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The forgotten vulnerability: A geology- and history-based approach for ranking the seismic risk of earthquake-prone communities of the Italian Apennines

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ABSTRACT

The 2016–2017 Central Italy earthquakes have shown that the local seismic risk is dominated by the extreme vulnerability of the building stock. We attempt to rank the vulnerability of Apennines' settlements based on a combined geological-historical approach. We first discuss the reasons of the apparent paradox caused by the very different seismic response of Amatrice and Norcia, both strongly hit by the 24 August 2016 earthquake (M_w 6.0). Based on the awareness that strong earthquakes force building reconstructions and changes in the individual and societal perception of seismic risk, we assume that the global vulnerability of Italian settlements increases with time since the last significant earthquake. We focus on the very active seismogenic areas straddling Italy's Apennines. We then use data on the local seismogenic sources and earthquake history to (1) select the municipalities that are more likely to suffer from destructive ground shaking, and (2) rank them as a function of the time elapsed since the latest earthquake, i.e. in terms of increasing vulnerability. We hence identified 716 municipalities, totaling about 5% of the Italian population, over 50% of which have not experienced destructive shaking since 1861, when the Kingdom of Italy reunited a number of smaller states. As such they are primary candidates to a poor performance in future significant earthquakes ($M_w > 5.5$) and should be given priority in any statewide vulnerability reduction plan. All results and elaborations, including the seismic histories of each of the selected localities, are also supplied in a specifically designed web-GIS.

1. The 2016 Central Italy earthquake sequence

For over two millennia the Italian Apennines have been known for their large earthquake potential. An extraordinary large number of scholars have left accounts on Apennines earthquakes, to the point that the very word “Seismology” is credited to Robert Mallet, an Irish civil engineer, after his long visit to Val d’Agri, a region of southern Italy struck by a M≈7.0 earthquake on 16 December 1857 [32]. The earthquake potential of this youthful mountain chain is well portrayed in the official seismic hazard map of Italy [34,38], where the Apennines seismogenic zone is shown as the largest hazard portion of the entire country. Hence, the M_w 6.0 earthquake that on 24 August 2016 shattered a sparsely inhabited area of the Central Apennines at the crossroad of the Abruzzo, Lazio, Marche and Umbria administrative regions (see Fig. 1 and Table 1) was all but unexpected.

The earthquake took 299 lives and caused extensive damage in a 20 × 40 km region elongated parallel to the axis of the mountain chain. In particular, it destroyed the majority of buildings in Amatrice, a quiet mountain village that in summer increases the number of its residents nearly tenfold. In marked contrast, Norcia, a small ancient town dating back to pre-Roman times and located a mere 25 km to the NW, was rather mildly affected. Preliminary engineering analyses [15,30] have shown that in terms of PGA, PGV (Peak Ground Acceleration, Peak Ground Velocity) and frequency contents the ground motion was only slightly stronger in Amatrice than in Norcia (Table 2). According to Lanzano et al. [30] and Pischiutta et al. [35], the rupture exhibits along-strike directivity towards the NW, i.e. towards Norcia. Despite its limited size, however, the source of this earthquake has been shown to comprise two well-separated slip patches [41]; the southernmost patch exhibits a strong up-dip directivity, thus justifying a short but strong acceleration pulse toward Amatrice. This finding is supported also by [9]. Whatever the case, no sizable directivity effect can be invoked to

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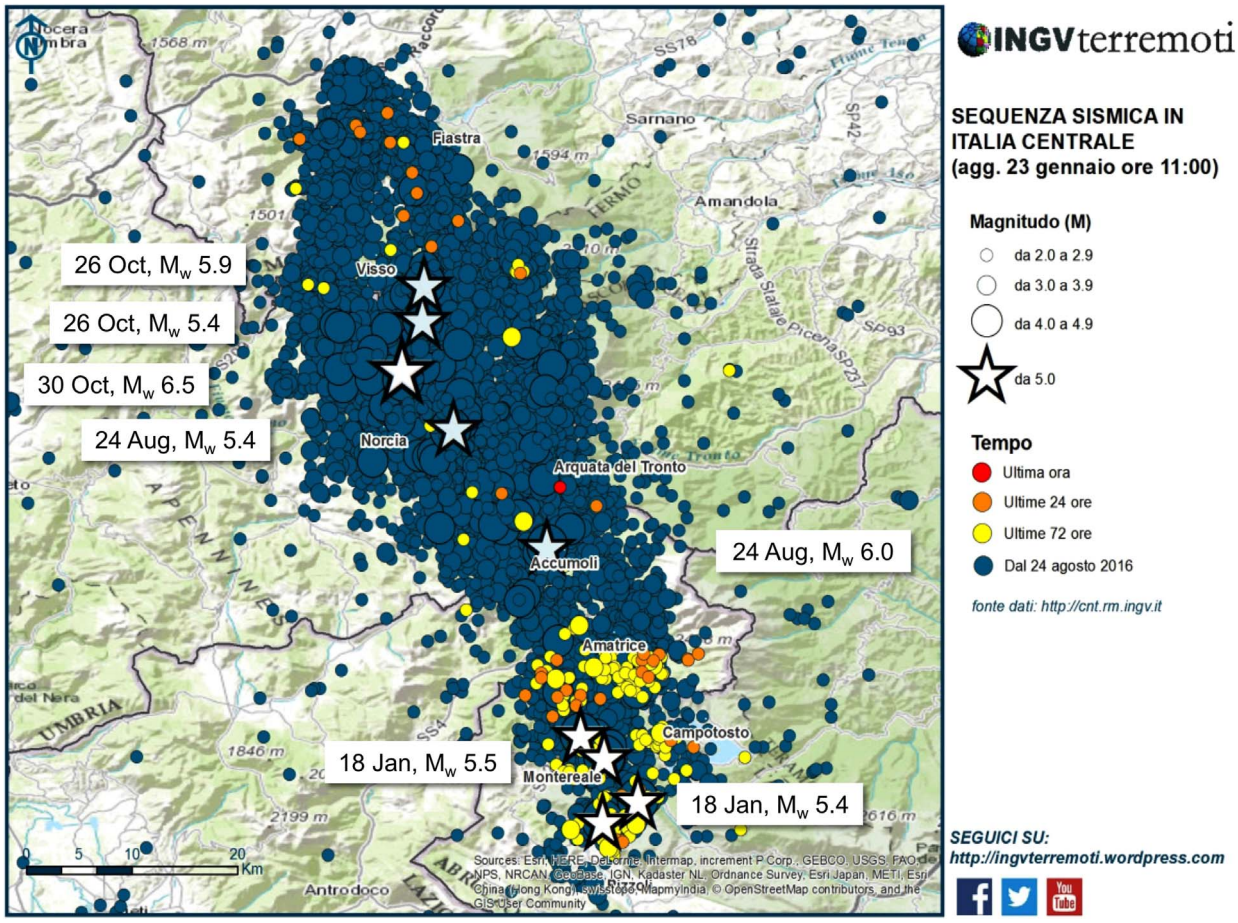

Fig. 1. Evolution of the 2016–2017 earthquake sequence as of 23 January 2017 (see also Table 1), showing the location of all mainshocks of M_w 5.4 and larger. All in all, the sequence affected an area that extends for about 80 km, straddling the axis of the Central Apennines and encompassing four administrative regions (Abruzzo, Lazio, Marche, Umbria).

justify major differences in the earthquake response of these two localities: yet Amatrice was assigned an intensity X–XI – a cumulative effect of the mainshock and of the largest aftershocks – while Norcia did not exceed intensity VI [6,20]: unless otherwise noted, all intensities are supplied according to the Mercalli-Cancani-Sieberg [MCS] scale). See also Zimmaro et al. [44] for a comprehensive summary of the earthquake effects.

On 26 October a M_w 5.9 shock hit a region northwest of the area struck by the August quake, causing extensive damage in many municipalities of the southern Marche region, and on 30 October a M_w 6.5 struck the region in between the epicentral areas of the two previous shocks (Fig. 1). The epicenter of the latter and largest shock falls very close to Norcia, and its epicentral area encompasses many of the localities already shattered by the first two largest shocks and by a vigorous aftershock sequence. Unsurprisingly, the sequence continued into 2017 (Fig. 1): on 18 January two further shocks of M_w 5.5 and 5.4 hit the region of Montereale-Campotosto, about 10 km southeast of Amatrice, raising concerns that additional ruptures could take place further to the southeast, towards and into the area hit by the 6 April 2009, L'Aquila event (M_w 6.3).

The 24 August shock was not preceded by foreshocks, which are rather common in Central Apennines earthquakes sequences [4]; nevertheless, the global complexity of the 2016–2017 sequence is reminiscent of other earthquake sequences that have struck this portion of the Italian peninsula [26].

The 30 October shock was the largest earthquake to have occurred in Italy since the catastrophic 23 November 1980, M_w 6.9, Campania-Basilicata earthquake (southern Italy), which claimed over 2900 victims. In contrast, no people were killed in the 26 and 30 October shocks, largely due to the limited number of residents still living in their homes by then, but almost all localities suffered additional damage with respect to the effects of the 24 August shock. Amatrice was reported

Table 1
Summary of parameters of the seven largest shock of the earthquake sequence (M_w 5.4 and larger: all data from [27]).

Earthquake date	Origin time (UTC)	M_w	Epicentral area/ Municipality (Region)	Hypocentral Depth (km)	Lat N (°)	Lon E (°)
24 August 2016	01:36:32	6.0	Accumoli (L)	8.0	42.70	13.23
24 August 2016	02:33:28	5.4	Norcia (U)	7.5	42.79	13.15
26 October 2016	17:10:36	5.4	Visso (M)	8.7	42.88	13.13
26 October 2016	19:18:05	5.9	Visso (M)	8.0	42.91	13.13
30 October 2016	06:40:17	6.5	Norcia (U)	9.0	42.83	13.11
18 January 2017	10:14:09	5.5	Montereale (A)	10.0	42.53	13.28
18 January 2017	10:25:23	5.4	Montereale (A)	9.0	42.49	13.31

The complete sequence includes a large number of strong aftershocks (at least 65 earthquakes in the M_w range 4.0–5.3 have been reported to date). Administrative regions: A – Abruzzo; L – Latium; M – Marche; U – Umbria.