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Seismic quiescence preceding the 2016 central Italy earthquakes

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ABSTRACT

A complex multiple mainshocks sequence (24/08/2016, Mw 6.0; 26/10/2016, Mw 5.4 and 5.9; 30/10/2016, Mw 6.5) occurred in central Italy, causing the death of nearly 300 people and widespread destruction of entire villages. The Region-Time-Length (RTL) method is used to analyze the seismicity preceding the first Mw 6.0 Amatrice mainshock. This analysis is performed using the earthquake catalogue maintained by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) after a preprocessing, which includes the declustering of aftershocks. A well-evident quiescence that preceded the sequence was detected. The quiescence extended throughout a broad region north of the epicenter. The largest event of the sequence and the aftershocks covered most of the quiescence region, except for a small area to the west. The quiescence started from the beginning of September 2015 and lasted for approximately 1 year up to the Amatrice mainshock.

1. Introduction

The devastating 2016 central Italy seismic sequence was the most powerful recorded since the 1980 M 6.9 Irpinia earthquake. It extended along a sector of the Central Apennines, within a seismic gap lying between the epicenters of the 1997–1998 Mw 6.0 Umbria-Marche seismic sequence to the northwest and the 2009 L'Aquila sequence to the southeast (Fig. 1).

This sequence began on August 24 with the so-called Amatrice earthquake (Mw 6.0), destroying the town of Amatrice and several localities in a wide area (Azzaro et al., 2016) and causing the death of nearly 300 people. The Amatrice earthquake was followed within an hour by a Mw 5.4 earthquake located approximately 12 km to the NW. Intense earthquake activity, with damaging events, spread progressively over a large area ~40 km long and ~15 km wide along a NNW-SSE trending proximal to the main faults (Fig. 1). By the end of April 2017, over 65,000 earthquakes were recorded in the area by the National Seismic Network (RSN, INGV; http://iside.rm.ingv.it). Two major events occurred on October 26 within 2 h, having a magnitude Mw 5.4 and Mw 5.9, located at the northern front of the aftershock sequence, approximately 30 km northwest of the August 24 earthquake. After 4 days, on October 30, the largest earthquake of the sequence, Mw 6.5, occurred close to the town of Norcia, between the epicenters of the 24 August and 26 October major earthquakes. The complexity of the sequence is also manifested in source parameters: the two most destructive shocks had opposite predominant directions of rupture propagation—toward the NNW during the Mw 6.0 Amatrice earthquake and toward the SSE during the Mw 6.5 Norcia earthquake (Calderoni et al., 2017). The sequence extend across at least three main faults, including the Sibillini Thrust (Centamore and Rossi, 2009) that separates the Umbria-Marche and the Latium-Abruzzi domains. The Apennines chain, where the sequence occurred, is the result of three different simultaneous processes: the opening of the Tyrrhenian Sea, the retreat of the lithosphere dipping beneath the Italian peninsula, and the eastward migration of the contractional front along the northeastern border of the chain (Malinverno and Ryan, 1986; Doglioni, 1991; Doglioni, 1995). Currently, the Apennines are characterized by a Northeast-Southwest striking extension (Devoti et al., 2011; Carafa and Bird, 2016). Moment tensor solutions of the 2016–2017 earthquakes indicate prevailing normal-faulting mechanisms (http://cnt.rm.ingv.it/tdmt/ and http://www.eas.slu.edu/eqc/eqc_mt/MECH.IT/), in good agreement with the seismotectonic setting of the area.

Many studies have attempted to investigate seismicity changes before large earthquakes and to explain their occurrence in terms of physical processes. The scientific literature provides an in-depth discussion of the seismicity changes before a large earthquake, such as seismic quiescence, foreshock activation and clustering. In this study, we applied the RTL (Region Time Length) statistical method proposed by Sobolev and Tyupkin (1996) to investigate the seismic quiescence occurring before the 2016 Amatrice earthquake. The RTL method analyzes declustered

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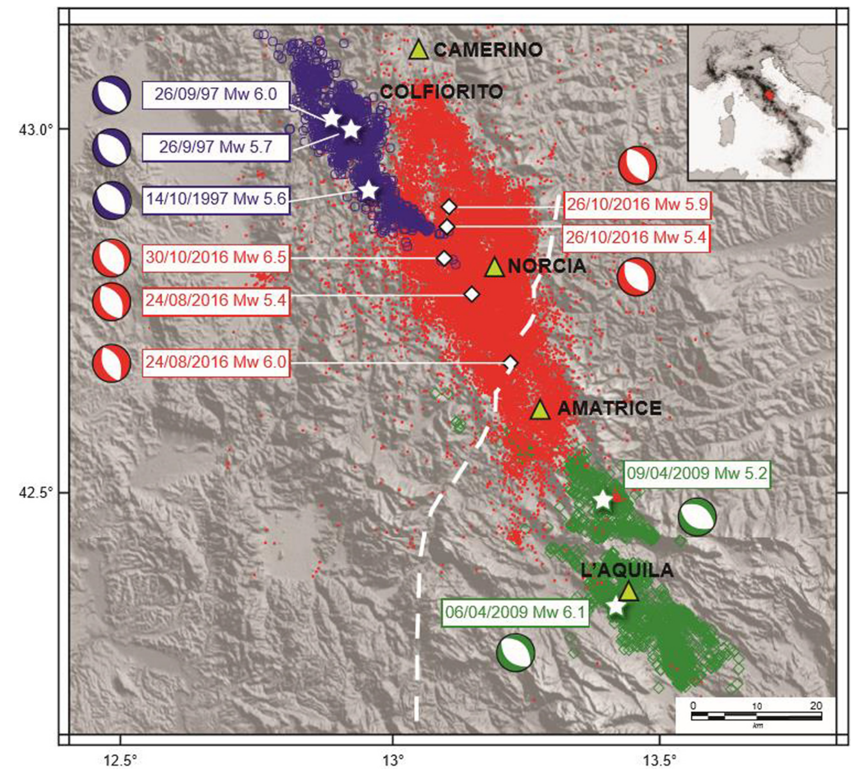

Fig. 1. Map of the relevant seismic sequences that affected the study area in the last few decades. The red dots represent the epicenters of the 2016–2017 central Italy sequence. The white diamonds indicate the strongest events of the sequence. The white stars indicate the epicenters of the strongest earthquakes of the 1997 Umbria-Marche (blue dots) and 2009 L'Aquila-Campotosto (green dots) seismic sequences. The beach balls are fault plane solutions of the strongest shocks. The dashed white line is the surface trace of the Sibillini Mts. thrust. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

catalogues and is sensitive to anomalies in background seismicity, which may precede a large seismic event. Our analysis therefore aims to identify a precursor of the whole sequence, also in terms of spatial extension, and does not target the individual mainshocks composing it.

Several studies in Italy using RTL (Di Giovambattista and Tyupkin, 2000; Gentili and Bressan, 2007; Gentili, 2010) Z (Wyss et al., 1997; Console et al., 2000) and beta statistics (Bragato, 2014) have shown a decreased seismicity before strong events in Italy. While methods like beta-statistics and Z have been applied only to the number of earthquakes over a given magnitude threshold, giving the same weight to earthquakes of different magnitude, the advantage of RTL is that it depends also on the energy of the earthquakes and is therefore more influenced by stronger earthquakes than by smaller ones.

2. Data and declustering

The study is principally based on the earthquake catalog (ISIDE, 2017) compiled at the Istituto Nazionale di Geofisica e Vulcanologia (INGV), using data downloaded on March 5, 2017. The completeness level of the ISIDE catalog in central Italy has been evaluated as $M_c = 2.2$, and weaker earthquakes are not involved in the analysis. The RTL method is applied to declustered earthquake catalogs. Declustering, however, is especially problematic in the Apennines, where different earthquake clusters occur very close in space and time and have a typically elongated distribution of epicenters (Fig. 1), which makes classical windowing methods crude approximations. Therefore, in this study, earthquake clusters are identified applying a novel statistical approach, which is based on the "nearest-neighbor" distances η between pairs of earthquakes in the space-time-energy domain (Baiesi and Paczuski, 2004). The distance η_{ij} between any earthquake j to an earlier earthquake i is defined as:

$$\eta_{ij} = \begin{cases} t_{ij} r_{ij}^{d} 10^{-bm_i}, & t_{ij} > 0 \\ \infty, & t_{ij} \leqslant 0 \end{cases} \quad (1)$$

where $t_{ij} = t_j - t_i$ is the inter-occurrence time; r_{ij} is the epicentral distance between the two earthquakes; d corresponds to the fractal dimension of epicenters and b is the slope parameter of the Gutenberg-Richter law in the study area. The nearest-neighbor distance η_{ij} can be equivalently decomposed into the corresponding *rescaled space* (R_{ij}) and *rescaled time* (T_{ij}) distances between the parent and its offspring event (Zaliapin et al., 2008), where space and time distances are rescaled depending on the magnitude of the parent event:

$$T_{ij} = t_{ij} 10^{-bm_i/2}, \quad R_{ij} = r_{ij}^{d} 10^{-bm_i/2} \quad (2)$$

It has been demonstrated by Zaliapin et al. (2008) that the 1D empirical distribution of the nearest-neighbor distances η and the 2D density map of its components (R, T), which are obtained from models of Poissonian seismicity and individual clusters, are both unimodal, although the cluster distribution is centered around much shorter space-time distances. On the other side, the distributions that are obtained from real seismicity and from models of clustered seismicity (including Epidemic Type Aftershock System, ETAS model – Ogata, 1998), are prominently bimodal because of the different location of the distributions of distances η, R and T associated with background and clustered activity (Fig. 2). This bimodality can be used to separate earthquakes into Poissonian background seismicity and cluster populations (Zaliapin and Ben-Zion, 2013). Specifically, clusters are formed by earthquakes that are sufficiently close in the space-time-energy