Title

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Authors

Gori, Stefano
Falcucci, Emanuela
Kayen, Robert E
et al.

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SURFACE FAULT RUPTURE FROM 2016 CENTRAL ITALY EARTHQUAKE SEQUENCE

Stefano Gori[1], Emanuela Falcucci[2], Robert E. Kayen[3], Paolo Zimmaro[4], Bret Lingwall[5], Fabrizio Galadini[6], and Jonathan P. Stewart[7]

ABSTRACT

The 2016 central Italy earthquake sequence produced distinctive surface faulting on the Mt. Vettore-Mt. Bove normal fault system. Using a combination of ground measurements and aerial surveys, we have produced a detailed record of surface rupture from all mainshocks of the sequence: 24 August 2016 (**M**6.1), 26 October 2016 (**M**5.9), and 30 October 2016 (**M**6.5). Our data includes locations, amount, and direction of slip observed following these events. As such, we have a record of the progression of rupture from event-to-event. The data recorded from this work have several useful features: (1) they enable robust comparison of displacements evaluated from ground surveys and 3D models produced from aerial imagery (2) they provide valuable data points on amount of slip, fraction of fault producing surface rupture, and distribution of slip across the fault, and (3) they provide information on slip or lack of slip on apparent secondary features along with the main fault plane for different events.

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[1] Researcher, Istituto Nazionale di Geofisica e Vulcanologia (INGV), Italy
[2] Researcher, Istituto Nazionale di Geofisica e Vulcanologia (INGV), Italy
[3] Research Civil Engineer, United States Geological Survey (USGS), Menlo Park, CA 94025
[4] Project Scientist and Lecturer, Dept. of Civil and Env. Eng., University of California, Los Angeles, CA 90095
[5] Assistant Professor, Dept. of Civil and Env. Eng., South Dakota School of Mines & Technology, Rapid City, SD 57701
[6] Senior Scientist, Istituto Nazionale di Geofisica e Vulcanologia (INGV), Italy
[7] Professor and Chair, Dept. of Civil and Env. Eng., University of California, Los Angeles, CA 90095

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Introduction

The 2016 Central Italy earthquake sequence produced three mainshocks: **M**6.1 24 August, **M**5.9 26 October, and **M**6.5 30 October. This earthquake sequence occurred in the central portion of the inner Apennine range, in the sector of the Laga Mountains known as the Sibillini Mountains. These mountains have a complex geological history characterized by multiple phases of tectonic deformation [1]. The surface expression of the Mt. Vettore-Mt. Bove fault is clearly visible on the southern ridge and western flank of the Mt. Vettore-Mt. Bove Massif within the Sibillini Mountains. On the southern and western flanks of Mt. Vettore, the fault trends approximately 30° west of north, whereas the trend is nearly northward on the north flank. Galadini and Galli [2] mapped a complex zone of three major normal fault splays on the western slope of Mt. Vettore. The earthquake sequence produced evidences of surface rupture along the whole Mt. Vettore-Mt. Bove fault system. Surface rupture data gathered following these events provides an opportunity to evaluate the effectiveness of these mapping studies.

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Surface Rupture Observations

The **M**6.1 24 August 2016 earthquake rupture resulted in clearly observable normal-mechanism displacements on the southern and western slopes of Mt. Vettore [3, 4]. The **M**6.5 30 October earthquake greatly increased the observable normal-mechanism displacements in the area in both magnitude and length [5]. The **M**5.9 26 October event resulted in limited visible movements to the north of the length of rupture in the other two events, in the area of Mt. Bove. Following all three mainshocks, we collected observations on surface fault ruptures using traditional visual inspections and hand measurements in combination with imaging techniques including: (1) photography from unmanned aerial vehicles (UAV), and (2) terrestrial light detection and ranging (LiDAR). The imagery was then used to produce 3-D orthomosaics of the scanned area. Fig. 1 shows the locations of the observed surface ruptures. In Fig. 1, observed ruptures north of 42.90° are principally from the 26 October event. The observed surface ruptures are nearly coincident with fault segments mapped before the 2016-2017 earthquake sequence and summarized by Falcucci et al. [6].

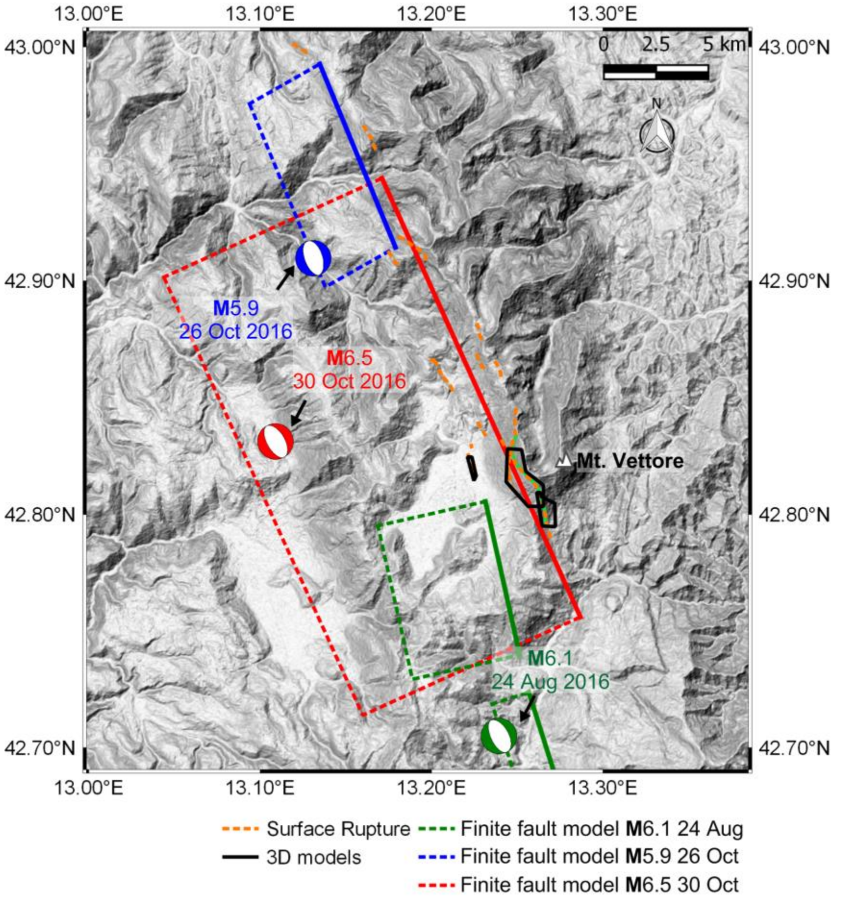

Figure 1. Map of surface fault rupture observed during the sequence, finite fault models for all three mainshocks, and locations of 3D models.

The **M**6.1 24 August event produced surface rupture that extended approximately 5 km north of the southern terminus of the Mt. Vettore-Mt. Bove fault. Fault displacements of 0-35 cm (average of 12 cm) occurred in the down-dip direction and horizontal cracks were opened. These fault displacements were observed at tens of sites that include bedrock exposures on both sides of the fault and colluvium and soil near to or adjacent to the bedrock fault plane. Limited observations were made following the 26 October event, which do not include detailed mapping, as a result of the short time window between this event and the subsequent **M**6.5 30 October event. Nonetheless, observations establish the presence, and magnitude of surface rupture and its extent north of the August rupture (Fig. 1).

Following the 30 October event, several phases of reconnaissance were performed that establish the fault segments on which rupture was and was not observed, and which provide details on the amounts and distributions of slip in some areas. This rupture began at the south end of the Mt. Vettore-Mt. Bove fault and continued north to partially overlap the rupture from the 26 October event. Detailed mapping in the southern part provides cumulative maximum tectonic displacements of up to about 170 cm. Inclement weather prevented full mapping of fault rupture after the 30 October event. Approximately the southern half of the rupture of the 30 October event was observed before winter snows. Fig. 2 shows the geometry of the rupture, following the 30 October event, from a UAV imaging-derived 3D orthomodel. Fig. 3 shows multi-epoch pictures of the rupture following the 24 August and the 30 October mainshocks. The incremental fault offset is clearly visible from the inspection of Fig. 3. A more detailed and comprehensive analysis of these features is discussed in Gori et al. [7].

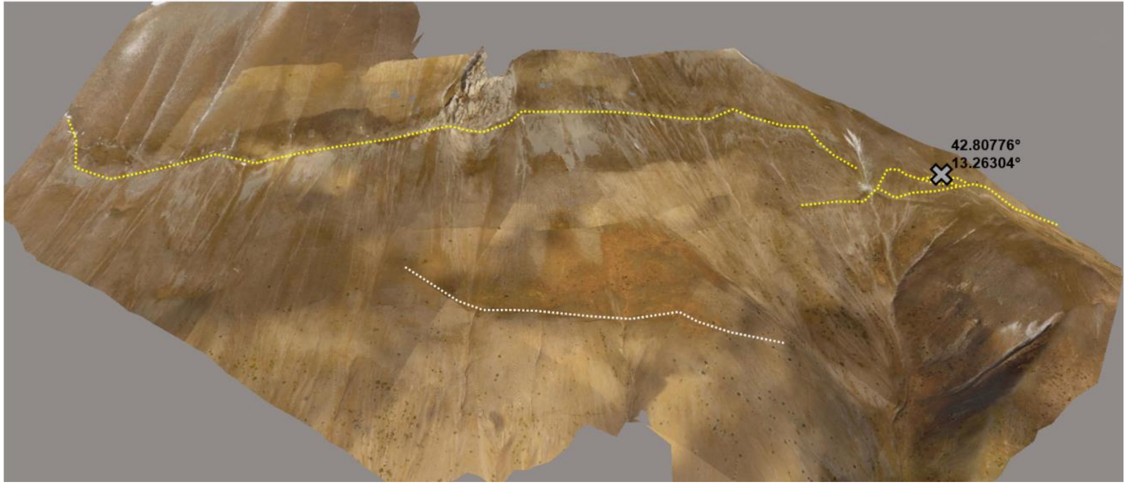

Figure 2. UAV-based orthomosaic model of the SW face of the Mt. Vettore Massif after the 30 October earthquake.

Figure 3. Comparative fault offset between the **M**6.1 24 August event (left picture) and the **M**6.5 30 October event (right picture).

Conclusions

We investigated surface ruptures of the Mt. Vettore-Mt. Bove fault system using both conventional field mapping and UAV/LiDAR imaging. Our observations have relevance for microzonation efforts in Italy intended to guide land management in areas of active and capable faults [8]. Once an active and capable normal fault has been mapped, in a relatively detailed (Level 3) study, the criteria identify hazard zones 160 m in width, with a 30m setback zone. In these zones, development may be made, but only following prescriptions that may vary case by case [8]. That set back zone is asymmetrically shaped around the fault trace (footwall/hanging wall ratio = 1:4). These setback criteria are conservative with respect to our observations, which generally indicated narrow primary fault ruptures. However, the presence of newly formed or previously unrecognized fault strands in areas where sediments overlie the fault support may suggest the use of broader setback and hazard zones in such areas to reflect mapping uncertainty.

An important consideration in locating zones of surface rupture hazards from geologic-structural field mapping pertains to major fault splays (e.g., length > 0.5-1 km), which can occur on the hanging wall of active faults. Activation of such splays was not observed in the **M**6.1 August event nor in the **M**5.9 October event, but did occur in the larger **M**6.5 event as shown for example in Fig. 2. While such ruptures on fault splays produce in effect a wide rupture zone (up to several kilometers), it is encouraging that the splay locations in addition to the main fault location had been identified pre-event. As a result, the experience from the 2016 surface rupture is that fault-specific detailed investigations can be effective for locating zones of rupture hazard both from principle fault structures and major secondary features.

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