

Temporal characteristics of the fore-aftershock sequences of the 1999 Mw7.5 Turkey earthquake

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Abstract

Strong earthquake with moment magnitude MW7.5 hit the city of İzmit, Turkey with devastating effect in August 1999. The earthquake occurred in the North Anatolian Fault (NAF), and was followed by an intensive aftershock activity. It is assumed that the studied earthquake is a part of a seismic sequence that started in 1939 along the North Anatolian Fault. Over a period of 60 years or more, a series of large earthquakes moved progressively from east to west by the fault. The analysis of the space-temporal pattern of seismic clusters (foreshocks and aftershocks) distribution of the 1999 Turkey earthquake, is presented in the research. The properties of aftershock sequence (distinct cluster in space and time) allow for a time-dependent prediction of aftershock probabilities. Aftershock activity can sometimes cause more destruction than the main earthquake, due to factors such as radiation pattern, location and the cumulative nature of building damage. If the distribution of aftershocks over time is considered as a non-stationary Poisson process, the maximum likelihood method is used to estimate the parameters of the modified formula of Omori - power-law decay. A transformation from the time scale t to a frequency-linearized time scale τ is applied to test the correspondence between different statistical models and the occurrence of an aftershock sequence. As a final step of the study, a criterion - Akaike's information criterion is used to determine the best model for the temporal distribution of aftershocks.

The results of the study show that the precursor aseismic gap before the August 1999 MW7.5, Turkey earthquake is not observed. The aftershock sequence shows a complex temporal pattern - one secondary aftershock sequence with a different value of p - parameter.

Key words: Foreshocks, aftershocks, temporal distribution, 1999 Turkey MW7.5 earthquake, North Anatolian Fault



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Introduction

The Eastern Mediterranean region is characterized by a complex arrangement of tectonic structures. In the Eastern Mediterranean, active geodynamic processes are basically influenced by three large plates: African, Arabian and Eurasian. A number of subsidiary continental microplates (e.g., Adriatic, Aegean and Anatolian) have resulted from the collision process, complicating the general setting and its interpretation (among others in Reilinger and McClusky 2011).

The direction and movement of the plates related to the formation of major active fault lines in Turkey is presented in Fig.1.

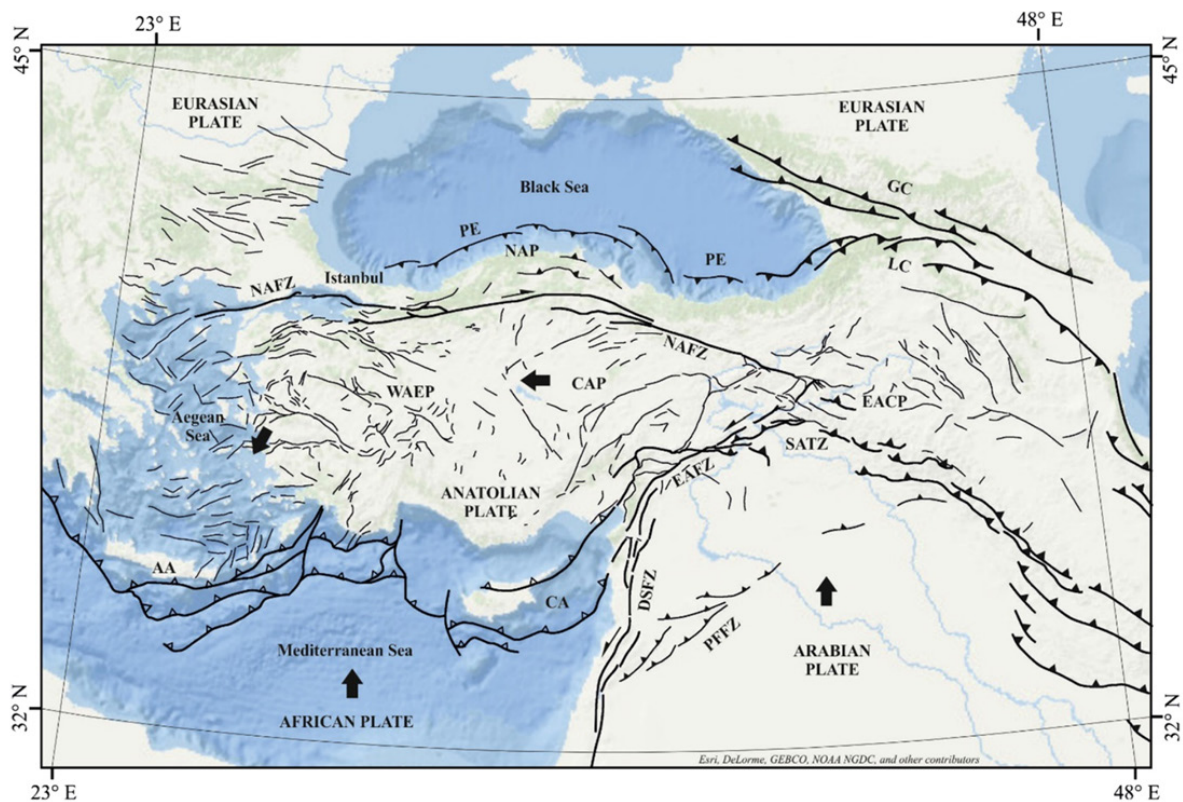


Figure 1. The map of tectonic plates and major active faults for the territory of Turkey, illustrating the North Anatolian Fault Zone among others (Source: Duman et al. 2018)

The tectonic position of the Anatolian Plate where Turkey is located is characterised by active neotectonics movement and a long history of devastating earthquakes. The westward movement of the Anatolian Plate results from: differences in the rates of motion between the Arabian and African plates, different directions of motion between the Anatolian block and Eurasian plate to the north, and also subduction of the African plate beneath the Anatolian block. The westerly motion of Anatolia with respect to Eurasia and Africa caused a great change in the tectonic evolution of the eastern Mediterranean, giving rise to the Aegean extensional regime and to internal deformation of Anatolia.

The North Anatolian Fault (NAF) is an active right-lateral strike-slip fault which extends for about 1200 km in northern Anatolia. The fault is the transform boundary between the Eurasian plate and the Anatolian sub-plate and takes up the relative motion between the Black Sea and the Anatolian plate (Sengör 1979).

The North Anatolian Fault Zone (NAFZ) was first described in the late 1940s (Ketin 1948) and it is now one of the best-studied strike-slip fault zones on Earth. The (NAFZ) is a region of high seismicity. It is one of the seismically most active dextral fault systems in the world. Historical earthquake studies have shown that major earthquake sequences associated with faulting have occurred in the past. The largest event related to the North Anatolian Fault Zone was the 17 August 1668 earthquake “This was stronger than any previous earthquakes there and affecting a large part of northern Anatolia...

The earthquake was strong enough to be felt in Istanbul ...In Ankara ...the ground opened up and many houses, which had already been damaged by foreshocks, were ruined” (Ambraseys 2009).

Several cycle-like earthquake sequences with magnitudes greater than 7 ($M > 7$) have occurred along the NAFZ over the past centuries. The best studied and known to the community is the migrating series that began in 1939. The series consists of several strong earthquakes that occur in an east-to-west direction along the fault zone, over a period of 60 years. The Izmit ($M_w 7.4$) and Düzce ($M_w 7.1$) Turkey events of 1999 are the last earthquakes from westward-migrating seismic activity to date, along the NAF (e.g. Barka 2002; Reilinger et al. 2011; Bohnhof et al. 2016).

As a first approximation, the seismic activity can be modeled as a Poisson process if dominant non-random elements such as the temporal clustering of fore-aftershocks are removed. (Gardner and Knopoff 1974).

Foreshocks are one of the few well-recognized precursors of the strong earthquakes. This type of sequence can be recorded within a few hours, several months or sometimes a year before the main shock (among others Papadopoulos et al. 2000). Therefore, understanding foreshock nature is of fundamental importance for earthquake prediction.

Aftershocks are identified as an activity above the background seismicity following a main shock (Liu and Stein 2011). Aftershock activity is obtained after the main event and their frequency decays over time, and is well represented by the Omori’s law, which in 1961 is remodeled by Utsu (1961) and is noted as modified Omori’s law. The power-law decay presented by the Omori relation is an example of time self-similarity of the earthquake source process.

In our research, statistical analysis is applied to explore the time pattern of cluster seismicity - the foreshock and aftershock sequences of the 17 August 1999 $M_w 7.5$ ($M_d = 6.7$) Turkey earthquake. The maximum likelihood method is proposed to estimate the parameters of the modified Omori formula for the aftershock sequence. The accuracy of statistical models has then been tested using a transformation from the time scale t to a frequency-linearized time scale τ . Finally, the best statistical model for aftershock occurrence is selected using the Akaike Information Criterion – AIC (Akaike 1974).

Methods

For frequency of aftershock per time interval, we propose the model following the modified Omori’s law, described by Utsu in 1969. The law empirically defines the frequency of aftershock sequence in time:

$$n(t) = K (t + c)^{-p} \quad (1)$$

where $n(t)$ is frequency of aftershocks at time t , t is the time passed after the realization of the main shock, and K , p , c are constants.

Among these three parameters, p -value is the most important and defines the mode of aftershock decay as a function of time. Aftershock decay rate contains information about the mechanisms of stress relaxation and frictional strength heterogeneity (Mikumo and Miyatake 1979). The variability of the parameter p value is related to the structural heterogeneity, stress and temperature in the crust

(e.g. Kisslinger and Jones 1991) and associated with the tectonics of the region, fault heterogeneity and stress (e.g., Utsu et al. 1995).

The maximum likelihood estimates for parameters of the modified Omori formula are used for the non-stationary Poisson point process, which is completely described by an intensity function $\lambda(t)$:

$$\lambda(t) = \lim_{\Delta t \rightarrow 0} \text{Pr ob} \{ \text{an event in } [t, t + \Delta t] \} / \Delta \quad (2)$$

Representing the modified Omori formula, the intensity function becomes:

$$\lambda(t) = K(t + c)^{-p} \quad (3)$$

The transformation from the time scale t to a frequency-linearized time scale τ is described by an integration of the intensity function $\lambda(t)$ (Ogata and Shimazaki 1984). If the selection of the intensity function $\lambda(t)$ (i.e., the parameters K , c and p) is accurate, the frequencies of aftershocks turn into the standard stationary Poisson process on this time axis.

The frequency-linearized time for an aftershock sequence is described by the equation:

$$\tau = A(t) = \int_0^t \lambda(s) ds \quad (4)$$

For examination of fits between selected model and occurrence of aftershocks, the time scale τ is used. If a proper model has been selected, a linear relation between the observed cumulative number of aftershocks N and τ should be observed. Variances in the aftershock activity are more obvious on the $N(\tau)$ plot than on $n(t)$ and the τ time axis can be used to discover secondary aftershock activity.

For the selection of the model which fits better the observations, the AIC is useful (Akaike 1974).

The AIC is defined by:

$$\text{AIC} = (-2) \text{Max} (\ln - \text{likelihood}) + 2 (\text{Number of the used parameters}) \quad (5)$$

The preferred model is the one with the minimum AIC.

Input Data

A data sample of 2898 earthquakes, with duration magnitude $M_d \geq 2.0$ located in the activated segments of the North Anatolian Fault Zone (NAFZ) from 17.08.1998 to 17.08.2004 is compiled on the base of Koeri earthquake catalogue and Disaster and Emergency Management Presidency (AFAD) - Earthquake Department, Continuous Seismic Data. Seismic moment magnitude estimates (M_w) for the main event and the strongest aftershock are from the Kalafat et al. (2011) catalogue.

The data set used in all the following analysis is presented in Fig. 2. Earthquakes with $M_d \geq 2.0$ are presented as circles in different colors and sizes. The figure shows also the configuration of the faults in the activated part of NAFZ. The faults (denoted by red lines in Fig. 2) are defined in European project SHARE (Seismic Hazard Harmonization in Europe - Basili et al. 2013).

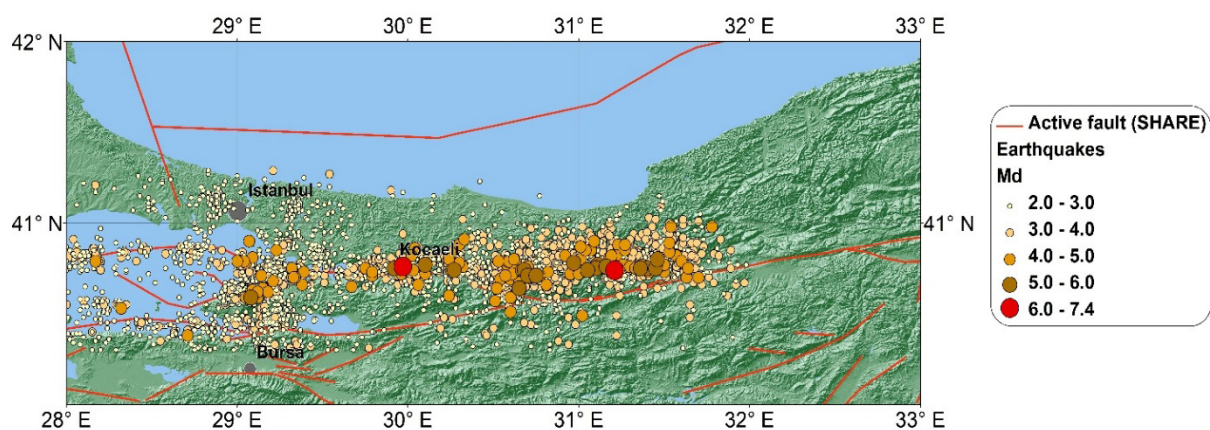


Figure 2. Epicentral map of earthquakes (with $M_d \geq 2.0$) located in the activated segments of the NAF from 17.08.1998 to 17.08.2004

To analyze the temporal distribution of the earthquakes (in both the fore-aftershock clusters), the use of a complete data set is essential for reliable results. To ensure a complete data sample we estimate the minimum magnitude of completeness M_{min} (the so-called minimum magnitude of complete reporting - or the threshold magnitude) based on the assumption of the Gutenberg-Richter (Gutenberg and Richter 1944) power law distribution of magnitudes. The distribution (illustrated in Fig. 3) indicates that the compiled data set (including earthquakes with $M_d \geq 2.0$) is incomplete below $M_d = 2.5$. Figures 2 and 3 presented extended and updated results of those which are shown in the article Raykova et.al 2025.

The compiled data set (earthquakes with $M_d \geq 2.5$) is divided into two subsets: first data sample includes foreshocks (435 earthquakes preceding the main event) and the second one includes the aftershocks (earthquakes following the main event 2725 quakes). The temporal distribution of the two data subsets (foreshocks and aftershocks) is analysed separately.

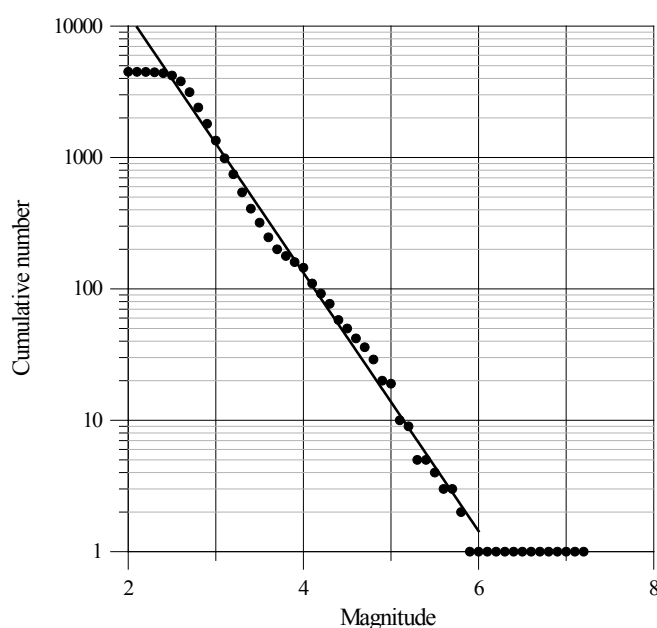


Figure 3. The magnitude frequency distribution.

Results

Temporal distribution of foreshocks

The seismicity before the main earthquake (17 August 1999 M_w 7.5) is analysed using 435 events with magnitude $M_d \geq 2.5$ occurring from 17.08.1998 to 17.08.1999. No high degree of clustering of foreshocks is observed, with the earthquakes are located in the activated segments of the North Anatolian Fault Zone (NAFZ). The distribution of foreshocks in space is presented in Fig. 4.

The temporal distribution of pre-shocks in months is shown in Fig. 5.

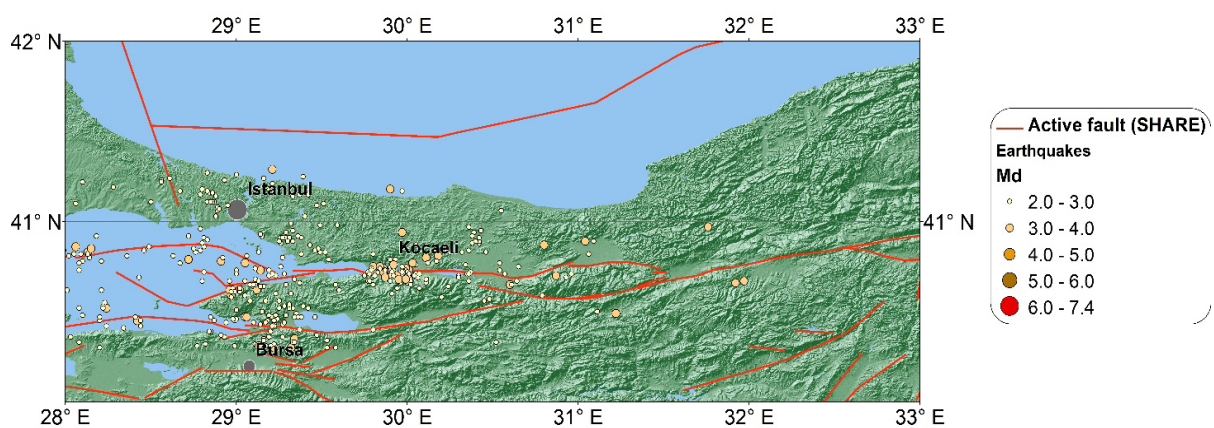


Figure 4. Epicentral map of earthquakes occurred one year before the 17 August 1999 M_w 7.5, Turkey earthquake.

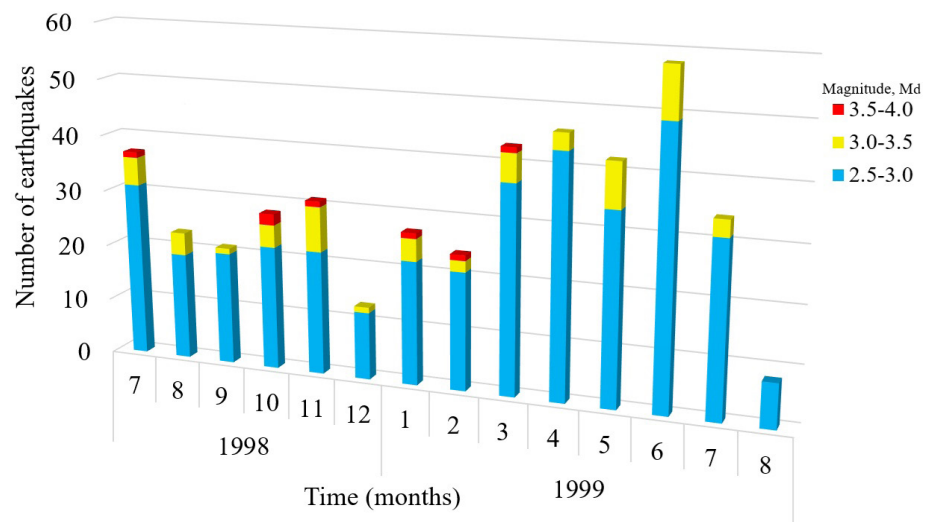


Figure 5. Temporal distribution of the 17 August 1999 M_w 7.5, Turkey earthquake foreshocks.

The figure indicates an uneven distribution of quakes over time. The increasing rate of the seismic activity (more than 40 shocks per month) was observed from March 1999, about 5 months before the main event. Seismic activity slightly decreased about a month before the 17 August 1999 earthquake. The main event occurs (17.08. 01^h01^{min}) about 2 minutes after last foreshock (in 16.08. 23^h59^{min}) and precursor aseismic gap before the August 1999 M_w 7.5, Turkey earthquake is not observed.

Temporal distribution of aftershocks

The power - low decay parameters are estimated using a data set of 2725 aftershocks with magnitude equal to and larger than 2.5 (the threshold magnitude is $M_{\min}=2.5$). The seismicity is assumed to follow a non-stationary Poisson process, consequently the parameters in the modified Omori formula are correctly calculated by the maximum likelihood method (Ogata 1983).

Depending on the different catalogues, the threshold magnitude value (M_{\min}) varies systematically. To test the reliability of the estimated p and c parameter values for the aftershock activity of the Turkey earthquake, we considered the effects of different M_{\min} . We estimated parameters in the modified Omori formula for 3 different $M_{\min} = 2.5, 3.0$ and 4.0 . Additionally, different models which take into account the effect of secondary aftershock activity are considered. Table 1 shows that for the best models (with the smallest AIC value) the p -value varies from 0.89 to 1.24 with variation of M_{\min} , for $M \geq 2.5$, p -values are close to unity, while slightly higher values are obtained for $M \geq 4.0$. Parameter c changes between 2.18 and 33.12; it decreases systematically from values of the order of 30–50 for $M \geq 2.5$ to values around 2–6 for $M \geq 4.0$, hence it decreases with increasing of M_{\min} . The results presented in our study support the concept that p -value slightly depends of M_{\min} , while the value of parameter c strongly depends on threshold magnitude of the input data (among others in Utsu et al., 1995).

Figure 6 illustrates the frequency-time distribution of aftershocks. The observed frequency distribution is compared with the so-called “theoretical” distribution that is expected from a selected process model (in this case, a modified Omori formula) presented with black curve.

In figure 7, the cumulative number of earthquakes is compared to the frequency-linearised time t , using parameters of the Omori formula for the data set. The blue curve illustrates the distribution observed from real data, which is compared with the theoretical distribution based on the modified Omori law, shown with the black curve. The observed increasing of cumulative number of events should be linear with time τ , if the modelling of the series is correct.

The time distributions presented in Figs. 6-7 illustrate the existence of some differences between observed and theoretical patterns, i.e., the modified Omori formula does not fit the observational data. The three plots show anomalies about 75 days after the main quake.

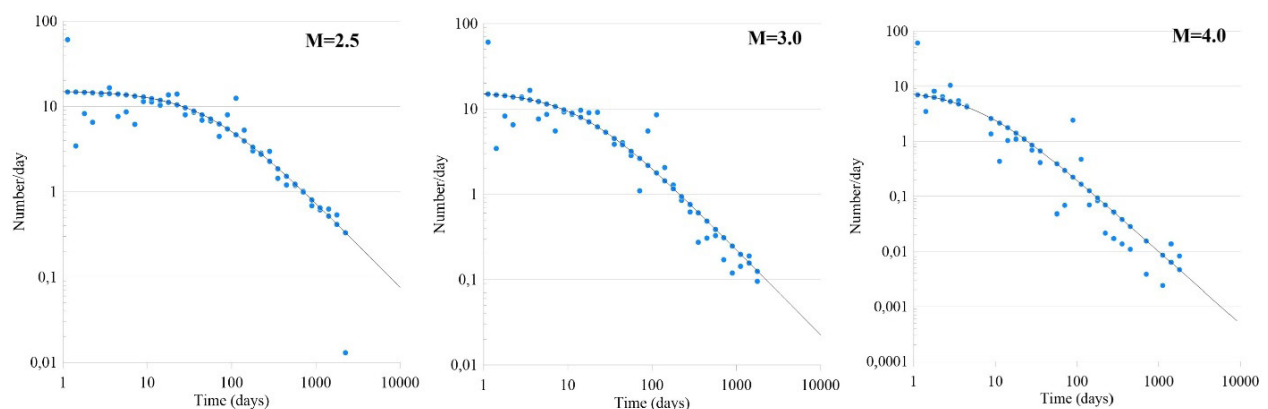


Figure 6. Frequency-time distribution of aftershocks (for the 3 data samples with different threshold magnitudes).

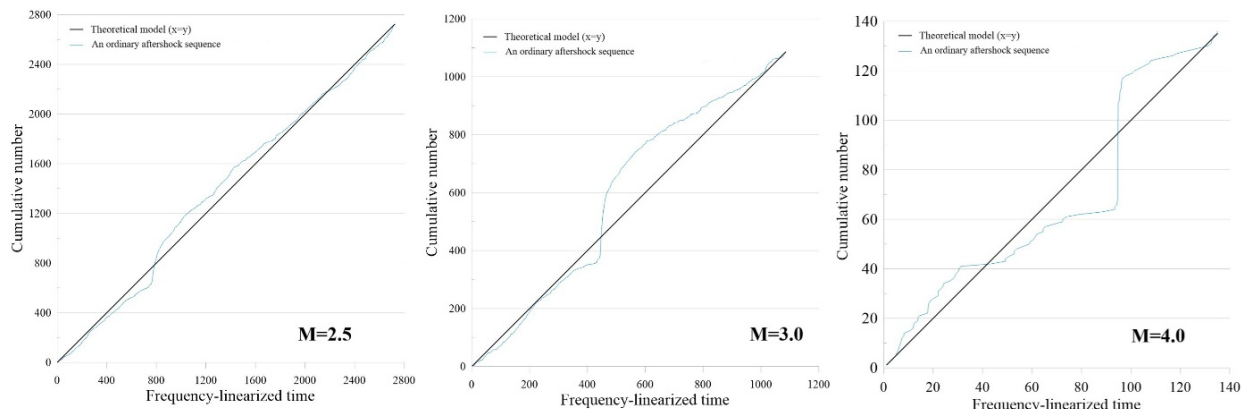


Figure 7. The cumulative number of earthquakes versus frequency-linearized time τ (for the 3 data samples with different threshold magnitudes).

The anomalies observed in the temporal sequences indicate that the series may contain secondary aftershock activity, caused by the strongest aftershock with $M_w 7.2$ ($M_d 6.5$).

Therefore, we recreated models taking into account the effect of secondary aftershock activity. We tested models with secondary aftershock sequences with the same and different estimation of value for p parameter for the main and secondary aftershock series. The models that are tested and the corresponding AIC are presented in Table 1.

Table 1. Estimation of the parameters in the Omori formula and corresponding AIC - criteria.

Model	K	p	c	K_1	p_1	c_1	AIC
An ordinary aftershock sequence - $M \geq 2.5$	755.62	0.99	49.89				307.734
Secondary aftershocks - $M \geq 2.5$	590.26	0.99	44.45	72.14	0.99	1.09	-90.138
Secondary aftershocks - $M \geq 2.5, p_1 \neq p_2$	301.92	0.89	33.12	1333.53	1.88	5.83	-109.508
An ordinary aftershock sequence - $M \geq 3.0$	223.69	0.99	13.93				974.44
Secondary aftershocks, $M \geq 3.0$	368.21	1.17	15.13	84.45	1.17	1.15	350.47
Secondary aftershocks - $M \geq 3.0, p_1 \neq p_2$	161.17	0.99	9.95	2647.32	2.20	6.01	336.4
An ordinary aftershock sequence - $M \geq 4.0$	89.99	1.32	5.82				411.18
Secondary aftershocks - $M \geq 4.0$	55.69	1.33	3.08	5.20	1.33	0.09	222.55

The best models for the three data samples with different threshold magnitudes ($M_{min} = 2.5, M_{min} = 3.0$ and $M_{min} = 4.0$) are illustrated in Fig.8.

Figure 8 shows a good fit between observed and theoretical distributions without strongly pronounced periods of decaying and activation of the process for the three data samples, and also that a nearly - linear tendency of aftershock decay continues up to 5 years after the main event. The transitions from aftershock activity to background seismicity is smooth, an evident ending of aftershock activity not being observed.

The AIC values for the models with secondary aftershock activity are smaller than those for the ordinary aftershock sequences for the three data samples with different threshold magnitude (as can be seen in Table 1).

The best model (with the smallest AIC value) for the aftershock sequence of the 17 August 1999 $M_w 7.5$, Turkey earthquake is a combination of one ordinary and one secondary sequence with $p_1 \neq p_2$.

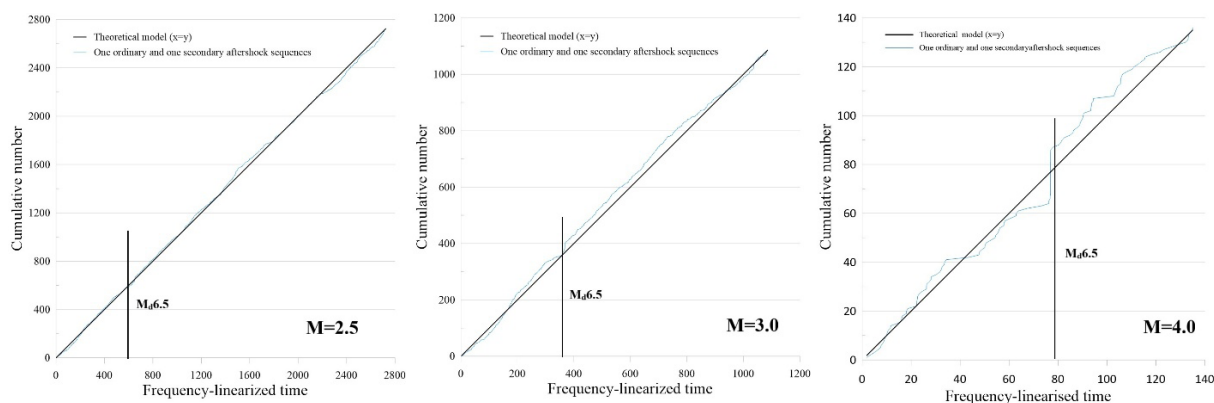


Figure 8. Cumulative number of earthquakes vs. frequency-linearized time τ for the best model (for the 3 data samples with different threshold magnitudes).

Discussion and conclusions

The uneven foreshock temporal distribution of the August 1999 M_w 7.5, Turkey earthquake is observed. The rate of seismic activity (more than 40 shocks per month with magnitude between 2.5 and 4.0) is increased about five months before the main event. A seismic gap in time between the foreshocks and main quake is not observed.

The rate of aftershock decay provides information about stress relaxation mechanisms and frictional strength heterogeneity (Mikumo and Miyatake 1979). More than 200 evaluations for value of p -parameter, in interval between 0.6 to 2.5 and a median of 1.1, have been published for aftershock sequences all over the world (e.g., Utsu et al. 1995). The p -value estimates in the present research are in the range of published p -values for aftershock series in the world.

The estimation of the parameters in the modified Omori law by the maximum likelihood procedure and the statistical model selection based on AIC, show that the aftershock series of the 17 August 1999 M_w 7.5 Turkey earthquake is well described by the combination of ordinary and one secondary sequences with different values of p - parameter. The anomalies observed in the temporal distribution of the aftershocks could be caused by the occurrence of the strongest aftershock on 12 November 1999, M_w 7.2.

We can summarize the principal findings from the study of the 17 August 1999 M_w 7.5, Turkey earthquake aftershock sequence as follows:

- Precursor aseismic gap before the August 1999 M_w 7.5, Turkey earthquake is not observed;
- Results presented in the study show that the p -value is slightly independent of M_{\min} , while the value of c - parameter indicates a strong dependence on the selected M_{\min} of the input dataset;
- The earthquakes distribution in the aftershock sequence of 17 August 1999 M_w 7.5, Turkey earthquake shows a complex temporal pattern. One secondary aftershock sequence with different value of p - parameter is recognized ($p_1 \neq p_2$);
- The transitions from aftershock activity to background seismicity are smooth, an evident ending of aftershock activity not having been observed;
- Consideration of recent earthquake sequences shows that aftershocks to large earthquakes, although they are still, by definition, smaller events, can be damaging and should be addressed in emergence planning scenarios.

Finally, we suggest that the public needs to have a better understanding of basic seismic hazard issues, including an awareness of potential hazardous shaking in the early aftermath of a damaging aftershock and of large events that may occur many months later.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Author contributions

All authors have contributed equally.

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Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.

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