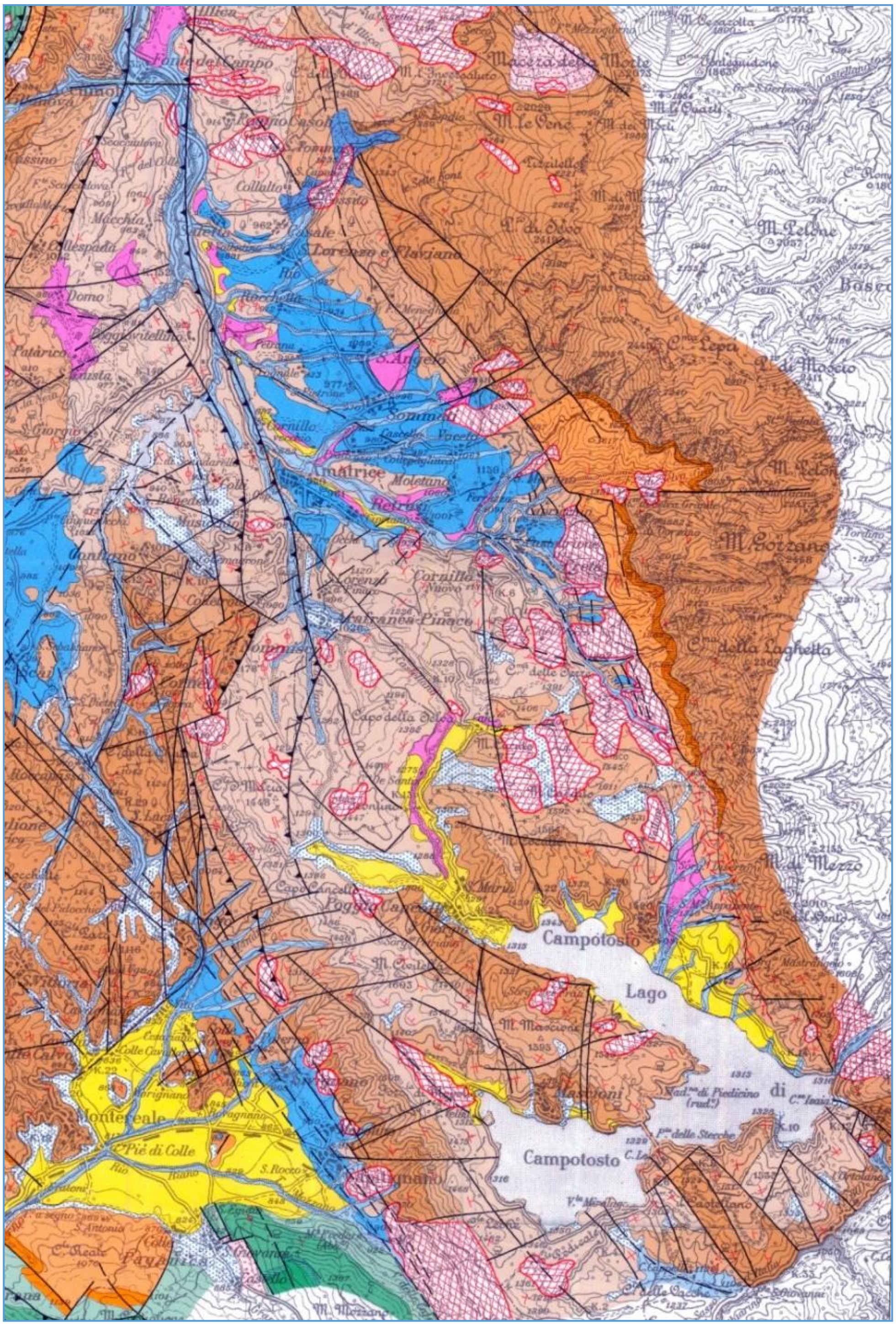

Fig. 22 – Geological map of the Amatrice and Campotosto plateau (source: Cacciuni et al., 1995)

Geomorphic offsets evaluated based on the differences in elevation between the intersection line of mountain crests and the Amatrice and Campotosto plateau are comparable to stratigraphic offsets. They are highest in the central part of the fault zone (1,500 m) and progressively decrease to zero at the fault tips), pointing out that this deformation was mainly produced during the Quaternary (Demangeot, 1965; Blumetti and Guerrieri, 2007).

The Laga fault is considered the causative fault of the October 7, 1639, Amatrice earthquake (I = X MCS, CPTI15).

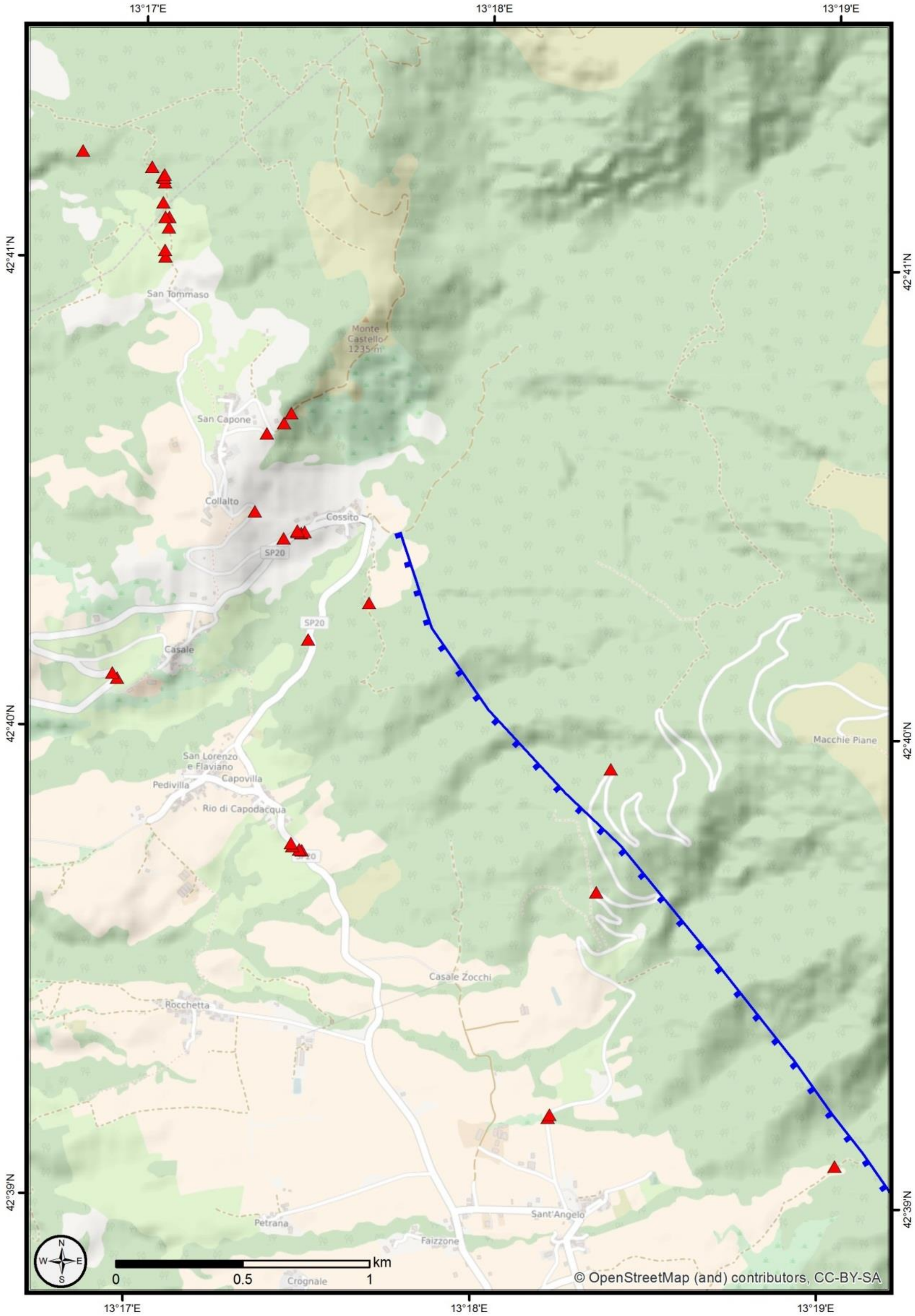

Fig. 23 – Observations points along the Laga fault (in blue as mapped in ITHACA)

In Fig. 23 the observation points close to the northern Laga fault (Amatrice fault), that is part of the seismogenic source, according to InSAR data and distribution of aftershocks are mapped. Our survey along the Amatrice fault has not detected unambiguous evidence of surface faulting to

date. Nevertheless, some effects may be somehow related to the coseismic slip on the fault, that is suggested by InSAR. The involved lithologies are generally the Laga Flysch and slope deposits from the degradation of the same material (sandstone and clay).
One of the most interesting observations comes from north of the village of San Tommaso, located on the eastern slope of the Tronto Valley, between Collalto and Poggio Casoli (Fig. 23). The whole intermediate and lower part of the slope, between San Tommaso village and the bottom of the Tronto Valley, is affected by several areas of instability, characterized by different morphologies of landslides.
The field surveys conducted in the area between the villages of Cossito and San Tommaso (Fig. 24) have found several breaks of the ground surface observed in the meadows and along the wide trails crossing the woods, which follow the slope trend and are concentrated within an area affected by diffuse slope instability (Fig. 25).

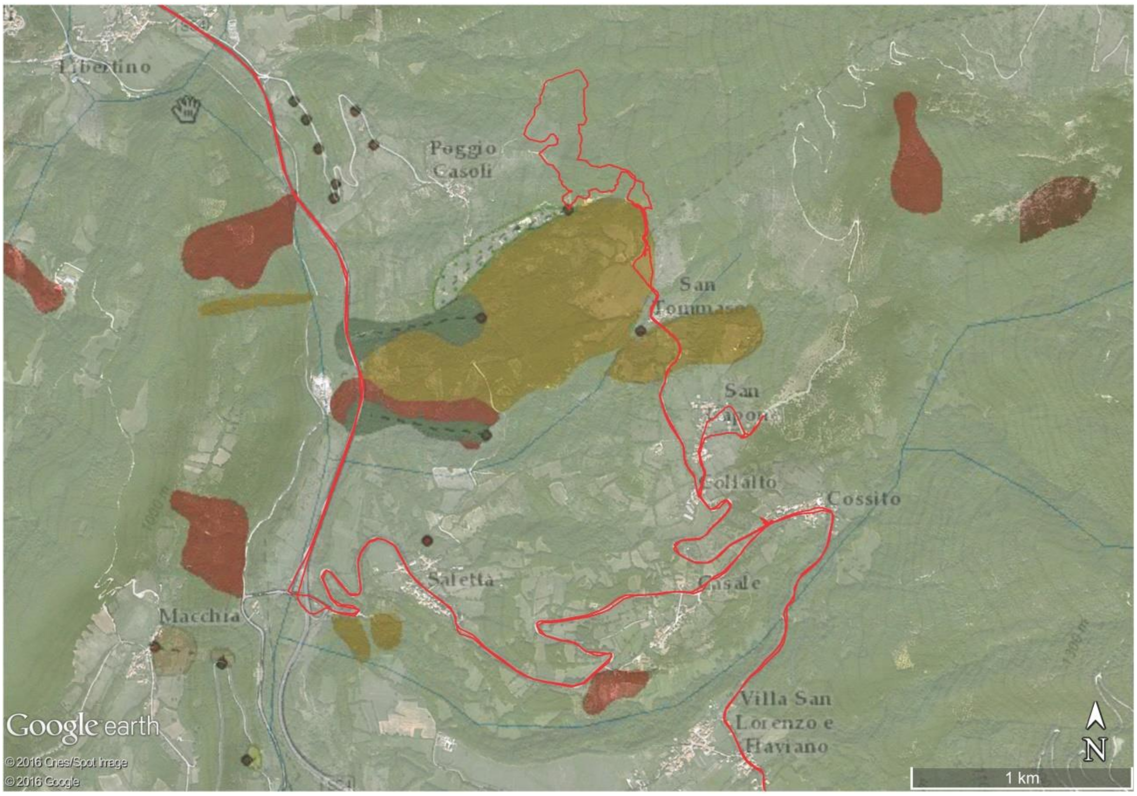

Fig. 24 - Instability phenomena (areas in brown and yellowish color) affecting the portion of the eastern slope of Tronto Valley between Poggio Casoli, Saletta and Villa San Lorenzo e Flaviano. Slope movements are classified according to the type of movement and activity. Source and legend in PAI - Piano di Assetto Idrogeologico and IFFI project (Inventory of Landslide Phenomena in Italy; http://www.isprambiente.gov.it/en/projects/soil-and-territory/iffi-project/default) databases.

The most representative ground breaks are located along a trail/dirt road a few hundred meters to the northeast of the old cemetery. They consist of 20 m to 25 m long surface ruptures, 5 to 20 cm wide, N140 - N160 trending and west-dipping (Figs. 25 and 26). The surface ruptures appear to affect solely the colluvial deposits covering the area: no evidence of ruptured bedrock was observed during the field survey. The slope morphology is here characterized by abrupt changes, with concave and convex forms, and by a step-like slope, with sub-horizontal surfaces delimited by possible landslide scarps several meters high. In particular, two scarps 7 to 15 m high are in the surroundings of the trail (green lines in Fig. 25). Thus, the observed surface breaks are located near the head of a large landslide, suggesting that they may be interpreted as tension cracks, sub-parallel, and connected, to the semi-crescentic crown of a seismically-triggered slide.

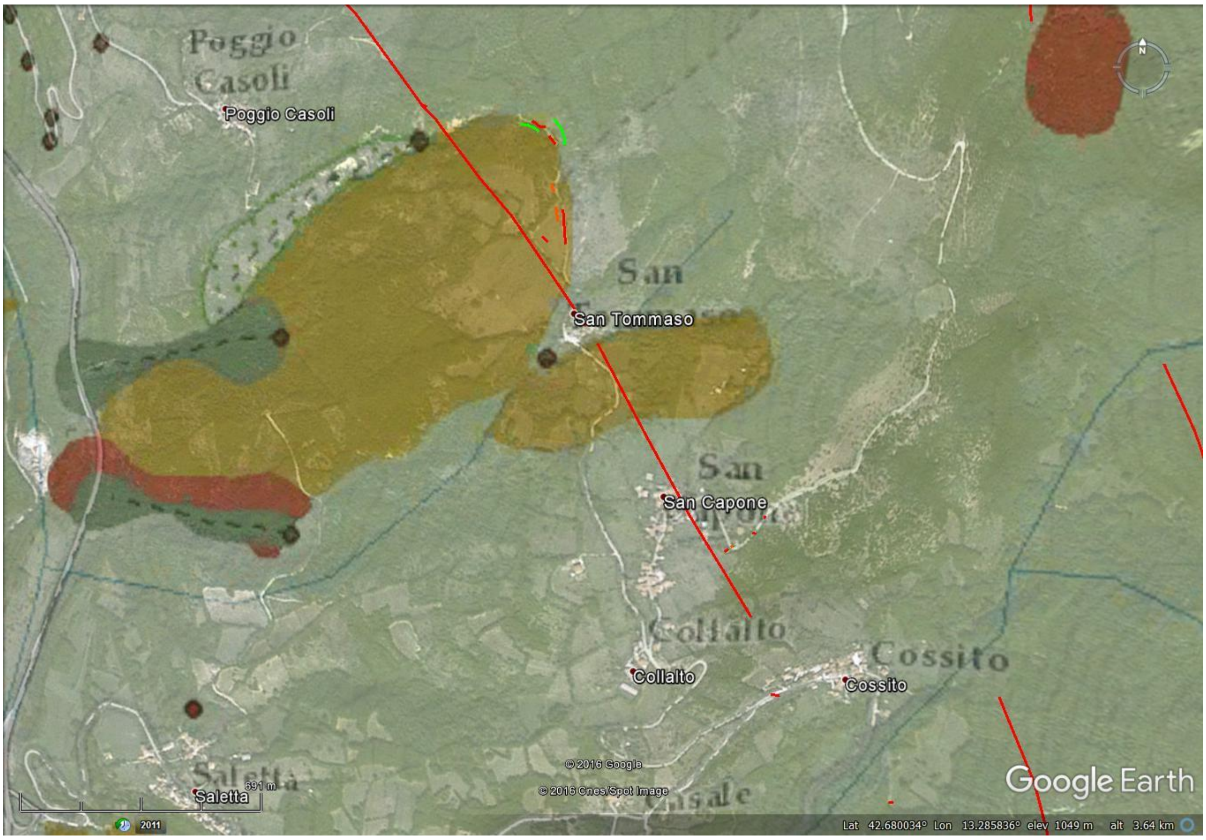

Fig. 25 – Small red lines correspond to the ground breaks observed in the area of San Tommaso and San Capone villages. The longer NW-SE directed red line is the northern termination of the Amatrice Fault included in the ITHACA database of capable faults. The green lines represent two morphological scarps observed around the broken trail.


Fig. 26 – San Tommaso. Surface rupture 25 m long, 5 to 20 cm wide. Some segments of the rupture are characterized by 5 cm to 10 cm vertical offset. Left: view to the north; Right: view to the south

Along the trail east of the small cemetery, we observed another fracture, several tens of meters long and oriented N-S (Fig. 27). Again, its location corresponds to the eastern border of a known slope movement (Fig. 25).

Fig. 27 – Fracture N-S oriented, about 50 m long, along the trail east of the small cemetery.

In summary, we followed the ground breaks for a few hundred meters, without finding any possible continuation. This piece of evidence, together with the local clay lithologies and nearby landslide morphologies, suggests that this phenomenon is to be interpreted as a local gravitational mass movement. Many other fractures, mainly across asphalt roads, were seen, mostly along a narrow belt possibly corresponding to the projected surface trace of the causative fault of the first and major shock (M 6). None of them displays along-strike continuity and features necessary to suggest primary surface faulting.

Nevertheless, the affected area corresponds to the zone where, according to the model of slip distribution (Fig. 5), shallow and maximum slip occurred on the fault at depth. Looking at the distribution of capable faults mapped in ITHACA database (Fig. 28), we can observe that the surveyed area is located on the northern extension of the Amatrice fault segment (northwestern tip between San Lorenzo e Flaviano and Accumoli) toward the Mt. Vettore fault (southeastern tip near Arquata del Tronto).

In the Amatrice area, the local clay-arenaceous lithology is less prone to reveal the expected modest surface faulting phenomena when compared to the limestone and hard compacted slope debris of Mt. Vettore. Therefore, we cannot rule out that, despite the basically gravity-driven cause of the observed coseismic surface failures, a tectonic control was somehow exerted by the seismogenic rupture propagation along the Laga fault.

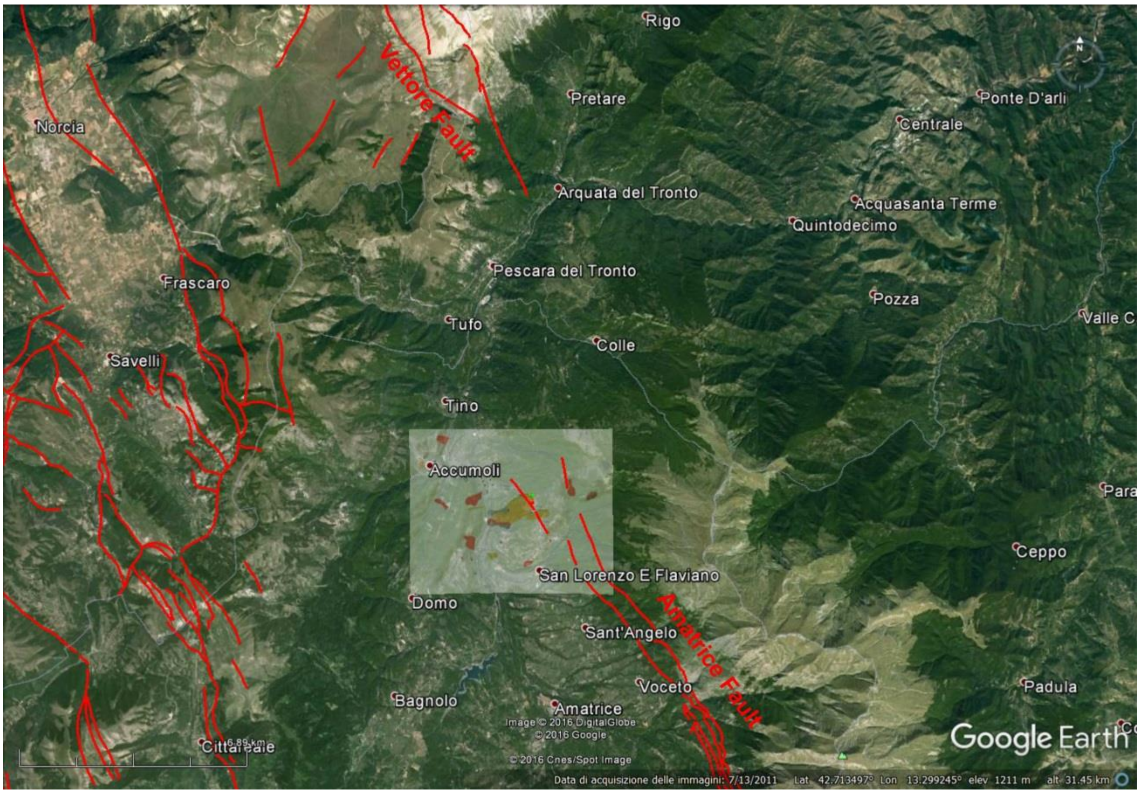

Fig. 28 – Capable faults (in red) from ITHACA catalogue showing that the investigated area is located in the projected northern prolongation of the Amatrice fault toward the Monte Vettore fault.

4. Final remarks

The assessed primary surface faulting along the Mt. Vettore Fault is relevant to earthquake geology and paleoseismology, and therefore to seismic hazard assessment based on geological investigation. Clearly, such small fault displacement can only be recorded where favourable lithologies crop out. Possibly, the Laga Fault ruptured together with the Mt. Vettore Fault, but no unequivocal fault surface displacement could be seen where expected and pointed out by SAR interferometry, i.e., between Arquata and Amatrice, due to the presence of the Laga Flysch, characterized by a more plastic behaviour and more prone to landsliding.

The Amatrice earthquake clearly confirms that the threshold for surface faulting during extensional events in the Apennines is between Mw 5.5 and 6.0, as already pointed out in the literature (e.g., Michetti et al., 2000). However, it is perhaps unlikely that such small slip events as those for the August 24, 2016, seismic sequence will be recognized on trench walls in the common coarse grained colluvial and alluvial sediments that palaeoseismology in the Apennines has to deal with. For example, the paleoseismic site excavated by Galli and Galadini (2000) across a fault on the hangingwall of the Vettore fault revealed surface faulting events probably associated with larger earthquakes (Mw possibly close to 6.5-7.0), because so such effects were produced in 2016, with only discontinuous ground cracks observed near this site. This is in agreement with both the historically observed maximum magnitude and the length of capable fault segments in the region: in fact, the Mt. Vettore scarps are part of a more than 40 km long major segment (e.g., Tondi et al., 1993; Galadini and Galli, 2000).

Given the series of events with roughly decadal inter-event times that have hit the region between Gubbio and high Sangro valley since 1984 along the Apennine fault system (Fig. 4), the Amatrice, 2016, earthquake was somehow expected to eventually fill the gap between the 1997 Colfiorito and the 2009 L'Aquila earthquakes. A similar "gap" may exist for the area south of L'Aquila, between the 1984 and the 2009 earthquakes (Fig. 4, right).

Geophysical data and surface geology indicate that during the 2016 earthquake the Laga fault ruptured at its northern tip. Calculations of Coulomb stress transfer in the coming weeks/ months will likely show that the present shock has induced stress accumulation on the southern portion of the Laga Fault (Fig. 2), while the 2009 L'Aquila earthquake had already induced stress increase on this same portion of the fault from the south (e.g., Falcucci et al., 2011; Serpelloni et al., 2012). Therefore, seismic gaps (*sensu lato*) and redistribution of Coulomb stress from recent earthquakes need to be studied in more detail because they may be interpreted to suggest an increased probability of occurrence of a $M \geq 6$ event on the Laga Fault between Amatrice and Campotosto.

Simply based on past history, in the next decades more earthquakes will affect the Italian territory. We cannot say when, but we know rather well where, i.e. in the areas where capable faults are mapped. Appropriate measures of seismic prevention are particularly urgent in these regions to reduce the local high vulnerability of built heritage.

Cited References

Amoroso, S., Bernardini, F., Blumetti, A.M., Civico, R., Doglioni, C., Galadini, F., Galli, P., Graziani, L., Guerrieri, L., Messina, P., Michetti, A.M., Potenza, F., Pucci, S., Roberts, G., Serva, L., Smedile, A., Smeraglia, L., Tertulliani,A., Tironi, G., Villani, F., and Vittori, E. (2016). Quaternary geology and Paleoseismology in the Fucino and L'Aquila Basins, Geological Field Trip of 6th International INQUA (International Union for Quaternary Research) Workshop on Paleoseismology, Active Tectonics and Archaeoseismology, 19-24 April 2015, Pescina, Fucino Basin, Italy, Geological Field Trips, 8, No.1.2 (2016), 88 p., 79 figs, 1 tab. doi: 10.3301/GFT.2016.02

Bachetti, C., Blumetti, A.M., Calderoni, G. and Ridolfi M. (1991). Attività tettonica e paleosismicità del settore meridionale dei Monti della Laga. Rendiconti Società Geologica Italiana. 13, 9-16.

Blumetti, A.M. (1991) - Evoluzione geomorfologica, attività tettonica quaternaria e paleosismicità in alcune depressioni tettoniche dell'Appennino Centrale. Unpublished doctoral thesis, University of Camerino.

Blumetti, A. M., Dramis, F. and Michetti, A.M. (1993). Fault generated mountain fronts in the Central Apennines (Central Italy): geomorphological features and seismotectonic implications. Earth Surface Processes and Landforms, 18, 203-223.

Blumetti, A. M. and Guerrieri, L. (2007). Fault-generated mountain fronts and the identification of fault segments: implications for seismic hazard assessment. Bollettino Società Geologica Italiana, 126(2), 307.

Blumetti, A.M., Bonadeo, L., Brunamonte, F., Comerci, V., Cowie, P., Di Manna, P., Ferrario, M.F., Faure Walker, J., Frigerio, C., Fumanti, F., Gregory, L., Guerrieri, L., Iezzi, F., Livio, F., Mccaffrey, K., Michetti, A.M., Mildon, Z., Phillips, R., Piccardi, L., Pompili, R., Rhodes, E., Roberts, G., Tondi, E., Vittori, E., Walters, R.J., Wedmore, L. and Wilkinson, M. (2016). Fagliazione superficiale ed effetti ambientali associati al terremoto del centro Italia del 24 agosto 2016: risultati preliminari e work in progress. 88° Congresso della Società Geologica Italiana, Napoli, 7-9 settembre 2016.

Boncio, P., Lavecchia, G., Milana, G., and Rozzi, B. (2004). Seismogenesis in Central Apennines, Italy: an integrated analysis of minor earthquake sequences and structural data in the Amatrice-Campotosto area. Annals of Geophysics.Cacciuni, A., Centamore, E., Di Stefano, R., and Dramis, F. (1995). Evoluzione morfotettonica della conca di Amatrice. Studi Geologici Camerti, 2, 95-100.

Cacciuni, A., Centamore, E., Di Stefano, R., and Dramis, F. (1995). Evoluzione morfotettonica della Conca di Amatrice. Studi Geologici Camerti, 2, 95-100.

Calamita, F., Coltorti, M., Farabollini, P., and Pizzi, A. (1994). Le faglie normali quaternarie nella dorsale appenninica umbro-marchigiana: proposta di un modello di tettonica di inversione. Studi Geologici Camerti, 211-225.

Cello, G., Mazzoli, S., Tondi, E. and Turco, E. (1997). Active tectonics in the central Apennines and possible implications for seismic hazard analysis in peninsular Italy. Tectonophysics 272, 43–68.

Coltorti, M. and Farabollini, P. (1995). Quaternary evolution of the Castelluccio di Norcia basin (Umbro-Marchean Apennines, central Italy), Il Quaternario 8, 149–166.

Cooper, M.A. and Williams, G.D. (1989). Inversion structures – recognition and characteristics. In: Cooper, M.A., Williams, G.D. (Eds.), Inversion Tectonics. Geological Society of London, Special Publication, 44, pp. 341–347.Demangeot J. (1965) - Géomorphologie des Abruzzes Adriatiques. Mém. et Doc. du C.N.R.S., Paris, pp. 403.

Di Domenica, A., Turtù, A., Satolli, S., and Calamita, F. (2012). Relationships between thrusts and normal faults in curved belts: New insight in the inversion tectonics of the Central-Northern Apennines (Italy). Journal of Structural Geology, 42, 104-117.

Falcucci, E., Gori, S., Moro, M., Pisani, A.R., Melini, D., Galadini, F.and Fredi, P. (2011). The 2009 L'Aquila earthquake (Italy): What's next in the region? Hints from stress diffusion analysis and normal fault activity. Earth and Planetary Science Letters 305, 350–358.

Galadini, F., and Galli, P. (2003). Paleoseismology of silent faults in the Central Apennines (Italy): the Mt. Vettore and Laga Mts. faults. Annals of Geophysics.

Michetti, A.M., Brunamonte, F., Serva, L. and Vittori, E. (1996). Trench investigations along the 1915 Fucino earthquake fault scarps (Abruzzo, Central Italy): geological evidence of large historical events. Journal of Geophysical Research, 101, 5921-5936.

Michetti, A.M., Ferreli L., , Esposito E., Porfido, S., Blumetti, A.M., Vittori, E., Serva L. and G.P., Roberts (2000). Ground effects during the September 9, 1998, Mw = 5.6, Lauria earthquake and the seismic potential of the aseismic Pollino region in Southern Italy. Seismological Research Letters, 71, 31-46 (2000).

Piccardi, L., Sani, F., Bonini, M., Boccaletti, M., Moratti, G. and Gualtierotti, A. (1997). Deformazioni quaternarie nell'Appennino Centro-Settentrionale: evidenze ed implicazioni. Il Quaternario, 10 (2), 273-280.

Piccardi, L., Gaudemer, Y., Tapponnier, P. and Boccaletti, M. (1999). Active oblique extension in the central Apennines (Italy): evidence from the Fucino region. Geophysical Journal International, 139 (2), 499-530.

Piccardi, L., Tondi, E., Cello, G. (2006). Geo-structural evidence for active oblique extension in south-central Italy. In: Pinter, N., Grenerczy, G., Weber, J., Stein, S., Medak, D., (eds.), The Adria Microplate: GPS geodesy, tectonics and hazards, Springer Ed., Netherlands, NATO Science Series IV, 61, 95-108.

Pierantoni, P., Deiana, G., and Galdenzi, S. (2013). Stratigraphic and structural features of the Sibillini Mountains (Umbria-Marche Apennines, Italy). Italian Journal of Geosciences, 132(3), 497-520.

Scarsella, F. (1947). Sulla geomorfologia dei piani di Castelluccio e sul carsismo nei Monti Sibillini. Bollettino Ufficio Geologico d'Italia.

Serpelloni, E., Anderlini, L., and Belardinelli, M. E. (2012) - Fault geometry, coseismic-slip distribution and Coulomb stress change associated with the 2009 April 6, Mw 6.3, L'Aquila earthquake from inversion of GPS displacements. Geophys. J. Int. (2012) 188, 473–489.

Serva, L., Blumetti, A.M. and Michetti, A.M. (1988) - Gli effetti sul terreno del terremoto del Fucino (13.01.1915); tentativo di interpretazione della evoluzione tettonica recente di alcune strutture. Mem.Soc.Geol.It., 35(1986), 893-907.

Cited Reports related to the 2016 Amatrice earthquake

EMERGEO Working Group (2016). The 24 August 2016 Amatrice Earthquake: Coseismic Effects. doi: 10.5281/zenodo.61568

Gruppo di Lavoro INGV sul terremoto di Amatrice (2016). Primo rapporto di sintesi sul Terremoto di Amatrice Ml 6.0 del 24 Agosto 2016 (Italia Centrale), doi: 10.5281/zenodo.61121

Gruppo di lavoro IREA-CNR and INGV (2016). Sequenza sismica di Amatrice: risultati iniziali delle analisi interferometriche satellitari, DOI: 10.5281/zenodo.60935EMERGEO Working Group (2016). The 24 August 2016 Amatrice Earthquake: Coseismic Effects. doi: 10.5281/zenodo.61568