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1 Reconnaissance of 2016 Central Italy

2 Earthquake Sequence

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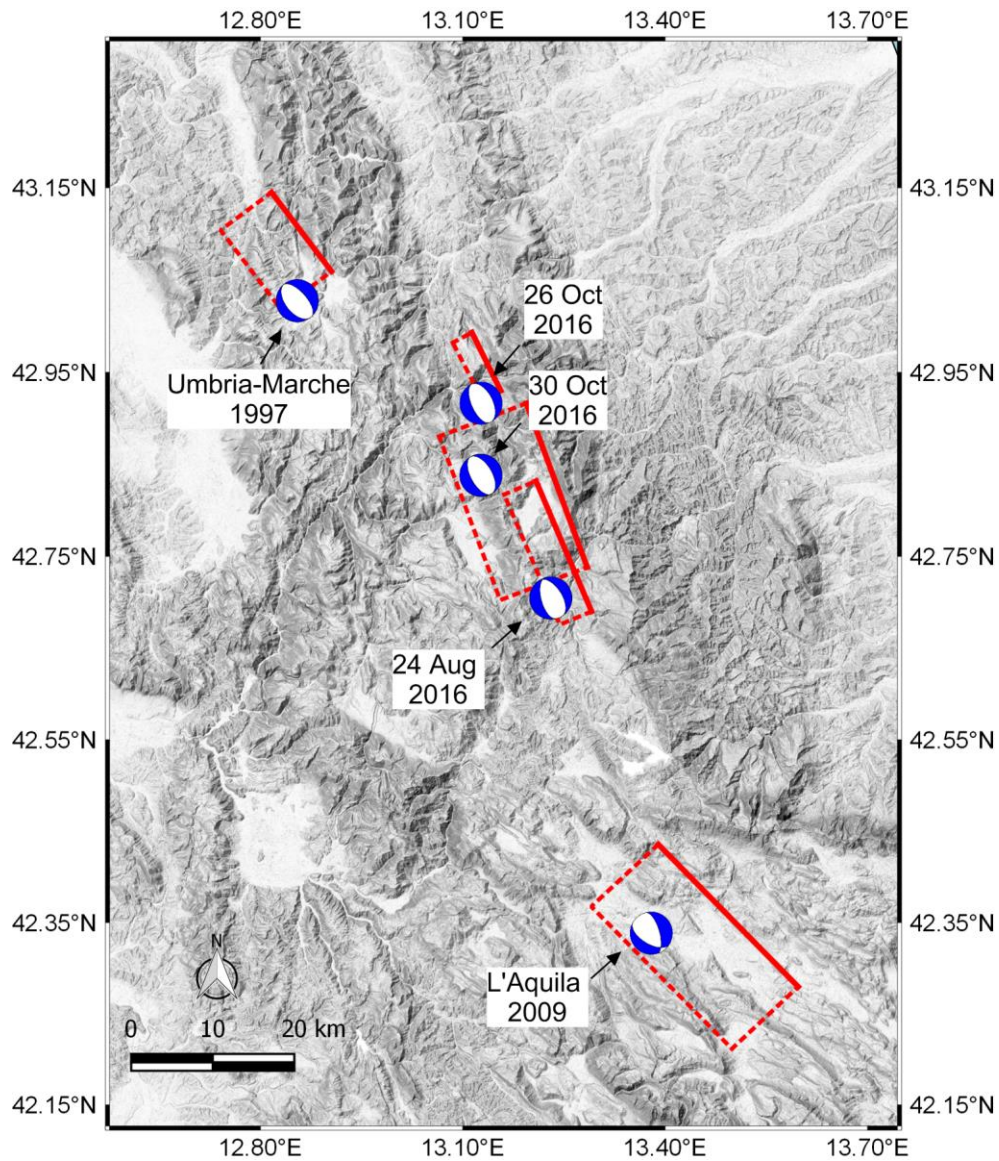
17 **Abstract:** The Central Italy earthquake sequence nominally began on 24 August
18 2016 with a **M6.1** event on a normal fault that produced devastating effects in the
19 town of Amatrice and several nearby villages and hamlets. A major international
20 response was undertaken to record the effects 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 (ReLUIIS),
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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