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# 1 Reconnaissance of 2016 Central Italy

## 2 Earthquake Sequence

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17       **Abstract:** The Central Italy earthquake sequence nominally began on 24 August  
18       2016 with a **M6.1** event on a normal fault that produced devastating effects in the  
19       town of Amatrice and several nearby villages and hamlets. A major international  
20       response was undertaken to record the effects of this disaster, including surface  
21       faulting, ground motions, landslides, and damage patterns to structures. This work  
22       targeted the development of high-value case histories useful to future research.  
23       Subsequent events in October 2016 exacerbated the damage in previously affected  
24       areas and caused damage to new areas in the north, particularly the relatively large  
25       town of Norcia. Additional reconnaissance after a **M6.5** event on 30 October 2016  
26       documented and mapped several large landslide features and increased damage  
27       states for structures in villages and hamlets throughout the region. This paper  
28       provides an overview of the reconnaissance activities undertaken to document and  
29       map these and other effects, and highlights valuable lessons learned regarding  
30       faulting and ground motions, engineering effects, and emergency response to this  
31       disaster.

32

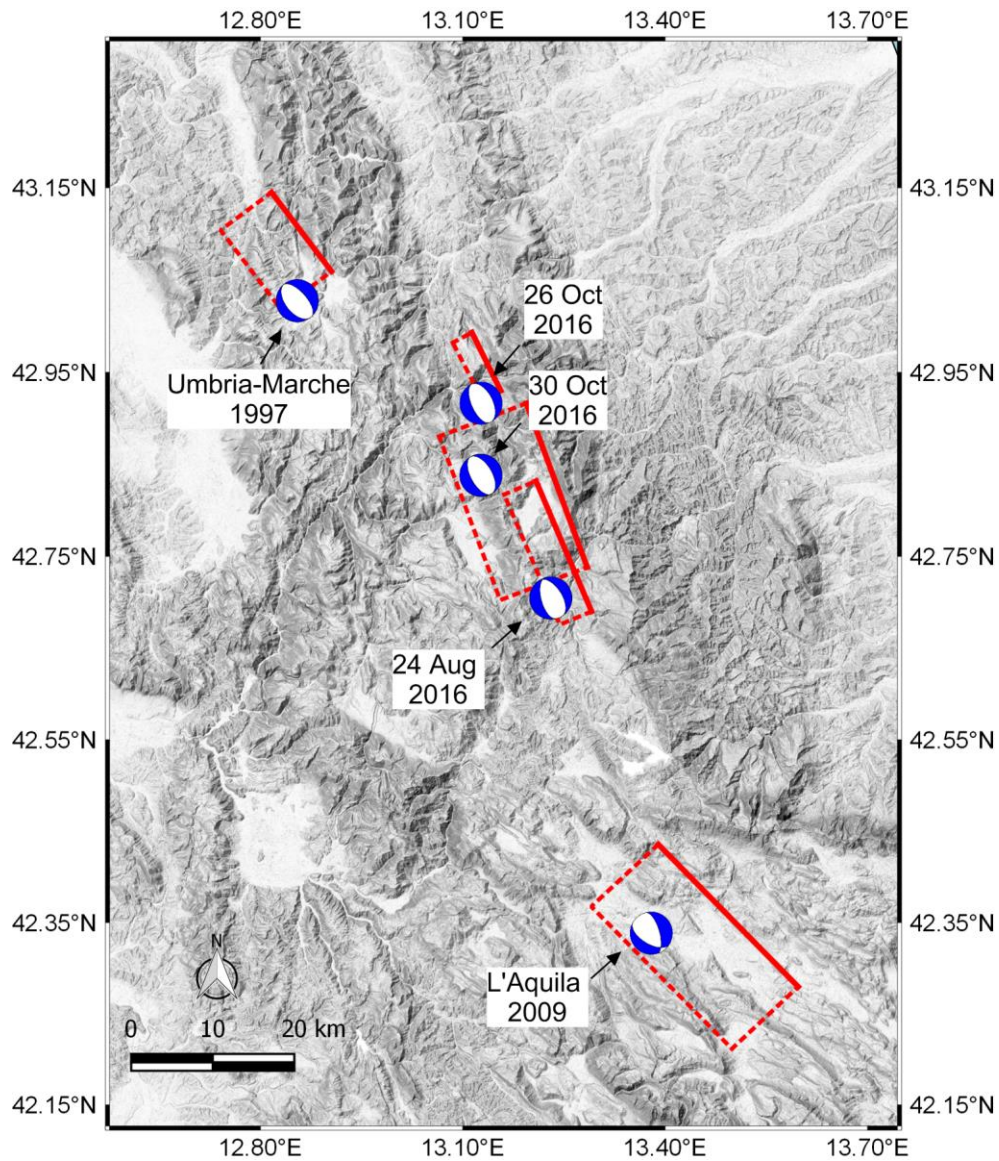
33

## INTRODUCTION

34       Between August and November 2016, three major earthquake events occurred in Central Italy.  
35       The first event (**M6.1**) occurred on 24 August 2016, the second (**M5.9**) on 26 October, and the  
36       third (**M6.5**) on 30 October 2016. Each event was followed by numerous aftershocks, some  
37       exceeding **M5**.

38       As shown in Figure 1, this earthquake sequence occurred in a gap between two earlier  
39       damaging events, the 1997 **M6.1** Umbria-Marche earthquake to the north-west and the 2009  
40       **M6.1** L'Aquila earthquake to the south-east. This gap had been previously recognized as a  
41       zone of elevated risk (GdL INGV sul terremoto di Amatrice, 2016). These events occurred  
42       along the spine of the Apennine Mountain range on normal faults and had rake angles ranging  
43       from -80 to -100 deg. Each of these events produced substantial damage to local towns and  
44       villages. The 24 August event caused heavy damage to the villages of Arquata del Tronto,  
45       Accumoli, Amatrice, and Pescara del Tronto. In total, there were 299 fatalities, generally from  
46       collapses of unreinforced masonry dwellings. The October events caused significant new  
47       damage in the villages of Visso, Ussita, and Norcia, and almost complete destruction of the  
48       villages of Arquata del Tronto, Accumoli, Amatrice, and Pescara del Tronto. The October

49 events did not produce fatalities, since the area had largely been evacuated and the tourist  
50 season had ended.



51

52 **Figure 1.** Map of central Italy showing moment tensors of major earthquakes since 1997 and the  
53 intermediate gap areas. Finite fault models for 1997 Umbria-Marche and 2009 L'Aquila are from  
54 Chiaraluce et al. (2004) and Piatanesi and Cirella (2009). Finite fault models for central Italy events are  
55 from Galadini et al. (201x, this issue).

56 As described in the next section, the post-event reconnaissance involved two teams  
57 working in a coordinated manner. The first and largest team, with whom most of the authors  
58 of this paper were associated, was organized under the auspices of the Geotechnical Extreme  
59 Events Reconnaissance (GEER) association, which is funded by the United States (US)  
60 National Science Foundation (NSF). We conducted major reconnaissance activities in  
61 collaboration with many partnering organizations in Italy and elsewhere, with a focus on the

62 scientific and engineering aspects of the events. The second team was organized by the  
63 Earthquake Engineering Research Institute (EERI), under the leadership of co-author S.  
64 Mazzoni, which worked with several Italian partnering organizations. The EERI team also  
65 documented structural damage, although their principal focus was emergency-response and  
66 medium and long-term recovery and reconstruction efforts, from a societal-resiliency  
67 perspective.

68 This paper describes the organization and objectives of the reconnaissance work and  
69 highlights some of the most significant findings, which are explained in more detail in other  
70 papers within this issue. Those papers have been prepared to document what we believe to be  
71 the most significant findings of the reconnaissance by the GEER and EERI teams. More  
72 information about the seismological and engineering aspects of the events are available in two  
73 detailed reports (GEER, 2016, 2017).

#### 74 **RECONNAISSANCE ACTIVITIES**

75 The NSF-funded Geotechnical Extreme Events Reconnaissance (GEER) association, with co-  
76 funding from the B. John Garrick Institute for the Risk Sciences at the University of California,  
77 Los Angeles and the NSF Industry–University Cooperative Research Centers Program (NSF  
78 IUCRC) Center for Unmanned Aircraft Systems (C-UAS) at Brigham Young University  
79 (BYU), mobilized the US-based team to the area in two main phases: (1) following the 24  
80 August event, from early September to early October 2016, and (2) following the October  
81 events, between the end of November and the beginning of December 2016. The US team  
82 worked in close collaboration with Italian researchers organized under the auspices of the  
83 Italian Geotechnical Society, the [Italian Center for Seismic Microzonation and its Applications](#),  
84 the Consortium of the Laboratories University Network of seismic engineering (ReLUIS),  
85 which is a Center of Competence of Department of Civil Protection, and the Disaster  
86 REcovery Team of Politecnico di Torino. The objective of our Italy-US GEER team was to  
87 collect and document perishable data. This work included the traditional GEER responsibilities  
88 for documenting geological, seismological, and geotechnical effects, as well as documenting  
89 the performance of buildings, bridges, and other structures.

90 The Italy-US GEER team was multi-disciplinary, with expertise in geology, seismology,  
91 geomatics, geotechnical engineering, and structural engineering. Our approach was to combine  
92 traditional reconnaissance activities of on-ground recording and mapping of field conditions

93 with advanced imaging and damage detection routines. The three-dimensional (3D) imaging  
94 was performed using UAVs (Unmanned Aerial Vehicles) and has produced three-dimensional  
95 models of landslide features, surface faulting, and structural damage patterns. Links to the 3D  
96 models resulting from this work are available at the [GEER](#) and [BYU-PRISM](#) web sites (both  
97 last accessed July 2017).

98 The Earthquake Engineering Research Institute (EERI) undertook additional  
99 reconnaissance of the events, in coordination with the GEER team and in collaboration with  
100 the European Centre for Training and Research in Earthquake Engineering (EUCENTRE) in  
101 Pavia and the ReLuis consortium. They visited the area in October 2016 and again in May  
102 2017. The EERI team focused on emergency response and recovery, in combination with  
103 documenting the effectiveness of public policies related to seismic retrofit. The EERI team  
104 visited numerous short and long-term temporary-housing sites, ranging from short-term  
105 temporary tent camps (Tendopoli) to locations where the ground was being prepared for long-  
106 term (5-10 yr) temporary homes, to long-term housing locations where people had been living  
107 for a month, to L'Aquila, where these residences had been in use for over 5 years.

108 Both the GEER and EERI reconnaissance teams required access to heavily damaged "Red  
109 Zones," which was facilitated by coordination on the part of EUCENTRE and ReLuis with the  
110 Italian government for the assessment of buildings and infrastructure. In particular, we worked  
111 closely with the Italian Department of Civil Protection to gain (in some cases escorted) access  
112 to these restricted areas. This level of coordination and cooperation was essential to the  
113 reconnaissance effort.

114

## **OVERVIEW OF MAJOR FINDINGS**

### **SEISMOLOGY AND ENGINEERING**

116 The initial objective of the GEER team was reconnaissance related to ground failures (surface  
117 fault rupture, landslides, other ground deformations), soil-structure interaction (e.g., retaining  
118 wall failures), and indicators of site response effects (such as localization of damage, often in  
119 a manner consistent with topographic features). However, for both the August and October  
120 events, our mission broadened to include documentation of structural performance for a variety  
121 of reasons including: (1) it supported our mission of evaluating damage patterns; (2) the  
122 structural performance data was indeed perishable, and as the principal reconnaissance team in  
123 many of the visited areas, we felt a duty to document the broader impacts of these events.

124 Papers in this issue present significant technical findings related to the seismological,  
125 geotechnical, and structural engineering aspects of these events. A few highlights, with  
126 references to the respective manuscripts, are as follows:

127 Earthquake probabilities: When a large earthquake occurs, there are two schools of thought  
128 regarding its effect on the risk of subsequent large events. One is that stress release lowers  
129 earthquake rates relative to the long-term (Poisson) rate until stresses can again build-up on the  
130 fault. Another is that stress release on one portion of the fault may increase stress on adjoining  
131 portions of the same fault segment or adjacent segments. This would tend to locally increase  
132 earthquake rates (and hence short-term probabilities) relative to the long-term rate. This subject  
133 is of substantial practical significance for regional risk assessment. As shown in Figure 1, the  
134 August 2016 and October 2016 events occupy a gap along the NW striking Apennine chain  
135 between the locations of the 1997 Umbria-Marche and 2009 L'Aquila events. The occurrence  
136 of this cluster of earthquakes suggest that latter (probability increasing) mechanism occurred  
137 and may continue into the future. This important topic is elaborated upon by Galadini et al.  
138 (201x).

139 Faults as seismic sources: The portions of the Apennines affected by the Central Italy  
140 events is undergoing extension accommodated by numerous normal faults, many of which are  
141 well expressed at the surface. Galadini et al. (201x) show that the mainshock events occurred  
142 on the Mt. Vettore fault and the Amatrice segment of the Laga Mountains fault. Both of these  
143 faults had been recognized prior to the 2016 event sequence, but were not considered in  
144 previous Italian national seismic hazard studies. A review of these and other faults suggests  
145 that while most are expected to rupture separately (not cross between faults in a single event),  
146 the Laga Mountains fault and Mt. Vettore fault are an exception, and in fact did rupture together  
147 in the 24 August 2016 mainshock. Galadini et al. (201x) encourage the use of seismic source  
148 models that utilize fault sources as a principal driver of hazard when those sources are well  
149 characterized, as is the case in the subject region of Italy.

150 Surface fault rupture: Gori et al. (201x) describe data on surface faulting from this event  
151 sequence and its association with prior geologic mapping. The **M**6.1 24 August event produced  
152 vertical offsets on the Mt. Vettore-Mt. Bove fault system that ranged from 0-35 cm over a 5  
153 km interval of the fault near its southern end. The **M**6.5 30 October event ruptured a 15 km-  
154 long section of the fault, with vertical offsets typically ranging between 70 and 200 cm. Data

155 compiled for the three mainshocks (24 August, 26 and 30 October) will be a valuable resource  
156 for modeling of surface rupture characteristics of normal fault earthquakes.

157 Ground motions: Zimmaro et al. (2018) describe the ground motion database developed  
158 from recordings of these events. Those ground motions significantly extend the world-wide  
159 inventory of normal fault recordings in tectonically active regions. Zimmaro et al. (2018)  
160 describe important near-fault aspects of the ground motions and provide maps showing spatial  
161 variations of ground motion from mainshock events. They also demonstrate that the data  
162 exhibits fast anelastic attenuation at large distances (>100 km), which is predicted by Italy-  
163 adjusted global models, but not by Italy-specific models.

164 Landslides: Franke et al. (2018) describe how landslide effects were relatively modest in  
165 the August 2016 events, but were appreciable from the October events. They undertook a  
166 phased reconnaissance that combined traditional (i.e. existing landslide maps and manual  
167 inspection and measurement) and innovative (i.e. satellite imagery, interferometry, and  
168 unmanned aerial vehicles (UAVs) images) approaches. The geometry of the landslide source  
169 zones, as well as depositional areas, are well-documented with 3D models from UAVs. Franke  
170 et al. (2018) show that such models can be used to evaluate landslide ground movements in  
171 complex topographic geometries and boulder runout distances from rock falls. The geology of  
172 these areas is also documented, although subsurface characterization data is currently  
173 unavailable. Two aspects of these case histories of interest to future work include: (1) the  
174 occurrence of landslides in some events but not others (predictive models should be able to  
175 forecast both) and (2) the landslide fall/runout distances.

176 Masonry structure fragility: Sextos et al. (2018) describe reconnaissance to document  
177 damage and non-damage to building structures in numerous villages and hamlets affected by  
178 the event sequence. Through both fieldwork and interpretation of 3D imagery, they document  
179 structural performance according to a common classification scheme at high resolution – in  
180 many cases a full inventory of performance of every structure within a hamlet or village (or  
181 portions thereof) was developed. Moreover, the damage mapping is multi-epoch, meaning that  
182 the performance of the same structures was recorded following the August 2016 events and the  
183 October 2016 events. Detailed multi-epoch structure-by-structure damage mapping and  
184 statistics are shown for many towns in the epicentral area including Amatrice, Norcia, and  
185 Accumoli. We anticipate that some empirical structural fragility models (e.g., Sabetta et al.,



186 1998; Rossetto and Elnashai, 2003; Rota et al., 2008) will be re-evaluated in consideration of  
187 the data from these events.

188 Site effects: Sextos et al. (2018) associate damage distributions within selected villages and  
189 hamlets with geological and topographic conditions. They describe horizontal-to-vertical  
190 spectral ratios (HVSr) from microtremor measurements and their azimuthal dependence,  
191 which were taken in selected areas with pronounced topographic relief and concentrated  
192 damage. These results reveal apparent site amplification polarized in the direction normal to  
193 the slope, which may have been responsible for some damage concentrations. A representative  
194 detailed example of this approach is presented for the small hamlet of Fiume. These findings  
195 will guide the selection of sites to be investigated with specific numerical ground response  
196 analyses for seismic microzonation.

197 Retrofit effectiveness: Mazzoni et al. (2018) describe the history of seismic design and  
198 retrofit of building structures in the area, and how similarly sized towns of Amatrice and Norcia  
199 had vastly different levels of preparation for these events and different levels of structural  
200 performance. They describe how the historical center of Amatrice, which largely lacked retrofit  
201 measures, was damaged extensively by the August event. Destruction in Amatrice was almost-  
202 complete following the 30 October event. In contrast, the historical center of Norcia, for which  
203 retrofit programs had been implemented, did not experience significant damage from the  
204 August event, and even following stronger shaking in the 30 October event, the damage was  
205 largely limited to one collapsed church and distress to several historical buildings. Mazzoni et  
206 al. (201xa) describe several individual case studies that illustrate the effectiveness of retrofit  
207 measures that were tested across multiple events.

208 Bridge performance: Durante et al. (201x) describe the characteristics of bridges in the  
209 strongly shaken regions, including traditional masonry construction and relatively modern  
210 reinforced concrete and steel structures. They show that failures were confined to masonry  
211 structures and illustrate the modes of deformation that were observed, typically in abutments.

212

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