Engineering Reconnaissance following the October 2016 Central Italy Earthquakes

GEER Team Leaders: Giuseppe Lanzo and Jonathan P. Stewart

Report Editors:

Paolo Zimmaro and Jonathan P. Stewart

DOI:10.18118/G6S88H

Geotechnical Extreme Events Reconnaissance Association

Report No. GEER-050C

9 January 2017

GEER Team Members

Leaders: Jonathan P Stewart, University of California Los Angeles (UCLA) and

Giuseppe Lanzo, Sapienza Università di Roma

Ernesto Ausilio, Roberto Cairo, Università della Calabria

Francesca Bozzoni, Eucentre, Pavia

Maria Chiara Capatti, Università Politecnica delle Marche

Fernando della Pasqua, GNS Science

Francesca Dezi, Università degli Studi della Repubblica di San Marino

Luigi Di Sarno, Maria Giovanna Durante, Armando Lucio Simonelli, Università degli studi del Sannio, Reluis Consortium

Sebastiano Foti, Filiberto Chiabrando, Paolo Dabove, Vincenzo Di Pietra, Paolo Maschio, Federico Passeri, Antonio Sgobio, Lorenzo Teppati Lose', Politecnico di Torino

Kevin Franke, Brandon Reimschiissel, Brigham Young University

Fabrizio Galadini, Emanuela Falcucci, Stefano Gori, Istituto Nazionale di Geofisica e Vulcanologia (INGV)

Robert E Kayen, US Geological Survey (USGS)

Bret Lingwall, South Dakota School of Mines and Technology

Alessandro Pagliaroli, Silvia Giallini, Zurab Gogoladze, Alberto Pizzi, Giovanna Vessia, Università degli Studi di Chieti-Pescara

Filippo Santucci de Magistris, Massimina Castiglia, Tony Fierro, Dipendra Gautam, Luciano Mignelli, Fiorenzo Staniscia, Università del Molise

Anastasios Sextos, Raffaele De Risi, University of Bristol

Stefania Sica, Michele Mucciacciaro, Università degli Studi del Sannio

Paolo Tommasi, Istituto di Geologia Ambientale e Geoingegneria (IGAG), CNR

Giuseppe Tropeano, Università di Cagliari

Paolo Zimmaro, University of California Los Angeles (UCLA)

Introduction

Between August and November 2016, three major earthquake events occurred in Central Italy. The first event, with **M**6.1, took place on 24 August 2016, the second (**M5**.9) on 26 October, and the third (**M**6.5) on 30 October 2016.

As shown in Figure 1, this earthquake sequence occurred in a gap between two earlier damaging events, the 1997 **M**6.1 Umbria-Marche earthquake to the north-west and the 2009 **M**6.1 L'Aquila earthquake to the south-east. This gap had been previously recognized as a zone of elevated risk (GdL INGV sul terremoto di Amatrice, 2016). These events occurred along the spine of the Apennine Mountain range on normal faults and had rake angles ranging from -80 to -100 deg, which corresponds to normal faulting. Each of these events produced substantial damage to local towns and villages. The 24 August event caused massive damages to the following villages: Arquata del Tronto, Accumoli, Amatrice, and Pescara del Tronto. In total, there were 299 fatalities (www.ilgiornale.it), generally from collapses of unreinforced masonry dwellings. The October events caused significant new damage in the villages of Visso, Ussita, and Norcia, although they did not produce fatalities, since the area had largely been evacuated.

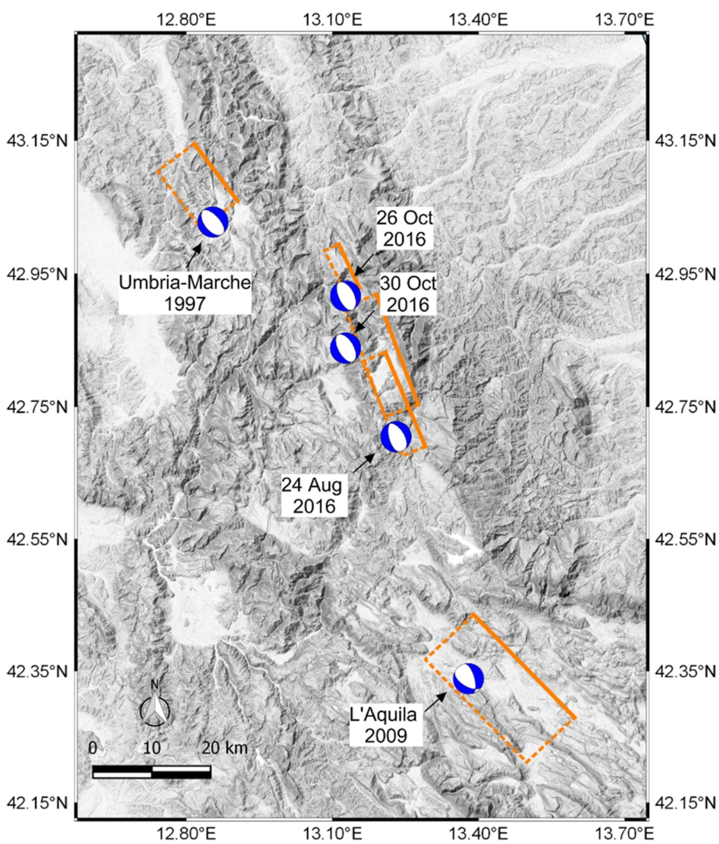


Figure 1. Map of central Italy showing moment tensors of major earthquakes since 1997 and the intermediate gap areas. Finite fault models from Chiaraluce et al. (2004; 1997 Umbria-Marche event), Piatanesi and Cirella (2009; 2009 L'Aquila event), Tinti et al. (2016, 24 August event), and GdL INGV sul terremoto in centro Italia, 2016, 26 and 30 October events). Moment tensors for 26 and 30 October 2016 earthquakes are also shown.

The NSF-funded Geotechnical Extreme Events Reconnaissance (GEER) association, with co-funding from the B. John Garrick Institute for the Risk Sciences at UCLA and the NSF I/UCRC Center for Unmanned Aircraft Systems (C-UAS) at BYU, mobilized a US-based team to the area in two main phases: (1) following the 24 August event, from early September to early October 2016, and (2) following the October events, between the end of November and the beginning of December 2016. The US team worked in close collaboration with Italian researchers organized under the auspices of the Italian Geotechnical Society, Italian Center for Seismic Microzonation and its Applications, the Institute of Environmental Geology and Geoengineering (IGAG) of the Italian National Research Council, the Consortium ReLUIS, Centre of Competence of Department of Civil Protection and the DIsaster RECovery Team of Politecnico di Torino. The objective of the Italy-US GEER team was to collect and document perishable data that is essential to advance knowledge of earthquake effects, which ultimately leads to improved procedures for characterization and mitigation of seismic risk.

The Italy-US GEER team was multi-disciplinary, with expertise in geology, seismology, geomatics, geotechnical engineering, and structural engineering. The composition of the team was largely the same for the two mobilizations, particularly on the Italian side. Our approach was to combine traditional reconnaissance activities of on-ground recording and mapping of field conditions, with advanced imaging and damage detection routines enabled by state-of-the-art geomatics technology. GEER coordinated its reconnaissance activities with those of the Earthquake Engineering Research Institute (EERI), whose activities were focused on emergency response and recovery, in combination with documenting the effectiveness of public policies related to seismic retrofit. As such, GEER had responsibility for documenting structural damage patterns in addition to geotechnical effects.

This brief report is focused on the reconnaissance activities performed following the October 2016 events. More information about the GEER reconnaissance activities and main findings following the 24 August 2016 event, can be found in GEER (2016). The main objective of this document is to provide to the technical community, emergency responders, and public a brief initial account of our activities and preliminary findings. A more complete report will be presented subsequently.

Similar to reconnaissance activities following the 24 August 2016 event, the GEER team investigated earthquake effects on slopes, villages, and major infrastructure. Figure 2 shows the most strongly affected region and locations described subsequently pertaining to:

1. Surface fault rupture;
2. Recorded ground motions;
3. Landslides and rockfalls;
4. Mud volcanoes;
5. Investigated bridge structures;
6. Villages and hamlets for which mapping of building performance was performed;

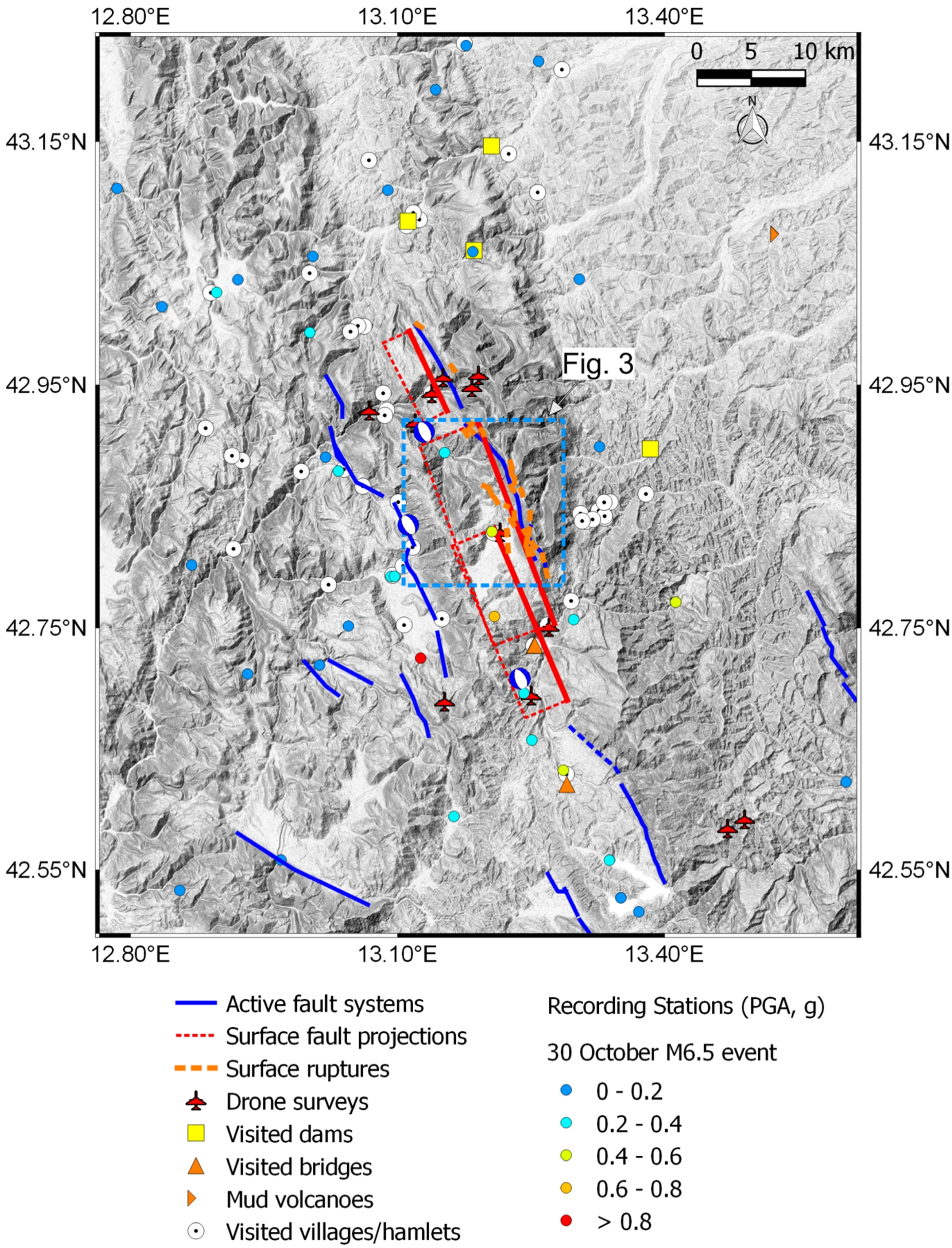


Figure 2. Regional map showing the active fault systems, finite fault models and epicenters of the 24 August, 26 and 30 October events, ground motion station locations and recorded peak ground accelerations (PGA) for the 30 October events, and locations of various earthquake effects discussed in this report.

Surface Faulting

The 26 and 30 October 2016 mainshocks occurred on the Mt. Vettore fault, which was recognized as a seismogenic source previously (Galadini and Galli, 2000, 2003). This fault was one of two fault segments involved in the 24 August event (GEER, 2016). The 30 October event re-ruptured the southern 4.8 km of the fault, but the rupture also extended to the north, producing an overall rupture length of approximately 15-20 km (the northern-most 10-15 km of which was not involved in the 24 August event). Figure 2 shows the length of the surface rupture as recorded by GdL INGV sul terremoto in centro Italia (2016) and observations by INGV members of the GEER team. We do not have information on surface rupture produced by the 26 October event.

We performed detailed measurements and imaging of fault rupture in three areas shown in Figure 3. Whereas the 24 August event produced displacements on the main fault trace ranging from null to 35 cm (mostly 10-25 cm), we found in some of these same areas displacements of up to ~ 1.6 m on the main fault trace. We also found displacements of up to several tens of cm on two secondary faults (Figure 3), which had not displaced on the 24 August event. Figure 4 shows an example of large fault displacement at the location shown in Figure 3.

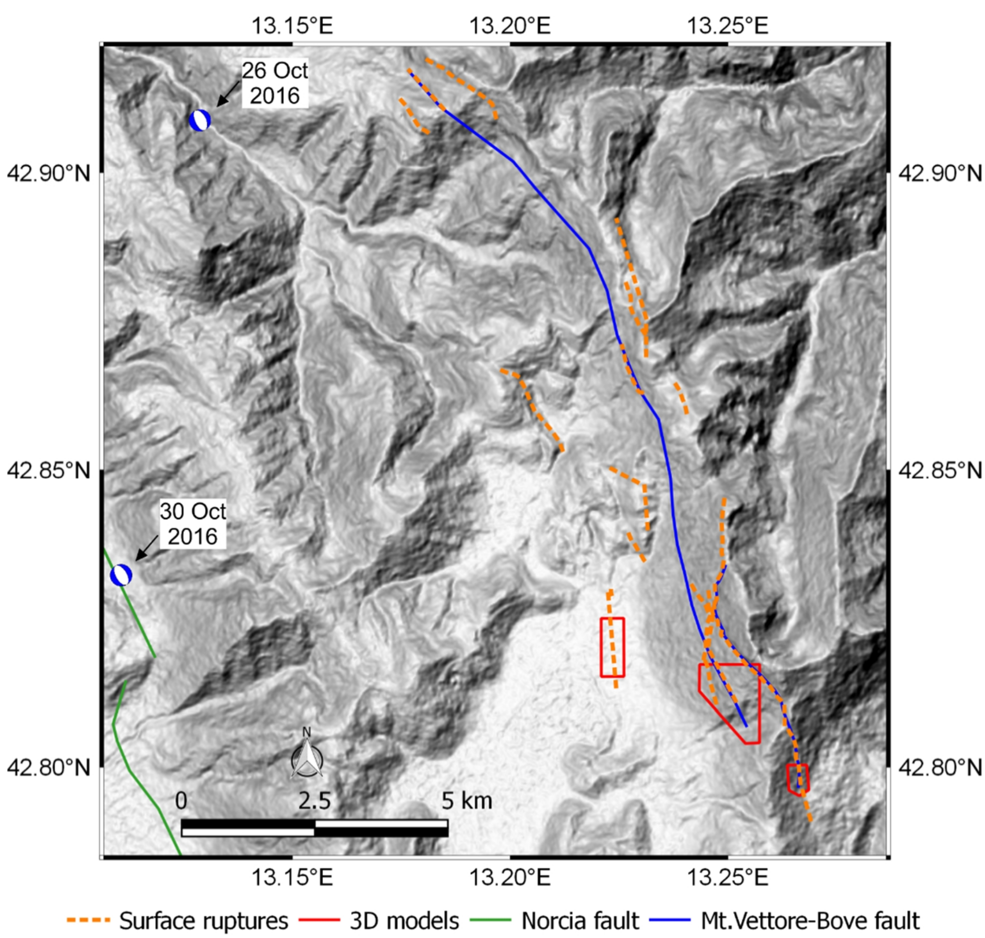


Figure 3. Detailed map of surface fault rupture, pre-event mapping of Mt. Vettore-Mt. Bove (blue) and Norcia (green) fault systems, and locations of 3D models.

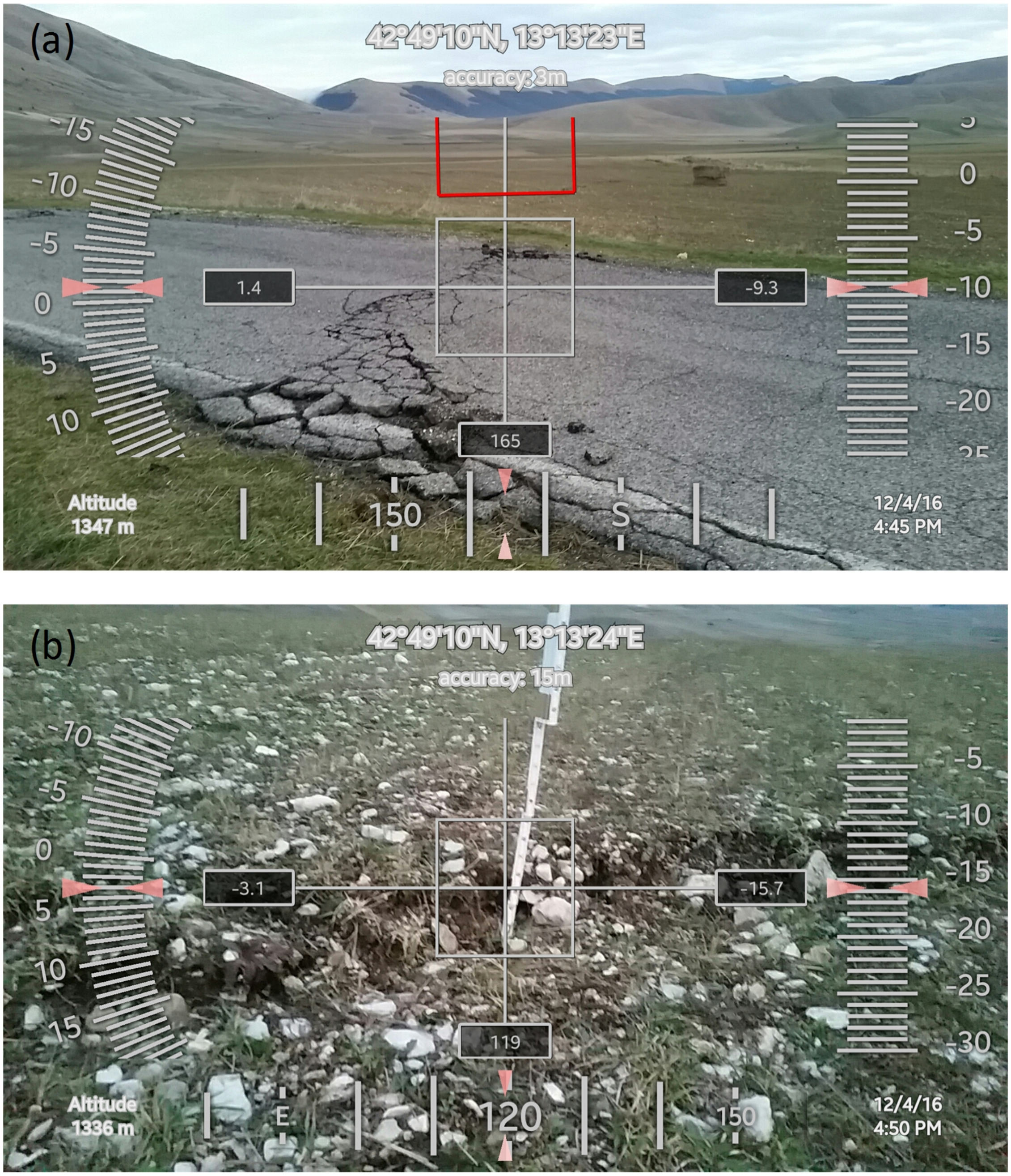


Figure 4. Pictures of the Piano Grande fault offset location; (a) surface rupture manifestation on the road, and (b) rupture manifestation with vertical offset equal to 15 cm.

Ground Motions

Two networks operate broadly distributed permanent ground motion installations in Italy: INGV and Dipartimento della Protezione Civile (DPC). Data from these networks are disseminated at http://esm.mi.ingv.it. We have not downloaded and processed ground motion data at this time, although we have noted the locations of stations that appear to have produced usable recordings. The locations of such instruments in the near-fault region are shown in Figure 2.

Figure 2 also shows the locations of temporary instruments deployed after the 24 August event, which we expect to have been operational for the 26 and 30 October events. Data from these temporary arrays have not been released as of this writing. Further information on temporary arrays is available in Table 3.1 of GEER (2016).

Landslides and Rockfalls

GEER activities following the 24 August event built upon prior work by the Italian Institute for Environmental protection (ISPRA, 2016), and the Research Center for Prediction, Prevention and Monitoring of Geological Risks of Sapienza University (CERI working group, 2016). To our knowledge, GEER is the first organization to systematically investigate rockfalls and landslides following the October 2016 events. Figure 5 shows locations of identified earthquake-induced rockfalls and landslides caused by the October 2016 events. Whereas the 24 August event produced relatively small features (mostly rockfalls) (GEER, 2016), the slope instabilities and rockfalls induced by the October events were much larger and more destructive.

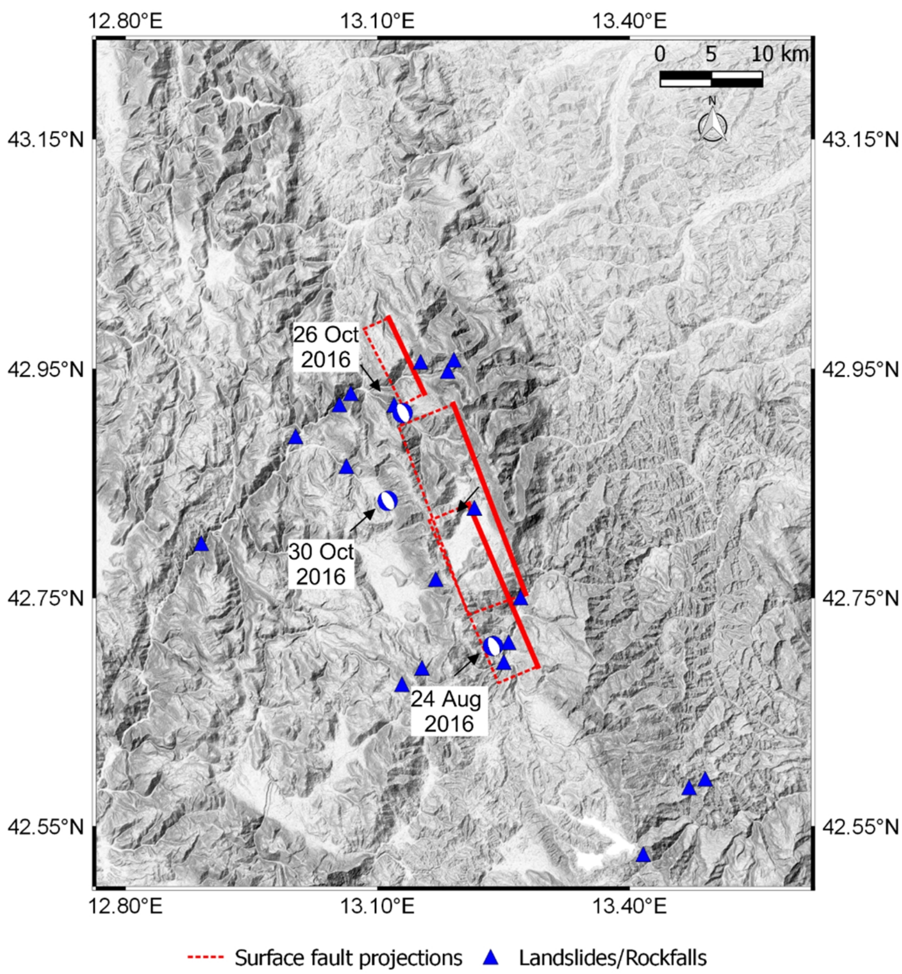


Figure 5. Mapped rockfalls and landslides relative to finite faults of earthquake sequence.

Two particularly massive landslides were the Mt. Bove landslide and the Nera river landslide. Aerial images of each are shown in Figure 6. The Mt. Bove landslide source area is near the summit and involved a large volume of slide debris. We have aerial imagery of this feature, which has been used to produce a 3D model. This landslide was detected by the damage proxy map by JPL-Caltech[1] using satellite images collected after the 26 October event; hence, the landslide is attributed to that earthquake. This information has been confirmed by a local engineer who observed the feature following the October 26 event but prior to 30 October. The Nera river landslide, is a 300 meter-high wedge-type translational slide that became a large rockfall that dammed the river below and closed the highway. We performed extensive imaging of this feature, which has been interpreted to form a 3D model. From the similar markings and discolorations on the mountainside, it appears that similar events may have occurred previously.

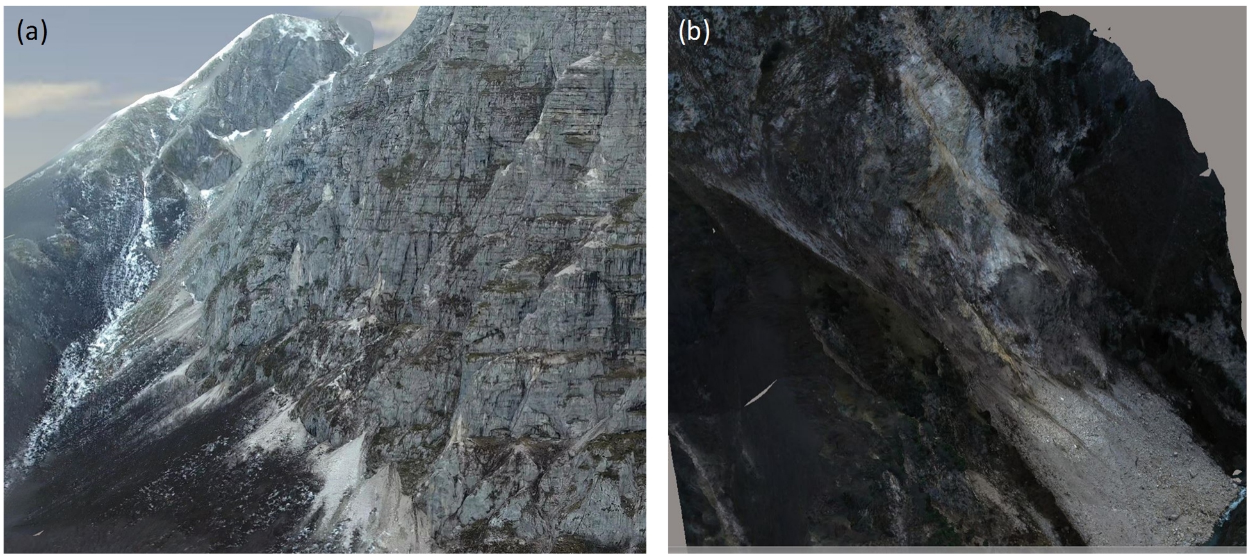


Figure 6. (a) Screenshot of the Mt. Bove landslide 3D model, and (b) screenshot of the Nera river landslide 3D model.

When possible, we re-visited sites that had already experienced landslides/rockfalls from the 24 August event. In particular, landslides that had occurred within the villages of Pescara del Tronto and Accumoli were re-activated, with notably larger displacements in the recent events.

As shown in Figure 2 and Table 1, aerial imaging was performed of eight landslide features. This imaging was performed using one or more of the following apparatus: a DJI™ Phantom 4 drone, a customized Align™ T-Rex 800 drone, or an Ebee Sense Fly drone. These data are being used to develop digital maps (ortophotos), Digital Surface Models (DSM), and 3D models of the surface morphology. Table 1 also shows locations of landslides mapped as part of the GEER activities that do not have sufficient aerial imagery to develop 3D models.

[1] Damage proxy maps, ARIA project, JPL-Caltech, available at: http://aria-share.jpl.nasa.gov/

Table 1. Summary of the documented landslides/rockfalls

Location name	Type	Coordinates	Description	3D model
Rockfall above road between SP45a and Cesacastina (Crognaleto-TE) Teramo rockfall	Rockfall	42.584333 N 13.47075 E	Very large boulders (>12 m in length)	Y
Landslides Savelli-Pescia (reappraisal) Pescia landslides	Landslides /rockfalls	42.697651 N 13.145074 E (Landslide 1), 42.689016 N 13.152763 E (Landslide 2)	Landslides of various sizes in the weathered and highly-fractured limestone rock were observed along this road	Y
Rockfalls/ landslides along SP135 Visso - Castelsantangelo	Landslides /rockfall, teetering rock column	42.9201589 N 13.1149947 E (teetering rock), 42.9096674 N, 13.12981472 E (landslide/rockfall)	Large landslide/rockfall (boulders ~1-2m in diameter). The teetering rock column had become dislodged during the 26 October event.	Y
Nera landslide	Landslide	42.929 N 13.068 E	Dammed river, buried highway. The road was closed as a result. Volume of material is significant.	Y
Mt. Bove landslide	Landslides /rockfalls	42.93618 N 13.18875 E	No damage to infrastructure. Massive phenomenon	Y
Valle di Panico rockfall	rockfall	42.9485943 N 13.1877576 E	Moderate sized rockfall that nearly impacted a small pump station at the bottom of the valley. Boulders estimated to be 2-3 meters in diameter	Y
Valle di Panico landslide	landslide	42.9471626 N 13.1435794 E	Small landslide soil that damaged the road. Scarp in the road produced an estimated 25 cm vertical offset	Y
Pescara del Tronto landslide	landslide	42.750608 N 13.272256 E	Large landslide in the fill below the city of Pescara. Significant incremental damage.	Y
Accumoli landslide	landslide	42.694082 N 13.250121 E	Damage to retaining walls, road, and overlying structures. Significant incremental damage.	Y
Landslide along road Ortolano-Campotosto	Landslide	42.525667 N 13.416131 E	NE-SW trending fissures (max. vertical offset: 30 cm; max. horizontal offset: 42 cm) 60 m long. The road level was displaced 5 m (maximum).	N

Table 1 (cont.). Summary of the documented landslides/rockfalls

Location name	Type	Coordinates	Description	3D model
Rockfall SP 477 Arquata-Castelluccio (reappraisal)	Rockfall	42.766584 N 13.169153 E	Extensive rockfalls. Several damages on road embankments. Minor damages on culvert across the road section.	N
Landslide along SP746 road between Cittareale and Norcia	Landslide	42.674714 N 13.128963 E	No damages to the road detected. This landslide is localized near the failure in calcareous breccia documented in the GEER (2016)	N
Debris-flows/landslide in Pontechiusica	Debris-flows/ landslide	42.891342 N 13.002303 E	Debris-flow/rock avalanche. No damages on the road.	N
Rockfalls between Piedipaterno and Cerreto	Rockfalls	42.798017 N 12.890086 E	Extensive rockfalls along the road. Many sections of rockfall protection barriers were damaged.	N
Roadway slope failure along road (Castelluccio)	Landslide	42.828611 N 13.215 E	Small slope failure on the approach embankment to Castelluccio	Y
Landslide below the village of Tino	Landslide	42.7114 N 13.2559 E	Landslide features	N
Landslide near the village of Crognaleto	Landslide	42.5919 N 13.4899 E	Landslide features	Y
Rockfalls along SP209 between Molini and Nera landslide	Rockfalls	42.919212 N13.054421 E	Extensive rockfalls. Extensive rockfalls. Several damages on road embankments. Boulders ~1-2m in diameter.	N

Mud Volcanoes

Mud volcanoes are naturally occurring formations created by gasses or water extruded through sediments by deeper geologic processes (https://en.wikipedia.org/wiki/Mud_volcano). They are typically a few meters in dimension and the extruded fluids may be warm, indicating that their driving mechanism is related to heat dissipation.

In an area near the village of Monteleone di Fermo, mud volcanoes are a regularly occurring phenomenon, in fact comprising a tourist attraction. Following the 30 October seismic sequence, observers from INGV (INGV Terremoti blog, available at: https://ingvterremoti.wordpress.com/2016/11/11/sequenza-sismica-in-italia-centrale-i-vulcanelli-di-fango-in-provincia-di-fermo/, last accessed 8 January 2017) found an accelerated rate of water extrusion that continued for several days from four pre-existing mud volcanoes.

The materials extruded appeared to be fine-grained (even clayey) in composition. At a nearby location (Santa Vittoria in Matenano), two new mud volcanoes formed after the 30 October event. These too continued to flow for several days following the event. Figure 8 shows photographs of mud volcanoes from pre-existing features in Monteleone di Fermo.

Figure 8. mud volcanoes in Monteleone di Fermo: (a) along the Ete river (Porto San Giorgio), and (b) in the area of Valle Corvone.

Performance of Bridge Structures

GEER and the Consotium ReLuis inspected 12 bridges following the 24 August event, with results presented in Chapter 6 of GEER (2016). While most of the inspected bridges had no observable damage, three had experienced damage that affected roadway operations. Those three bridges were re-visited following the October events.

The three bridges in question are of masonry construction, and are identified as follows: (1) Roman-era bridge on the SP129 Trisungo-Tufo (1-span), in the Tufo hamlet, (2) Roman-era bridge on the SP129 Trisungo-Tufo (3-span), in the Tufo hamlet, and (3) SR260 Ponte a Tre Occhi in the town of Amatrice. All three bridges suffered substantial additional damage following the October earthquakes.

Figure 9 shows two comparative pictures (taken after the 24 August and the October events) of the 1-span masonry bridge along the Trisungo route (along the SP129). The bridge now presents additional cracks in the internal part of the arch (Figure 9b), but there was no additional spalling of masonry elements, as had occurred in the 24 August event. Figure 10 shows the response of the second arch along the Trisungo route (3 spans bridge) after the different events (24 August and October 2016). In this case the cumulative damage was significant: part of central arch, already damaged after the first event, collapsed after the October earthquakes (Figure 10b and 10d). The Ponte a Tre Occhi (Three eyes) near Amatrice (Figure 11) also experienced additional damage, consisting mainly of spalling of outer-layer masonry elements located along abutment areas (not involving the three arches) (Figure 11b).

Figure 9. Roman-era bridge along the Trisungo route (1 span bridge - Tufo area – Arquata del Tronto): (a) after the 24 August event (photo on September 7 2016) and (b) after the October events (photo on December 13 2016) (N42.735981, E13.254862).

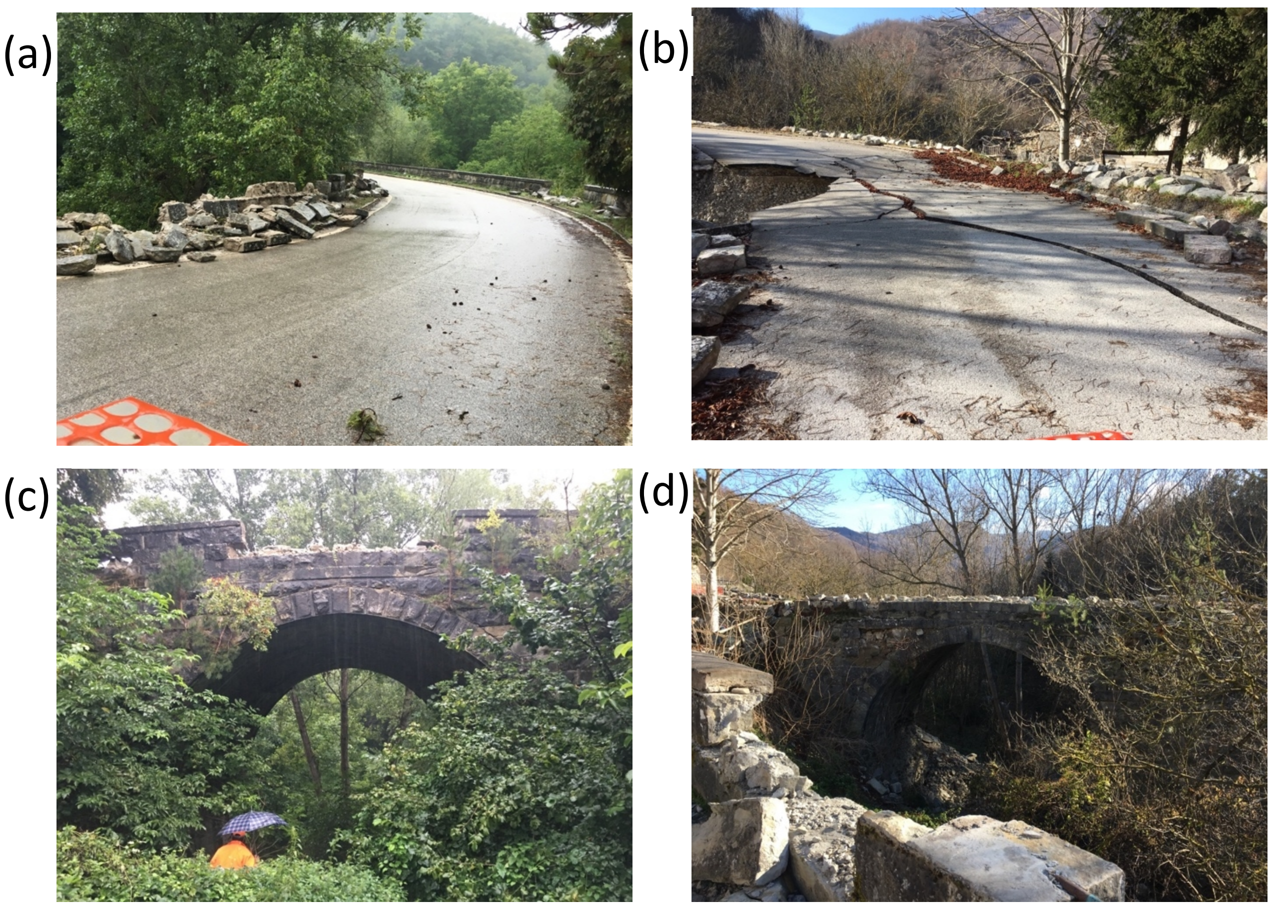


Figure 10. Roman-era bridge along the Trisungo route (3 spans bridge - Tufo area – Arquata del Tronto): (a, c) after the 24 August event (photo on September 7 2016) and (b, d) after the October events (photo on December 13 2016) (N42.73538, E13.253655).

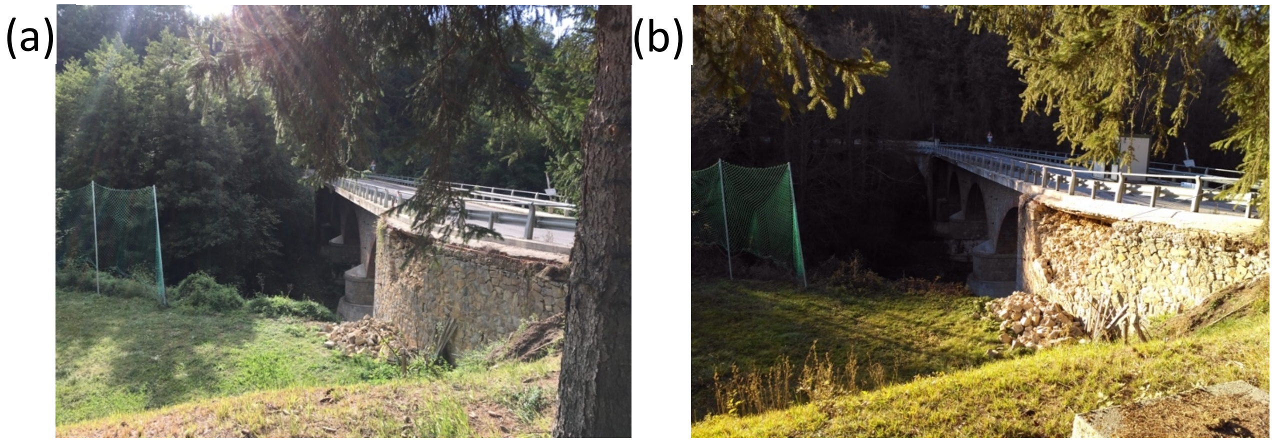


Figure 11. Ponte a Tre Occhi – Amatrice: (a) after the 24 August event (photo on September 7 2016) and (b) after the October events (photo on December 13 2016) (N42.620668, E13.290176).

Performance of Buildings Structures and Damage Patterns

Revisits

The 24 August earthquake produced devastating effects on dwellings in the villages of Arquata del Tronto, Accumoli, Amatrice, and Pescara del Tronto, the overwhelming majority of which are of masonry construction. Damage patterns and detailed structure-by-structure observations were made in these villages and surrounding hamlets during the first GEER team deployment in September 2016 (GEER, 2016). We re-visited these same villages and hamlets following the October events to evaluate possible additional damage. We also used UAVs to develop aerial imagery for several villages, which is being processed to develop 3D models (locations listed in Table 3).

Damage was classified based on visual inspections of buildings. Damage classifications followed the scheme provided by the Department of Civil Protection (DPC) in Italy for post-earthquake reconnaissance purposes in which the damage scale ranges from D0 (no damage) to D5 (full collapse) (Table 2). Table 3 presents a summary of approximate mean damage levels reported after the 24 August event (GEER, 2016) and the October events (this work). For the present report, we assign one approximate mean damage level per village, based on a synthesis of our detailed structure-by-structure damage assessments within each village. An important point to be made here is that the same group of researchers inspected these villages and hamlets following each event, and used identical mapping and damage classification approaches. Hence, we do not expect the change in results between events to be affected by observer bias.

As shown in Table 3, most villages experienced increase damage, in many cases dramatically so such that the average damage level became D5. Particularly dramatic is the situation in Pescara del Tronto, Arquata del Tronto, Accumoli, Amatrice, and Tufo. Figures 12, 13, and 14 show pictures taken from a common perspective following the 24 August and October events of Pescara del Tronto, Tufo, and Accumoli, respectively. The incremental damage is substantial.

Figure 12. Incremental damage in Pescara del Tronto after the October earthquake events. (a) Overview of Pescara del Tronto on 9 September 2016, (b) Overview of Pescara del Tronto on 12 December 2016.

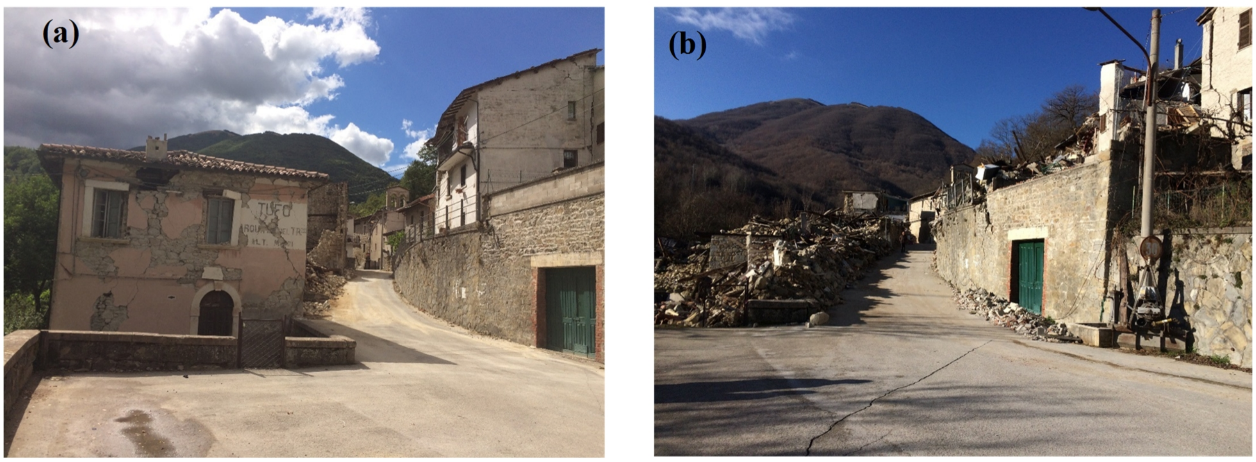


Figure 13. Incremental damage in Tufo after the October earthquake events. (a) Overview of Tufo on 9 September 2016, (b) Overview of Tufo on 12 December 2016.

Figure 14. Incremental damage in Accumoli after the October earthquake events. (a) Overview of Accumoli, September 2016, (b) Overview of Accumoli December 2016.

Several hamlets in the Montegallo municipality suffered major additional damages, with the exception of Piano. This hamlet is characterized by an apparently high vulnerability (mainly old unreinforced masonry structures), but it is located at the base of a ridge. We speculate that deamplification of ground motion might have taken place, due to the topography of this area.

Norcia is a critically important village from a population and cultural standpoint in the affected region. Norcia was largely spared from significant damage following the 24 August event (Section 5.4.1 of GEER, 2016). We performed detailed inspections within Norcia at that time, but no aerial imagery. This good performance was attributed to effective repair and strengthening interventions that followed the 1979 Norcia and 1997 Umbria and Marche earthquakes. Unlike the earlier event, the October events produced a number of collapses that caused local authorities to declare a 'zona rossa' (red zone) with restricted access in Norcia. GEER team members were able to secure access and perform UAV overflights. We found the collapses occurred among practically all of the churches, including the church of San Benedetto da Norcia, which is a major monument. The level of retrofit in church structures remains under evaluation. Otherwise, damage levels in the red zone of Norcia were only slightly increased or unchanged, with the overwhelming majority of privately owned retrofitted structures not suffering major damage.

Table 2. Definition of damage categories (adapted from Bray and Stewart 2000)

Damage Level	Description	Marker Color
D0	No damage	
D1	Cracking of non-structural elements, such as dry walls, brick or stucco external cladding	
D2	Major damage to the non-structural elements, such as collapse of a whole masonry infill wall; minor damage to load bearing elements	
D3	Significant damage to load-bearing elements, but no collapse	
D4	Partial structural collapse (individual floor or portion of building)	
D5	Full collapse	

Surveys in new areas

The October earthquakes produced significant damage in areas to the north of the damage zone from the 24 August event. As a result, we undertook reconnaissance in villages and hamlets that had not previously been inspected by GEER researchers. Table 4 lists these locations and the approximate mean damage levels, and also marks locations with aerial surveys.

Table 3. Comparison of approximate mean damage levels evaluated after the 24 August event (GEER 2016) and the October events.

Village/hamlet	Damage level 24 August (GEER, 2016)	Damage level 26-30 October	Note	Aerial imagery
Amatrice (red zone)	D4-D5	D5	Controlled demolitions after September	Y
Pescara del Tronto	D4-D5	D5		Y
Arquata del Tronto	D4-D5	D5		N
Accumoli	D1-D2 / D3-D4	D4-D5	After 24 August, two different areas with different damage levels.	Y
Tufo	D2-D3	D4-D5		N
Castro	D3-D4	D4-D5		Y
Piano	D0-D1	D0-D1		N
Astorara	D0-D1	D4-D5		N
Colle	D2-D3	D4-D5		N
Balzo	-	D2-D3		N
Colleluce	D1-D2	D4-D5		N
Collefratte	D2-D3	D2-D3		N
Pistrino (lower part)	D2-D3	D3-D4		N
Pistrino (upper part)	D0-D1	D1-D2		N
Norcia	see text	see text		Y

Table 4. Summary of the damage levels observed after the October events.

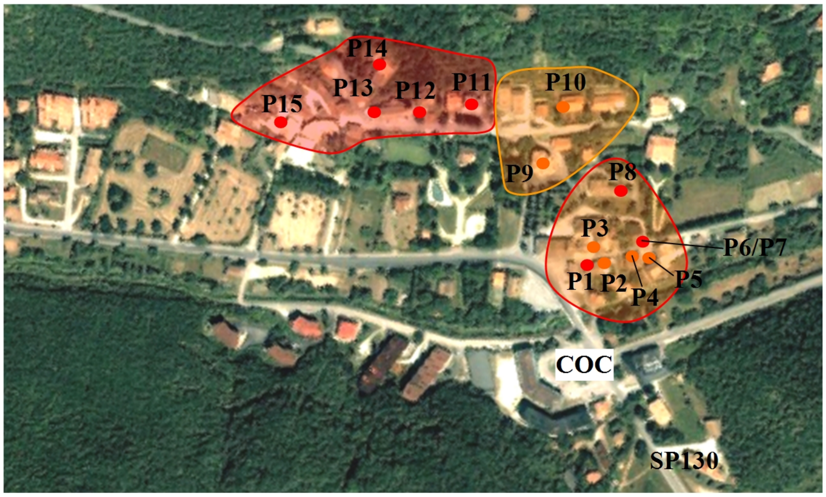
Village/hamlet	Damage level	Note	Aerial imagery
Visso	D3-D4		N
Ussita	D3-D4		Y
San Pellegrino	D4-D5		N
Popoli	D3		N
Tolentino	D1-D3		N
San Severino Marche	D0-D1 – D4-D5	Two different areas with different damage	N
Sellano	D1-D2		N
Colfiorito	D0-D1		N
Fiume	D2-D3		N
Casavecchia alta	D3-D4		N
Pieve Torina	D3-D4		N
Pievebovigliana	D3		N
Fontevena	D3-D4		N

Table 4 (cont.). Summary of the damage levels observed after the October events.

Village/hamlet	Damage level	Note	Aerial imagery
Pontechiusica	D0		N
Borgo Cerreto	D0-D1		N
Serravalle	D0-D1		N
Ancarano (pié del colle)	D2-D3		N
Preci	D0-D1	Damage assessment based on spot checks	N
Piedivalle	D0-D1	Damage assessment based on spot checks	N
Cessapalombo	D1-D2		N
Caldarola	D0-D1	Damage assessment based on spot checks	N
Camerino	D2	Including red zone	N
Castello di campi	D2-D3	Damage assessment based on spot checks	N

Visso and Ussita are the most proximate villages to epicenter of the 26 October event. In both villages, the majority of the structures are 2-3 story masonry buildings. The average damage level observed in both villages is D4-D5. Figure 15 shows damages in Piazza Martiri Vissani, located in the centre of Visso. Figure 16 shows the damage pattern and a damage zonation for Ussita. In both villages, historical buildings and monuments suffered heavy damage. Particularly in Ussita there are variations of structure ages and types; findings regarding relative performance by building type have not yet been developed.

Figure 15. Damages observed in Piazza Martiri Vissani (Visso).



D3/4: Heterogeneous area, which seems to be always characterized by high damages to non structural elements, often by damages to load bearing elements and in some cases, by local collapse.

D3: Overall, major damage to non structural elements and limited to significant damage to load bearing elements can be identified.

D4: Strip characterized by structures interested by huge damage to load bearing elements and local collapse.

Figure 16. Locations of representative structures inspected in Ussita, and damage zonation within the village.

Next Steps

We will provide a more detailed presenting of observations in a future report, especially in connection with surface rupture, landslides, and building performance. Our next report will also examine features of ground motions, and explore potential bias in the Amatrice recording that came to our attention following publication of the GEER (2016) report.

Acknowledgements

The work of the GEER Association, in general, is based upon work supported in part by the National Science Foundation through the Geotechnical Engineering Program under Grant No. CMMI-1266418. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF. The GEER Association is made possible by the vision and support of the NSF Geotechnical Engineering Program Directors: Dr. Richard Fragaszy and the late Dr. Cliff Astill. GEER members also donate their time, talent, and resources to collect time-sensitive field observations of the effects of extreme events.

Sponsorship of GEER activities was also provided by the B. John Garrick Institute for the Risk Sciences at UCLA and the NSF I/UCRC Center for Unmanned Aircraft Systems (C-UAS) at BYU under Project BYU13-03.

Sponsorship of the Italian Geotechnical Society was also provided. Support from the Department of Civil Protection (Engs. Paola Pagliara and Paola Bertuccioli) is also kindly acknowledged.

The technical support by Consortium ReLUIS (Network of Italian Laboratories of Earthquake Engineering), headquarted in the University of Naples Federico II, Italy, and the Department of Engineering of University of Sannio, Benevento, Italy, is also acknowledged.

We thank Matteo Francesco Stancato, master's student at Università della Calabria for his contribution to damage to building strutures data collection.

Politecnico di Torino (Italy) kindly provided the technical and financial support for his personnel involved in the reconnaissance.

Support for one team member was provided by EUcentre (European Centre for Training and Research in Earthquake Engineering; Pavia, Italy).

References

CERI working group (2017): S. Martino, P. Caporossi, M. Della Seta, C. Esposito, A. Fantini, M. Fiorucci, R. Iannucci, G.M. Marmoni, P. Mazzanti, S. Moretto, S. Rivellino, R.W. Romeo, P. Sarandrea, F. Troiani, C. Varone. Sisma Amatrice Effetti- Interazione rete infrastrutturale. Available at http://www.ceri.uniroma1.it/, last accessed 8 January, 2017.

Chiaraluce L., A. Amato, M. Cocco, C. Chiarabba, G. Selvaggi, M. Di Bona, D. Piccinini, A. Deschamps, L. Margheriti, F. Courboulex, M. Ripepe (2004). Complex Normal Faulting in the Apennines Thrust-and-Fold Belt: The 1997 Seismic Sequence in Central Italy. *Bulletin of the Seismological Society of America*, **94**(1), 99–116.

Galadini F., P. Galli (2000). Active tectonics in the Central Apennines (Italy) - Input data for seismic hazard Assessment. *Natural Hazards*, **22**, 225-270.

Galadini F., P. Galli, 2003. Paleoseismology of silent faults in the Central Apennines (Italy): the Mt. Vettore and Laga Mts. Faults. *Annals of Geophysics*, **46**(5), 815-836.

GdL 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 (in italian).

GdL INGV sul terremoto in centro Italia (2016). Summary report on the October 30, 2016 earthquake in central Italy Mw 6.5, DOI: 10.5281/zenodo.166238.

GEER (2016). Engineering reconnaissance of the 24 August 2016 Central Italy Earthquake: Ver 2, GEER Report 050, Geotechnical Extreme Events Reconnaissance Association, DOI: 10.18118/G61S3Z. (Ver 1 preliminary report DOI: 10.18118/G65K5W).

ISPRA (2016). Report attività svolta da ISPRA in data 25-26/08/2016, A (in Italian). Available at http://www.isprambiente.gov.it/files/notizie-ispra/notizie-2016/sisma-italiacentrale/ReportattivitsvoltadaISPRAindata26.pdf, last accessed 8 January, 2017.

Piatanesi A., A. Cirella (2009). Rupture Process of the 2009 Mw6.3 L'Aquila (Central Italy) Earthquake from Nonlinear Inversion of Strong Motion and GPS Data. Istituto Nazionale di Geofisica e Vulcanologia (INGV), Rome, Italy.

Tinti, E., L. Scognamiglio, A. Michelini, M. Cocco (2016). Slip heterogeneity and directivity of the ML 6.0, 2016, Amatrice earthquake estimated with rapid finite-fault inversion. *Geophysical Research Letters*, **43**(20), 10,745–10,752.