

# Coseismic effects of the 2016 Amatrice seismic sequence: first geological results

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## Abstract

*Since the beginning of the ongoing Amatrice seismic sequence on August 24, 2016, initiated by a Mw 6.0 normal faulting earthquake, the EMERGEO Working Group (an INGV team devoted to earthquake aftermath geological survey) investigated coseismic effects on the natural environment. Up to now, we surveyed about 750 km<sup>2</sup> and collected more than 3200 geological observations including differently oriented tectonic fractures together with intermediate- to small- sized landslides. The most impressive coseismic evidence was found along the known active Mt. Vettore fault system, where surface ruptures with clear vertical/horizontal offset were observed for more than 5 km, while unclear and discontinuous coseismic features were recorded along the Laga Mts. Fault systems.*

## I. INTRODUCTION

**O**n August 24, 2016, at 1:36 UTC an Mw 6.0 earthquake hit a large portion of the central Apennines fold and thrust belt, between the towns of Norcia and Amatrice, central Italy (Fig.1). The event nucleated at a depth of 8.2 km, with epicenter close to the village of Accumoli (Fig. 1) [AMA\_LOC

The mainshocks caused heavy damage in a wide area between the towns of Norcia and Amatrice and resulted in 298 fatalities, thousands of injured and over 3000 displaced people.

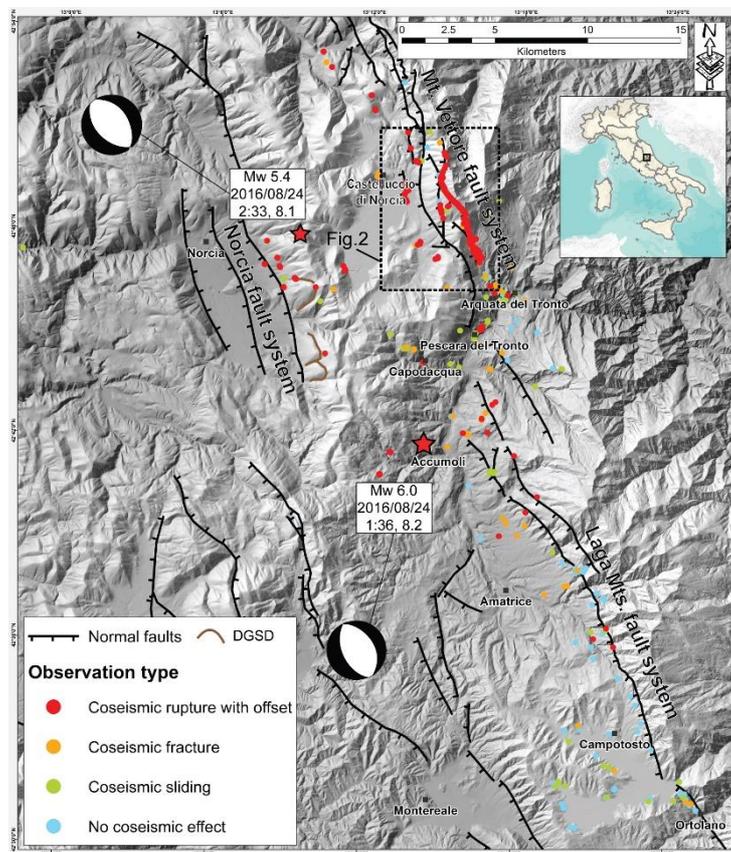
Focal mechanisms of the two main events show NW-SE striking normal faulting (Fig. 1). The seismic sequence was confined within the

upper 10 - 12 km of the crust and the volume affected by the aftershocks extends for about 50 and 15 km in the NW-SE and NE-SW directions, respectively.

This area of the central Apennines is characterized by a Quaternary extensional regime overprinting NE-verging thrust-sheets (i.e. Vai and Martini, 2001 and references therein), mostly made of Meso-Cenozoic carbonate rocks and Miocene flysch deposits. The resulting dense array of NW-SE and

NNW-SSE striking, mainly SW- dipping, up to 30 km-long active normal fault systems (Galli et al., 2008 and references therein; Fig. 1) accommodate the present-day 2-4 mm/yr regional NE-SW extension (Galvani et al., 2013, and references therein).

In this paper we present the dataset of coseismic effects on the natural environment collected by the Emergeo Working Group together with a preliminary discussion.

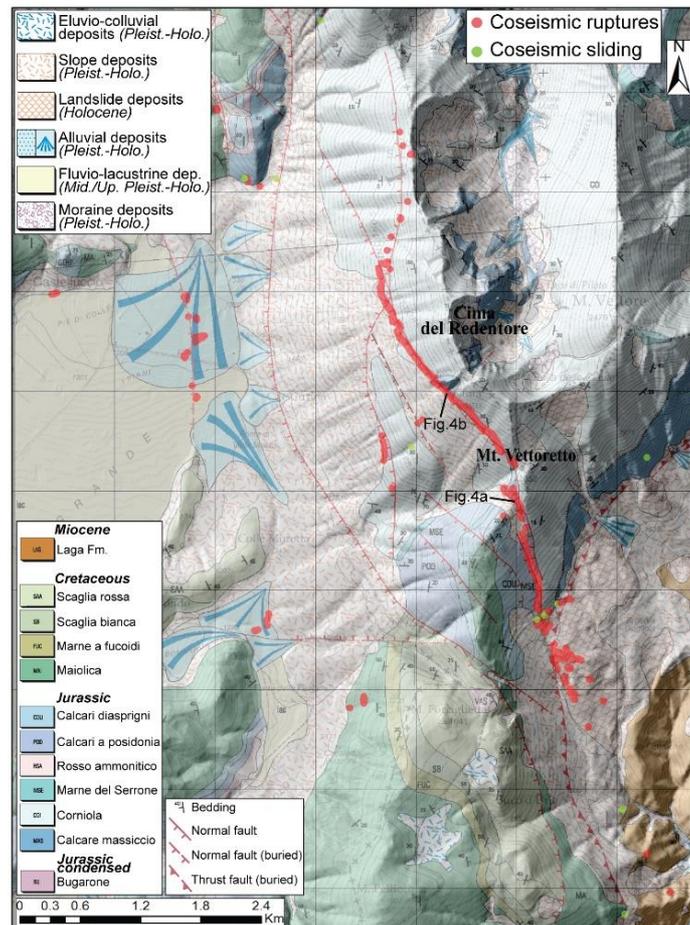


**Figure 1.** Location of the measurements and observations collected in the field. Normal faults are compiled from geological maps [Centamore et al., 1992; Pierantoni et al., 2013]. Hillshade from TINITALY 10m-DEM [Tarquini et al., 2012]. The 24 August 2016 mainshock and largest aftershock are reported with red stars. TDMT focal mechanisms available at <http://cnt.rm.ingv.it/event/7073641> and <http://cnt.rm.ingv.it/event/7076161>. DGSD (deep-seated gravitational slope deformations) with evidence of coseismic fracturing are shown.

## II. METHODS

Field surveying of the coseismic effects by EMERGEIO was mainly performed by using smartphones equipped with a range of software that use the phone's GPS, compass and orientation sensors. We used the Rocklogger application (rockgecko.com) to measure and store the data of the coseismic effects (type of observation, strike, vertical dislocation, fracture opening, etc.). GPS track loggers were used for monitoring and

subsequent planning the survey coverage. Low-altitude, easy deployable, aerial platforms (helikite and unmanned aerial vehicles - UAVs), together with a helicopter flight, have been used to support the post-earthquake documentation of surface ruptures. A web-based data sourcing was utilized to gather information on coseismic geological effects from local people. The collected data have been stored in a georeferenced-database (for details see EMERGEIO Working Group, 2012).



**Figure 2.** Map of the coseismic geological effects of the Mt. Vettore area. Geological map from Pierantoni et al. [2013]. Hillshade from TINITALY 10m-DEM [Tarquini et al., 2012].

### III. RESULTS

We surveyed an area of about 750 km<sup>2</sup>, recording more than 3200 measurements and observations. Among them, we collected: 230 coseismic fracture (<1 cm displacements) and 2600 coseismic rupture (>1cm displacements) measurements; evidence for 160 medium- to small-sized coseismic landslides, 28 coseismic features related to the shaking (e.g. clast extrusions, soil remobilization, etc.), and 130 locations where we documented the lack of coseismic effects. In addition, a fracturing pattern is hypothesised in the trench sector and along the upper limit of 3 DGSD (deep-seated gravitational slope deformations) between the villages of Castelluccio and Norcia as due to coseismic-induced acceleration (Fig. 1).

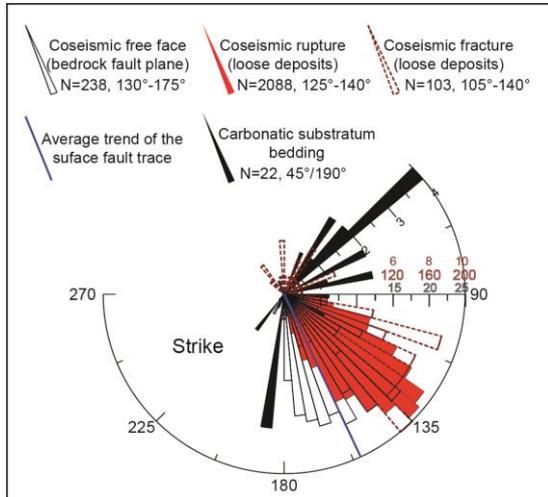
The inspection of the Laga Mts. Fault System provided only few sparse observations of discontinuous (maximum 300 m-long) equivocal ruptures with small displacements (maximum 5 cm), mostly concentrated along its northern sector. A few ruptures exhibit a trend parallel to the mapped fault, whereas most of them do not have a systematic pattern. In contrast, in the central-southern portion of this fault, no clear coseismic fracturing or rupturing was observed, but several coseismic landslides (rotational and rock falls) occurred, possibly due to the shear strength of the outcropping pelitic formations. Some of them are pre-existing landslides re-activated, partly known and mapped after the 2009 L'Aquila earthquake (Miccadei et al., 2013).

Conversely, to the north, along the Mt. Vettore Fault System, a continuous alignment of newly formed coseismic ruptures was mapped for

more than 5.2 km. The coseismic ruptures follow the Cima del Redentore and Mt. Vettoretto SW-dipping and N155°-striking normal faults (Fig. 2). The coseismic ruptures occur along a cumulative fault scarp made by bedrock at the footwall (mostly Corniola Fm.) and by highly fractured bedrock as well as unconsolidated deposits (generally cryoclastic debris) at the hanging wall. A few additional coseismic ruptures parallel continuously a southern fault splay for more than 400 m along the SW-flank of the Mt. Vettore, and another discontinuous set occurs at the slope foot, resulting in an alignment 1.2 km long (Fig. 2).

In detail the 5.2 km-long rupture consists of 5-6 m long segments, each up to 5-6 m-long, mostly displaying a right-stepping en-echelon arrangement (Fig. 3, 4a). The deformation zone width is generally confined on a single ground crack, rarely exceeding 5 m where maximum three parallel ground cracks and ruptures were found. The orientation of the different elements composing the coseismic rupture is: 1) N125°-140° for the coseismic ruptures (with offset) affecting unconsolidated deposits; 2) N105°-140° for coseismic fractures (with no offset) affecting unconsolidated deposits; 3) N130°-175° for coseismic ruptures occurring on the bedrock fault planes (coseismic free faces) (Fig. 3). Notably, the trend of the ruptures south of Mt. Vettoretto is oblique with respect to the slope, while northward, it becomes perpendicular to the slope of the southwestern Mt. Vettore flank (Fig. 3).

The coseismic rupture pattern is not influenced by the bedrock bedding attitude, while locally it re-utilizes joints. The rupture trace preserves its trend, even when cutting through debris cone apexes.



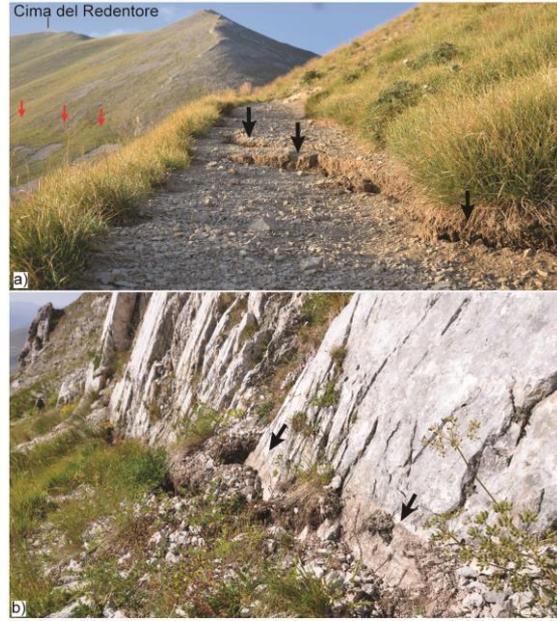
**Figure 3.** Geometrical pattern of the Mt. Vettore coseismic ruptures. The rose diagram shows different trends of the coseismic free face, rupture and fracture measurements with respect to the bedrock bedding and the average trend of the fault trace.

On bedrock fault planes, the newly formed free face looks like a fresh, light-coloured stripe of rejuvenated bedrock surface, with no lichens and soil shade (Fig. 4b). The coseismic ruptures always down-throw the SW side with vertical displacement being mostly below 16 cm and exceeding 35 cm in few locations of its northern portion (Fig. 5a). Moreover, the vertical displacement of the coseismic free faces is mostly between 16 and 20 cm. The width of open cracks is mostly below 16 cm

#### IV. DISCUSSION AND CONCLUSION

Based on the characteristics and distribution of the coseismic effects related to the 24 August 2016 Amatrice earthquake, we identified two areas: the Laga Mts. Fault System, to the south and the Mt. Vettore Fault System to the north. Along the northern portion of the Laga Mts. Fault System few sparse evidences of

with few outliers (up to 40 cm) along its central portion for both coseismic ruptures and free faces (Fig. 5b). Notably, the almost 2 km long coseismic ruptures south of Mt. Vettore tend to revert the topography.



**Figure 4.** Photos of the Mt. Vettore coseismic ruptures. a) en-echelon coseismic ruptures (black arrows) affecting unconsolidated slope deposits and a trail, the red arrows mark the Mt. Vettore fault scarp; b) coseismic free face on bedrock fault plane (black arrows).

discontinuous coseismic ruptures with small displacements were surveyed, while in the central-southern portion of this fault, no significant fracturing at the surface was observed. In general, along the Laga Mts. Fault System there is no clear deformation as expression of the seismogenic fault plane motion occurred at depth. A possible explanation for this negative evidence is due to the thick sequence (ca. 1-2 km) of flysch and marls, which may accommodate the coseismic

deformations without a purely brittle behavior.

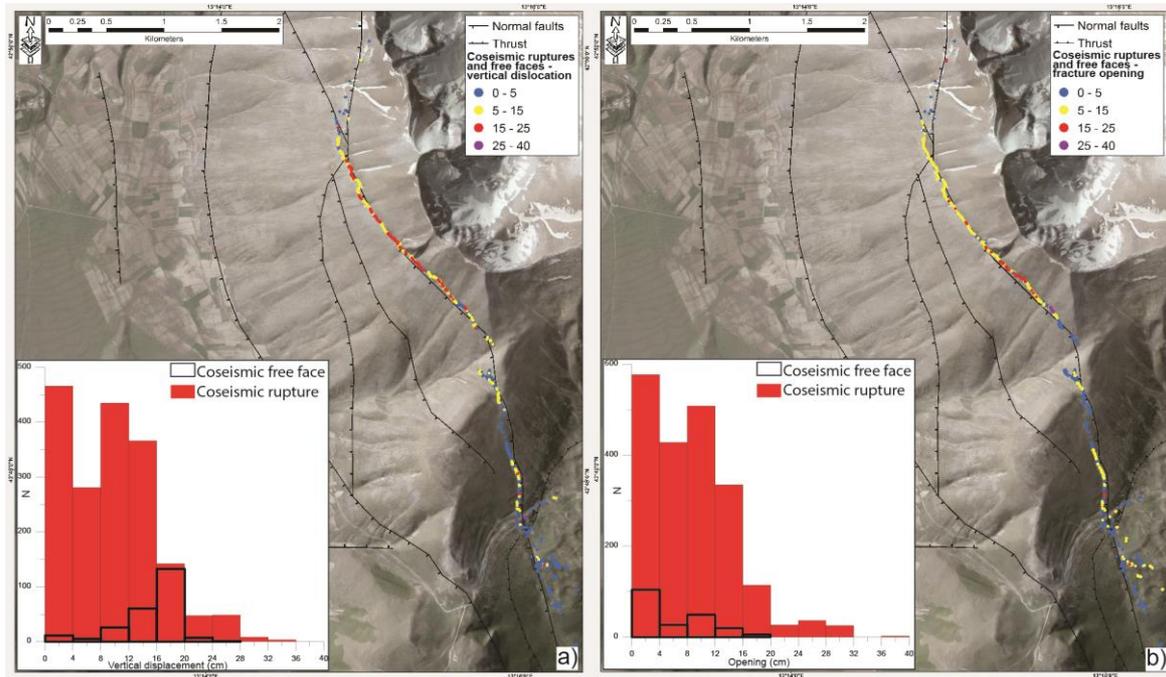
Along the Mt. Vettore Fault System sector we documented a localized and continuous concentration of coseismic ruptures with offset. Main characteristics are: i) the considerable length of the continuous alignment (more than 5 km); ii) the consistency of the structural pattern (often characterized by right en-echelon arrangement with kinematically coherent oblique transfer zones); iii) the downthrown side is systematically the SW one; iv) the structural pattern, the kinematics and the offset distribution is not influenced by topography and morphology (e.g. erosional scarp and debris cone crosscut, Figs. 3 and 5), v) the constant rupture characteristics over both bedrock and loose deposits.

All these features lead to infer that the observed displacement could be defined as primary surface faulting (i.e. propagation up to the surface of the seismogenic motion occurred at depth). However, shaking/gravity effects may have locally contributed to part of the observed displacement.

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A number of authors (P. Burrato, M. Carafa, D. Di Naccio, U. Fracassi, V. Kastelic, R. Vallone and P. Vannoli) are doubtful in straightforwardly interpreting the surveyed brittle features as effects of primary surface faulting. Rather, they maintain that the geologic and morphologic conditions have favored the instability of jointed and faulted rocks and unconsolidated sediments under dynamic conditions. Therefore, the hypothesis of the observed fractures as secondary earthquake effects driven by blind faulting cannot be ruled out a priori.

We all agree on the fact that future detailed comparison with other datasets like seismicity relocations, satellite data (InSAR and GPS) and modeling inversions of different seismic parameters will help in better understanding and evaluating the gravitational component vs tectonic displacement.



**Figure 5.** Variation in displacement along the strike of the Mt. Vettore coseismic ruptures. Distribution of a) vertical displacement and b) opening values. The inset shows the frequency of the displacements for ruptures in coincidence of loose deposits (coseismic rupture) and along preexisting bedrock fault planes (coseismic free face).

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