Journal of Maps

ISSN: (Print) 1744-5647 (Online) Journal homepage: http://www.tandfonline.com/loi/tjom20

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To cite this article: R. Civico, S. Pucci, F. Villani, L. Pizzimenti, P. M. De Martini, R. Nappi & the Open EMERGEO Working Group (2018) Surface ruptures following the 30 October 2016 M_w 6.5 Norcia earthquake, central Italy, Journal of Maps, 14:2, 151-160, DOI: 10.1080/17445647.2018.1441756

To link to this article: https://doi.org/10.1080/17445647.2018.1441756

JOURNAL OF MAPS, 2018
VOL. 14, NO. 2, 151–160
https://doi.org/10.1080/17445647.2018.1441756

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Surface ruptures following the 30 October 2016 M_w 6.5 Norcia earthquake, central Italy

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ABSTRACT
We present a 1:25,000 scale map of the coseismic surface ruptures following the 30 October 2016 M_w 6.5 Norcia normal-faulting earthquake, central Italy. Detailed rupture mapping is based on almost 11,000 oblique photographs taken from helicopter flights, that has been verified and integrated with field data (>7000 measurements). Thanks to the common efforts of the Open EMERGEO Working Group (130 people, 25 research institutions and universities from Europe), we were able to document a complex surface faulting pattern with a dominant strike of N135°-160° (SW-dipping) and a subordinate strike of N320°-345° (NE-dipping) along about 28 km of the active Mt. Vettore–Mt. Bove fault system. Geometric and kinematic characteristics of the rupture were observed and recorded along closely spaced, parallel or subparallel, overlapping or step-like synthetic and antithetic fault splays of the activated fault systems, comprising a total surface rupture length of approximately 46 km when all ruptures were considered.

ARTICLE HISTORY
Received 10 July 2017
Revised 27 December 2017
Accepted 9 February 2018

KEYWORDS
Surface faulting; coseismic ruptures; normal faulting; geological prompt surveys; 2016–2017 seismic sequence; central Italy

1. Introduction

Initiating in August 2016, a series of moderate to large earthquakes struck the central Apennines producing severe damage in several small towns including Amatrice, Norcia and Visso (Figure 1). The earthquakes resulted in almost 300 casualties and left more than 20,000 homeless. These events came seven years after the 6 April 2009 M_w 6.1 L'Aquila earthquake (Herrmann, Malagnini, & Munafò, 2011). The seismic sequence (Chiaraluce et al., 2017 and references therein; Figure 1) started with an M_w 6.0 mainshock (24 August), which was followed by an M_w 5.9 mainshock on 26 October located 25 km to the northwest to culminate on 30 October 2016, in the largest shock of the sequence, an M_w 6.5 near the town of Norcia. Other events occurred in the southern sector of the sequence on 18 January 2017, with a maximum M_w of 5.5 (Figure 1).

The 30 October 2016 (06:40 UTC) M_w 6.5 Norcia mainshock was the strongest Italian seismic event since the 1980 M_s 6.9 Irpinia earthquake (Bernard & Zollo, 1989; Westaway & Jackson, 1987). The Norcia mainshock occurred less than 5 km NE of the village of Norcia (Figure 1) as a result of upper crustal normal faulting on a nearly 30-km-long, NW-SE oriented and SW dipping fault system known as Mt. Vettore–Mt. Bove (VBFS). The aftershocks of the 2016–2017 central

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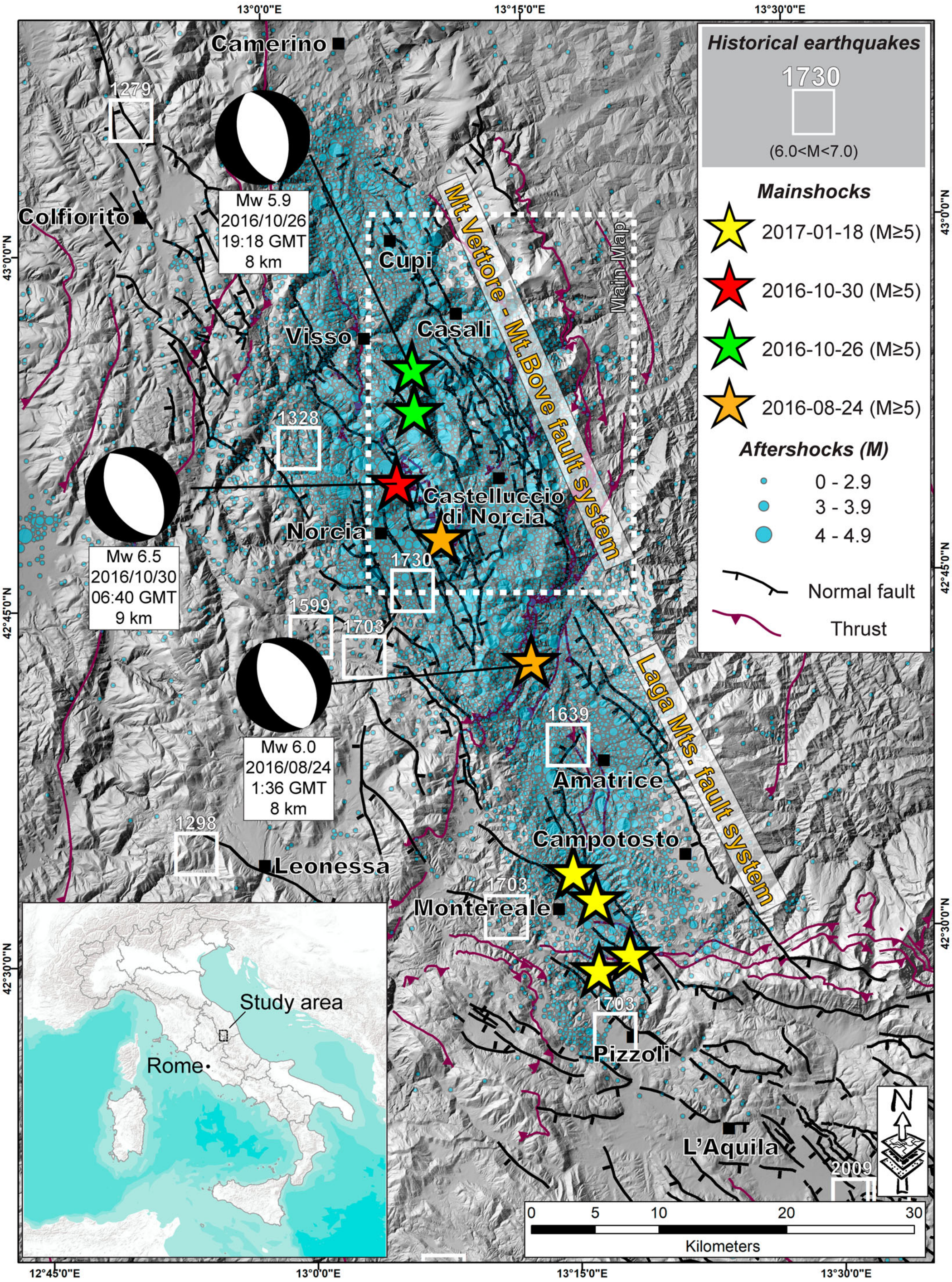

Figure 1. The 2016–2017 central Italy seismic sequence as recorded by the INGV Italian National Seismic Network (data from ISIDe – Italian Seismological Instrumental and Parametric Data-Base – http://iside.rm.ingv.it) for the time period 24 August 2016 through 23 January 2017. Stars indicate the mainshocks of the sequence. Time Domain Moment Tensor focal mechanisms of the three main earthquakes of the sequence are from the INGV web page (http://cnt.rm.ingv.it). Historical seismicity form CPTI15 (Rovida et al., 2016). Faults are compiled from Centamore et al. (1992), Pierantoni et al. (2013) and Galli et al. (2008). The white-dashed box encloses the area of the Main Map.

Italy seismic sequence are confined to the upper crust (10–12 km maximum depth) and follow a roughly NW-SE trend for *ca.*80 km between the towns of Camerino to the north and Pizzoli to the south (Chiaraluce et al., 2017).

This area of the central Apennines chain is characterized by a Quaternary NE-SW oriented extensional regime overprinting NE-verging thrust sheets (Lavecchia, Brozzetti, Barchi, Menichetti, & Keller, 1994; Vai & Martini, 2001), which mostly comprise Meso-Cenozoic carbonate rocks and Miocene flysch deposits. In the past 30 years, several attempts have been made to explain the space–time migration of the coupled extension–compression system affecting the Apennines. The most accepted idea is that back-arc extension related to the subduction roll-back

(Carminati & Doglioni, 2012 and references therein) may be a reliable large-scale underlying mechanism. Mantle uplift sustaining long-wavelength topography is invoked by D'Agostino, Jackson, Dramis, and Funiciello (2001) and by Chiarabba and Chiodini (2013). Extension is accommodated by a complex array of NW-SE and NNW-SSE striking, mainly SW dipping, up to 30-km-long, active normal fault systems. The cumulative rate of extension across the region is ∼1–3 mm/year based on the modeling of geodetic observations (Carafa & Bird, 2016; D'Agostino, 2014). The main active tectonic structures in the area affected by the 2016–2017 seismic sequence are the Mt. Vettore–Mt. Bove (Calamita, Pizzi, & Roscioni, 1992; Calamita & Pizzi, 1992, 1994; Cello, Mazzoli, Tondi, & Turco, 1997; Pizzi, Calamita, Coltorti, & Pieruccini, 2002), the Laga Mountains (Boncio, Lavecchia, Milana, & Rozzi, 2004; Galadini and Galli, 2000, 2003; Galli, Galadini, & Pantosti, 2008, also known as Mt. Gorzano fault), the Norcia (Galli, Galadini, & Calzoni, 2005) and the Montereale (Lavecchia et al., 2012; Civico et al., 2016) fault systems (Figure 1), which show Quaternary geologic slip rates ranging between 0.5 and 1.3 mm/year (Barchi et al., 2000; Boncio et al., 2004; Pizzi et al., 2002). Geological and paleoseismological studies conducted by Galadini and Galli (2003) along the VBFS anticipated that this active tectonic structure was one of the main seismic gaps of the central Apennines, potentially responsible for up to M 6.5 seismic event.

The area hit by the 2016–2017 seismic sequence has been repeatedly struck by $5.2 < M_w < 6.2$ earthquakes in the last 400 years, with the largest local earthquake occurring in 1639 (Io 9–10 MCS, M_w 6.2 – Rovida, Locati, Camassi, Lolli, & Gasperini, 2016). Apart from the 1703 earthquake sequence (with M_w up to 6.9), the broader region was the locus of other damaging moderate-sized earthquakes that struck central Italy in recent times: the M_w 5.8 1979 Norcia to the west (Brozzetti & Lavecchia, 1994; Deschamps, Iannaccone, & Scarpa, 1984), the M_w 6.0 1997 Umbria-Marche (Colfiorito) earthquake sequence to the northwest (Amato et al., 1998; Boncio & Lavecchia, 2000; Ferrarini, Lavecchia, de Nardis, & Brozzetti, 2014) and the M_w 6.1 2009 L'Aquila sequence to the southeast Chiaraluce et al., 2011; Lavecchia et al., 2012; Valoroso et al., 2013).

Within the Apennine chain, evidence of surface faulting was documented after the catastrophic M_s 6.9–7.0, 1915 Avezzano earthquake (Galadini & Galli, 1999; Michetti, Brunamonte, Serva, & Vittori, 1996; Oddone, 1915; Serva, Blumetti, & Michetti, 1988) as well as after the M_s 6.9, 1980 Irpinia earthquake (Pantosti & Valensise, 1990; Westaway & Jackson, 1984). More recently, for the M_w 6.1, 2009 L'Aquila earthquake, geologic data (Boncio et al., 2010; EMERGEO Working Group, 2010; Vittori et al., 2011) documented the occurrence of surface faulting. Conversely, the occurrence of primary seismogenic surface rupture remains controversial for the M_w 6.0 1997 Colfiorito earthquake (e.g. Basili et al., 1998; Cello et al., 2000; Cinti, Cucci, Marra, & Montone, 1999; Mildon, Roberts, Faure Walker, Wedmore, & McCaffrey, 2016).

Coseismic surface ruptures were observed following the M_w 6.0 24 August 2016 normal-faulting Amatrice earthquake (Figure 1). Ruptures trending ∼N155° with prevalent dip-slip kinematics, SW side down (average displacement of ∼0.13 m) were mapped for ∼5.2 km along the southern portion of the VBFS (EMERGEO Working Group, 2016; Lavecchia et al., 2016; Pucci et al., 2017). These coseismic features were interpreted as the result of primary surface faulting by Livio et al. (2016), Aringoli et al. (2016) and Pucci et al. (2017), while much less clear (1–2 cm of surface displacement) and discontinuous coseismic features were recorded along the Laga Mts. fault system by most of the research groups working in the area. Following the 26 October 2016, M_w 5.9 Visso earthquake (Figure 1), only sparse and discontinuous (each up to few hundred of meters long) ground ruptures were observed for a minimal length of about 7–10 km (Bendia et al., 2017) along the northern portion of the VBFS (approximately between the villages of Cupi and Casali, Figure 1), with an average vertical displacement of ∼0.15 m. Similar to the preceding event, the Visso earthquake surface ruptures show an average N145° strike and prevalent dip-slip kinematics, with the SW side down. Noteworthy, the field survey of the coseismic effects of the Visso event was not fully achieved having been overprinted by the occurrence of the 30 October M_w 6.5 mainshock.

The 30 October mainshock occurred with an epicenter close to the town of Norcia (Figure 1), and produced surface coseismic effects on the natural environment over a >400 km^2 wide area. The coseismic effects mainly consist of primary surface ruptures (those directly related to the earthquake fault; Figures 2 and 3), together with other coseismic effects related to ground shaking and permanent deformation (e.g. landslides, hydrological variations and liquefaction). An almost continuous NW-SE pattern of primary surface ruptures was observed for an overall extent of about 28 km along the VBFS, clearly overprinting and magnifying all the 24 August and, partially, the 26 October 2016 ground breaks. Surface rupture displacement exhibits predominantly normal dip-slip kinematics, with an average coseismic throw of ∼0.3 m. However, more than 2 km of almost continuous rupture in the southernmost portion of the activated fault system displayed >1 m average throw, and exceptionally high local peak throws up to ∼2.4–2.6 m were observed along the so-called Cordone del Vettore. In general, the ruptures are organized in a systematic pattern of dominantly synthetic (N135°-160° striking, SW-dipping) and subordinately antithetic (N320°-

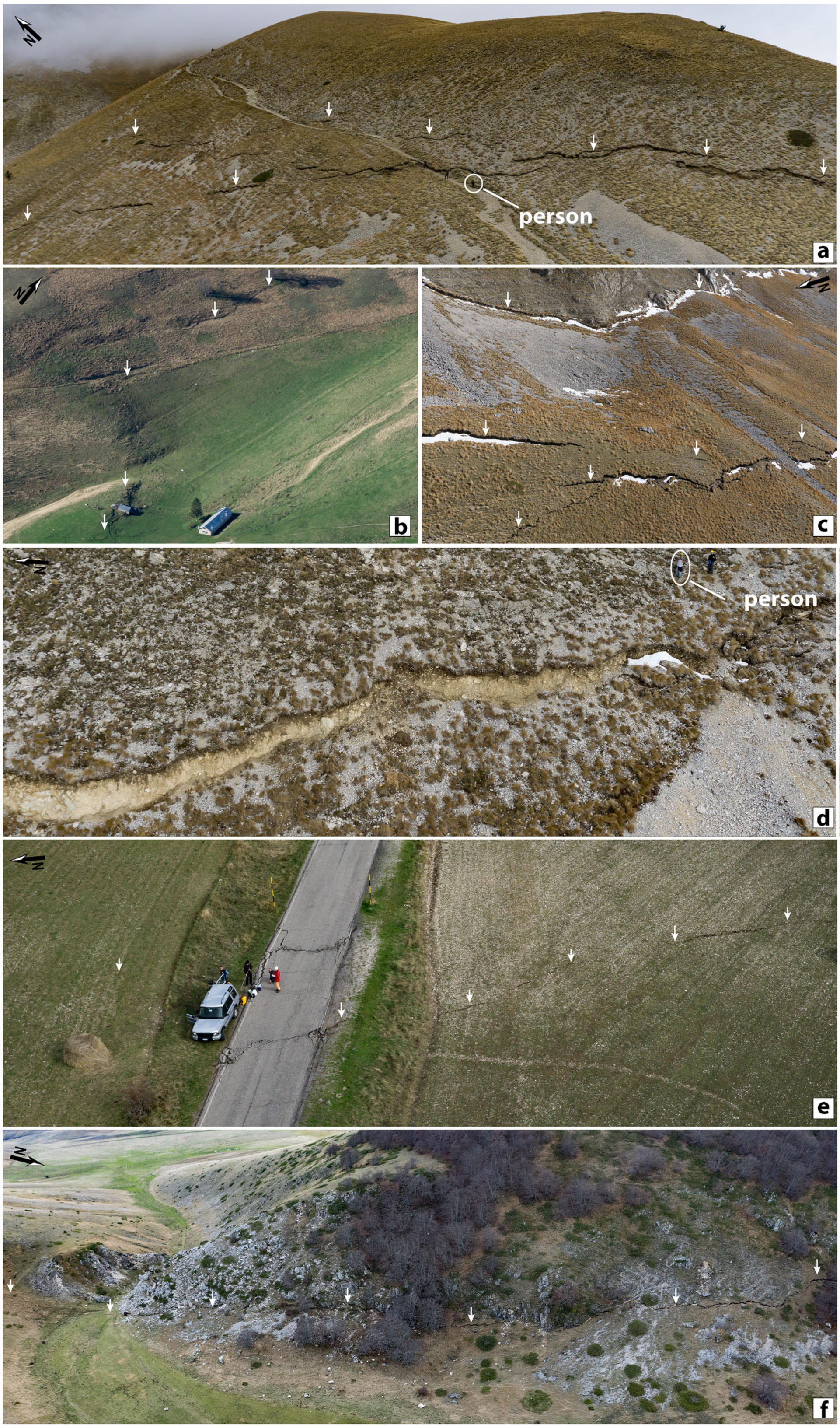

Figure 2. Examples of coseismic ruptures along the Mt. Vettore–Mt. Bove fault system as seen from helicopter surveys. White arrows mark the trace of the surface ruptures. (a) View of the continuous and stepping splay of the coseismic ruptures along the western Mt. Vettoretto flank (42.8083 N, 13.2630 E); (b) antithetic coseismic rupture in the middle sector of the VBFS (42.8489 N, 13.2213 E); (c) set of parallel coseismic ruptures along the western Mt. Vettore flank (42.8261 N, 13.2454 E); (d) Cordone del Vettore ruptured splay (42.8165 N, 13.2554 E); (e) coseismic ruptures along the Piano Grande di Castelluccio fault splay (42.8194 N, 13.2230 E) and (f) antithetic coseismic free-face following a cumulative fault scarp in both bedrock and alluvium (42.8531 N, 13.2119 E).

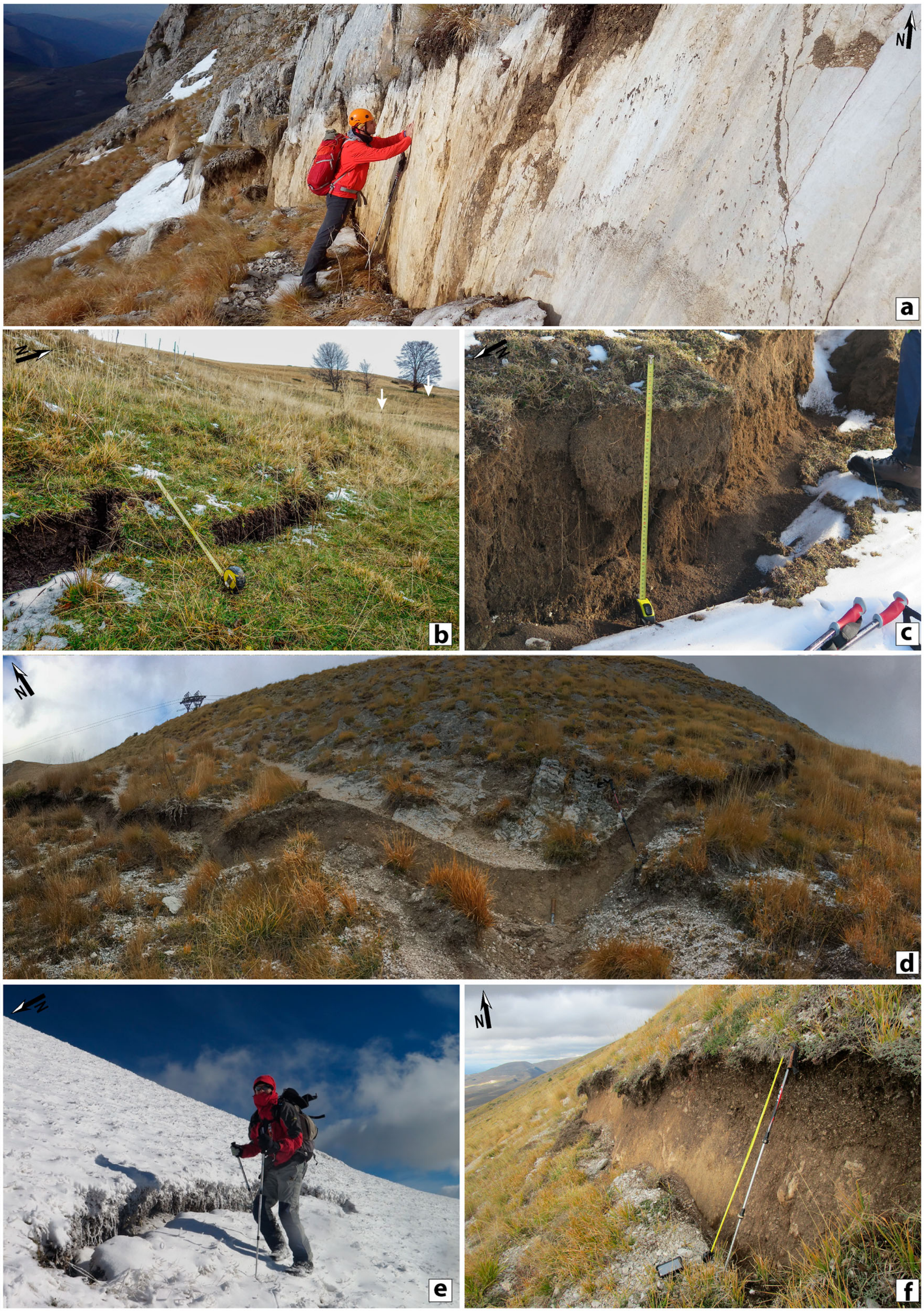

Figure 3. Examples of coseismic ruptures along the Mt. Vettore–Mt. Bove fault system as seen in the field. (a) Bedrock fault plane with freshly exposed free-face at Mt. Redentore (42.8189 N, 13.2522 E); note that the upper part of the free-face was exposed during the 24 August earthquake (10–20 cm); (b) right-stepping ruptures affecting colluvium, white arrows mark the trace of the ruptures in the distance (42.8488 N, 13.2213 E); (c) close view of decimetric throw affecting soil (42.8820 N, 13.2267 E); (d) metre-scale coseismic scarp cutting a small gully (42.9139 N, 13.1917 E); (e) frozen coseismic rupture (42.8751 N, 13.2290 E); (f) coseismic exhumation of buried bedrock fault plane covered by thin soil (42.8138 N, 13.2460 E).

345° striking, NE-dipping) strands. Notably, the alignment of ground ruptures typically follows the trace of mapped faults (Pierantoni, Deiana, & Galdenzi, 2013 and references therein), although in some cases, the coseismic ruptures occurred along fault splays that were not previously recognized. Subordinate and very discontinuous ruptures affected the SW edge of the Piano Grande basin and the Norcia town area.

Detailing all coseismic surface effects is crucial to identify and define primary surface faulting and its structural arrangement. This contributes to image the shallow-crust brittle deformation complexities and may provide useful information for describing the seismic source. Moreover, understanding the relations between the seismic source at depth and its evidence at the surface creates the basis for using the active faults at the surface to image which are the faults that can rupture next. Furthermore, this work provides new data on surface faulting in extensional domains, both on the earthquake causative fault splays and on other fault segments where deformation is distributed, implementing the community-sourced, worldwide and unified database of surface ruptures associated with earthquakes (SUrface Rupture Earthquake (SURE) database, International Union for Quaternary Research (INQUA) project 2016–2019 – http://www.earthquakegeology.com/index.php?page=projects&s=4). The final goals of this database are: (1) to generate a standardized method for describing surface ruptures and (2) to improve Probabilistic Fault Displacement Hazard Analysis (PFDHA) models through the assimilation of surface ruptures data from different earthquakes. Our data may also contribute updating the empirical relationships used to estimate the hazard related to surface faulting and to define the approximate magnitude of paleo-earthquakes (Stirling, Goded, Berryman, & Litchfield, 2013; Wesnousky, 2008).

The widespread occurrence of the ruptures, the large extent of the affected area, the amount of displacement and the complexity of the rupture geometry required a huge effort to document the impact that an M_w 6.5 seismic event had on the territory. Rapid and spatially dense collection of accurate surface rupture data after earthquakes can support emergency response, help coordinate scientific response and constrain coseismic slip that may be erased by degradation of fault scarps or by road/infrastructure repair, as well as overprinted by postseismic slip.

This paper represents a first synthesis of the common efforts of several European teams of earth scientists (Open EMERGEO Working Group – 130 people from 25 different research institutions and universities coordinated by the Istituto Nazionale di Geofisica e Vulcanologia – INGV). This is the first time that such a broad coordination of geoscientists was successful in studying together the geological coseismic effects following a large European earthquake. The response of the Open EMERGEO Working Group was focused on the detailed recognition and mapping from aerial and field surveys of: (1) the total extent of coseismic surface ruptures following the 30 October earthquake, (2) their geometric and kinematic characteristics and (3) the coseismic displacement distribution along the activated fault system. The full dataset supporting points 2 and 3 is presented in Villani et al., 2018.

In this study, we present a detailed and comprehensive report (Main Map) of the post-30 October 2016 M_w 6.5 earthquake surface ruptures along the VBFS and adjacent fault systems (e.g. Norcia Fault System). Mapping was carried out using both field observations and aerial surveys. It should be noted that due to the complex behavior of this seismic sequence with multiple mainshocks occurring close in time, our mapping includes surface deformation related to all of the mainshocks that occurred in the area (namely: the 24 August, 26 October and 30 October 2016 events).

2. Methods

Rapid and spatially dense collection of accurate surface rupture data after earthquakes can support emergency response, help coordinate scientific response and constrain coseismic slip that may be erased by degradation of fault scarps or by road/infrastructure repair, as well as overprinted by postseismic slip. Therefore, the Open EMERGEO Working Group began surveying the coseismic geological effects at the surface within hours of the 30 October 2016 mainshock. One of the main challenges for mapping the post-30 October coseismic surface rupture was to identify and locate the primary rupture path through a complex network of faults (Calamita et al., 1992; Pierantoni et al., 2013; Pizzi et al., 2002) within a wide and rugged terrain region (>400 km^2) with elevations up to ~2400 m. By the end of 31 October, a first picture of the surface rupture extent and of its general pattern was established by means of a helicopter flight, which formed the basis for planning the subsequent field and aerial surveys. Priorities were set to rapidly examine and document features that: (a) were likely to be quickly degraded by possible snowfall/rain and (b) posed a potential risk to people (e.g. coseismic ruptures in close proximity or intersecting roads/infrastructures, or incipient landsliding along steep slopes).

Comprehensive mapping of the extent and the geometric characteristics of the surface ruptures was facilitated by oblique photographs (more than 11,000 digital images, see Figure 2) taken with six helicopter flights, for a total of 12 h flight. This was particularly useful in scarcely accessible or dangerous areas. Oblique photographs were taken with two handheld cameras equipped with almost the same 24-megapixel APS-C CMOS sensor (Sony ILCE-5100 and Nikon D5300) and capable of a maximum resolution of 6000 × 4000 pixels. Photographs were acquired as raw image files with shutter speeds (a.k.a exposure times) between 1/320 and 1/2000 to avoid motion blur and using focal lengths variable from 24 to 75 mm (35 mm equivalent focal length). Each photo was then associated to its own geographical coordinates (latitude, longitude and altitude) using track files recorded with an external GPS receiver.

The coseismic ruptures detected from aerial surveys were traced on screen at up to 1:500 scale with the help of satellite and aerial imagery from Bing Maps Aerial and World Imagery web services. In addition, 0.5 m resolution Pleiades satellite images were provided by European Space Agency (ESA – CEOS_seismic pilot program) and *Centre National des Etudes Spatiales* (CNES) from France following the 24 August and the 30 October shocks. All the data were subsequently checked and integrated with field measurements, also taken in forested areas where remote surveys resulted less effective. Field measurements were greatly aided by the use of mobile devices equipped with a specific software employing GPS, compass and orientation sensors (Rocklogger© mobile app, www.rockgecko.com), which allowed for quick and accurate structural data collection and real-time sharing (see details of the method in EMERGEO Working Group, 2012). The huge amount of structural data collected was stored, managed and shared through a georeferenced database. The field measurements database (>7000 observation points) of the coseismic geological effects at the surface following the 30 October 2016 M_w 6.5 event is available in Villani et al., 2018. This database is presented in a specifically designed spreadsheet containing the full dataset of the geometric and kinematic characteristics of the ruptures.

Rupture traces are included in the Main Map as a line coverage. Rupture traces with measured or observed vertical offset are plotted with a red continuous line with tick marks on the downthrown side, while a blue continuous line has been used to show a rupture trace without measured or observed vertical offset. The traces of the recognized landslide head scarps are also reported (green lines). Rupture and landslide head scarps traces are drawn over a topographic base map built as a multilayer of: (a) hillshaded relief from the TINITALY (Triangular Irregular Network of Italy) 10-m-resolution digital elevation model (Tarquini et al., 2007), (b) World Imagery web service and (c) contour lines (20-m interval) and toponyms from vectorial topographic maps at 1:10,000 scale (C.T.R. from Regione Umbria and Regione Marche). The Main Map is reduced at 1:25,000 scale, as this is the best compromise between the paper size, the extent of the study area and the desired map detail.

3. Conclusions

Following the 30 October 2016 M_w 6.5 Norcia earthquake, a complex surface faulting pattern was observed and recorded along the causative VBFS and the nearby fault systems (e.g. Norcia Fault System). Thanks to the common efforts of the Open EMERGEO Working Group (130 people from 25 different research institutions and universities from Europe), we were able to record in high resolution the total extent of the coseismic surface ruptures and their geometric and kinematic characteristics. Noteworthy, the mapped ruptures also include all those that occurred after the 24 August M_w 6.0 event and partially those related to the 26 October M_w 5.9 shock.

Remote sensing surveys verified and integrated with field data showed an almost continuous alignment of ground ruptures for an overall NW-SE extent of about 28 km along the VBFS. Field observations after the 30 October 2016 earthquake reveal that the surface rupture pattern of this earthquake, involving closely spaced, parallel or subparallel, overlapping or step-like synthetic and antithetic fault splays pertaining to the VBFS, can be considered to be one of the most complex recorded in Italy and in the Mediterranean in the past 40 years, in terms of the number of involved fault splays, in a normal faulting earthquake context.

The earthquake ruptured mapped faults and (subordinately) previously unknown fault strands of different fault systems for a total cumulative surface rupture length of about 46 km, when all strands of the surface ruptures related to the three mainshocks of the sequence are considered (see Main Map). The structural pattern and kinematics of the coseismic ruptures appear to be independent of morphology and lithology, affecting both bedrock and different bodies of unconsolidated deposits (Figures 2 and 3). This resulted in primary surface faulting with a dominant strike of N135°-160° (SW-dipping) and a subordinate strike of N320°-345° (NE-dipping) in very good agreement with the long-term surface expression of the VBFS and with seismological data (Chiaraluce et al., 2017). The large-scale deformation zone of the VBFS at the surface ranges from 70 to 3200 m in width (distance between fault splays), while the width of each displacement zone (single fault splay) ranges from 3 to 60 m (distance between overlapping or *en echelon* ruptures). The average coseismic throw derived from all the mapped ruptures is ~0.3 m; notably, more than 2 km of these ruptures display >1 m average throw, with maxima of ~2.4–2.6 m along the so-called Cordone del Vettore fault scarp (Villani et al., 2018).

This map is based on two very dense datasets of photographs and field measurements (taken on average every *ca.*10 m), and as a result probably represents so far the most detailed and comprehensive collection of ground-surface fault rupture characteristics of any earthquake in Italy, and one of the richest documentations of earthquake surface ruptures worldwide (e.g. DeLong et al., 2016; Fletcher et al., 2014; Stirling et al., 2017). From a methodological perspective, a combined approach integrating remote surveys and field reconnaissance proved to be effective in mapping the extent and details of the surface ruptures even in limited accessibility or dangerous areas.

By providing a detailed map of the coseismic ruptures at the surface, the Main Map helps in understanding how slip is distributed at surface among the different fault splays thus resulting in a valuable contribution to surface faulting hazard assessment to better anticipate the potential location of future ruptures. In fact, the marked variability in the width of the rupture zone at surface observed for the 30 October 2016 M_w 6.5 Norcia earthquake, as well as for other recent earthquakes (e.g. 2010 M_w 7.2 El Mayor–Cucapah earthquake – Teran et al., 2015), has important implications in terms of support to decision makers for siting and designing facilities to be constructed in the vicinity of active faults (Boncio, Galli, Naso, & Pizzi, 2012). The results of this work represent also an important implementation to the worldwide database of earthquake surface ruptures (SURE, INQUA project 2016–2019). As a consequence, the presented data are valuable to enlarge the dataset used for the calculation of the empirical relationships applied to estimate the magnitude of paleo-earthquakes and the surface faulting hazard, which suffer to be based on a limited number of case studies (Stirling et al., 2013; Wesnousky, 2008).

Finally, this enormous collaborative experience has a twofold relevance: on the one side, it allowed for accurate and rich documentation of the earthquake ruptures before their deterioration; on the other hand, it represents the first large European survey of coseismic surface effects. In conclusion, we should use the Open EMERGEO Working Group experience as a leading example in order to establish, at the Euro-Mediterranean scale, geological survey teams who are prepared to respond rapidly to future seismic crises.

Software

Most of the field surveying of the coseismic effects at the surface (type of observation, strike, vertical dislocation, fracture opening, etc.) was performed using the Rocklogger© Android App for mobile devices. The data collected in the field have been managed and stored in a georeferenced database using Esri ArcGIS 10.5 and Google Earth Pro. The pictures taken during the aerial surveys have been organized and edited with Adobe Photoshop Lightroom 6.4. Adobe Illustrator CS6 was used for final map production.

Acknowledgements

We thank the Italian Civil Protection Department for the logistics. We are grateful to Corpo Nazionale dei Vigili del Fuoco (National Fire Corps) and Corpo Forestale dello Stato (State Forestry Corp) for the support on the aerial surveys; we also thank Corpo Nazionale Soccorso Alpino e Speleologico (Mountain Rescue) for the logistic support. We are grateful to the Editor and Associated Editor for the editorial handling. Juliane Cron, Mark Williamson Stirling and Christopher Milliner provided thoughtful comments that greatly improved the early version of this manuscript and of the Main Map. Digital cartographic elements of the Carta Tecnica Regionale 1:10,000 scale by courtesy of Regione Umbria and Regione Marche. We acknowledge ESA CEOS_seismic pilot program and CNES for their prompt response in providing us with Pleiades satellite images of the epicentral area.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

We thank the Italian Civil Protection Department for funding. Z. K. Mildon was funded by NERC Studentship NE/L501700/1. The UK team was supported by NERC Urgency grants NE/P018858/1 and NE/P01660X/1, and NERC Standard grant NE/I02318X/1.

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