

TEMPORAL CHARACTERISTICS OF THE FEBRUARY 6,
2023 $M_W7.8$, TURKEY EARTHQUAKE AFTERSHOCK
SEQUENCE

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Abstract

The devastating earthquake with moment magnitude $M_W7.8$, (local magnitude $M_L = 7.5$) which occurred in the East Anatolian Fault Zone, westwards of Gaziantep, Turkey on February 6, 2023 was followed by an intensive aftershock activity. Studying time distribution of aftershocks is important for understanding physics of the earthquake generation process.

In the present study temporal pattern of aftershock sequence of the 2023 $M_W7.8$ Turkey earthquake is analyzed. Because of the factors such as location and radiation pattern and the cumulative nature of building damage, aftershocks can cause more damage than the main shock. The temporal clustering of aftershocks is a dominant non-random element of the seismicity, so when the clusters are removed, the remaining activity can be modelled (as first approximation) as a Poisson process.

On the assumption that aftershocks are distributed in time as a non-stationary Poisson process, we use the maximum likelihood method for estimating the parameters (K , c and p) of the modified Omori formula. For testing the goodness of fit between the aftershock occurrence and different statistical models, a transformation from the time scale t to a frequency-linearized time scale τ is applied. Akaike's information criteria is used to select the best model for the temporal distribution of aftershocks.

It has been found that temporal distribution of the 2023 Turkey earthquake aftershocks is dominated by the classic power law decay in time and suggests the existence of secondary aftershock activity.

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Key words: aftershocks, temporal distribution, 2023 Turkey $M_W 7.8$ earthquake

Introduction. Statistical characteristics of aftershock occurrences can give reliable information about the fault structure, earthquake migration and the state of stress in the crust. The temporal clustering of aftershocks is a dominant non-random element of the seismicity. If the clusters are removed, the remaining activity can be modelled as a Poisson process – as first approximation [1]. Aftershocks happen after the main earthquake and their frequency decays over time, typically following a pattern known as the Omori's law. Later it is modified by UTSU [2] so it is well known as modified Omori's law.

It should be emphasized that aftershocks are essential because of their scientific and societal importance. Large aftershocks may be overlooked because they occur immediately after the main shock. A region close to a large aftershock may experience even higher ground motion than during the main shock. Late large aftershocks can also occur. These “ghosts of earthquake past” provoke fear in the population of the region and open scepticism in the media that such large aftershocks could occur so late [3]. Some authors recognize that the main causes of aftershocks include main shock-induced changes of frictional properties [4].

The territory of Turkey, analyzed in the study is the most active seismic area in the Balkan Peninsula. Turkey, and in general the Eastern Mediterranean region, are characterized by a complex arrangement of tectonic structures. The region is located where the Arabian and African Plates move toward the Eurasian Plate [5]. This compressional regime controls the formation of many active faults and the seismicity of the region. The Anatolian Plate includes the North Anatolian Fault Zone (NAFZ), the East Anatolian Fault Zone (EAFZ), and the Southeast Anatolian Thrust Zone (SAT), which form the plate boundaries and the important active fault segments throughout Western Anatolia [6]. Therefore, Turkey has experienced several great earthquakes ($M > 7.0$) in these fault zones. These earthquakes caused huge devastation on buildings and roads as a result of landslides and liquefaction [7].

The East Anatolian Fault Zone (Fig. 1a) is 80 km wide and 600 km long with NE-trending and seismically very active strike-slip fault system. The left-lateral EAFZ marks the 600 km long strike-slip boundary between the Arabian and Anatolian plates. The zone average slip rates are 10–11 mm/yr [8]. There are historical documents for destructive $M > 7$ earthquakes which occurred in this zone (Fig. 1b). The main known historical earthquakes in the area occurred on November 29, 1114 ($M > 7.8$), March 28, 1513 ($M > 7.4$), and March 2, 1893 ($M > 7.1$) [9]. The earthquake of December 4, 1905, with $M = 6.8$ is the strongest earthquake in EAFZ in the 20th century [10].

Figure 1 presents historical and recent seismicity in the Anatolia region and active faults of Turkey, where the North Anatolian Fault Zone and the Eastern

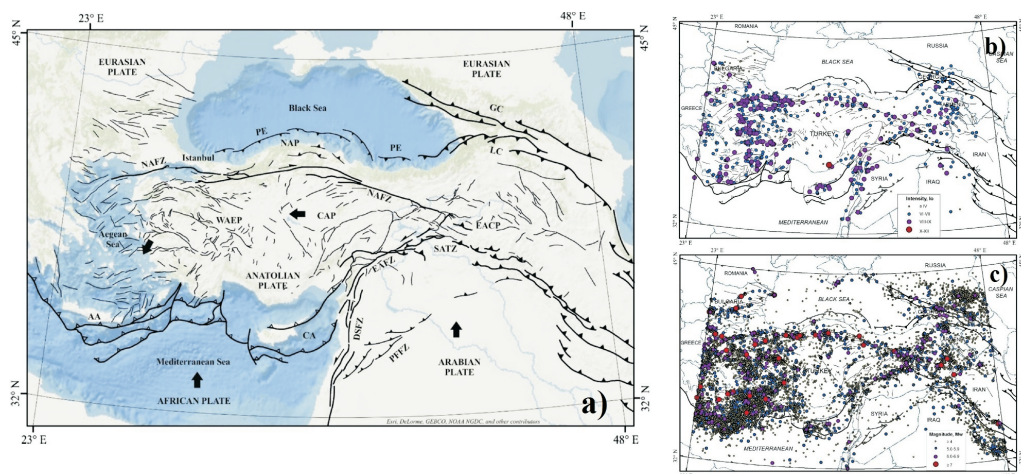


Fig. 1. Epicentral map of: a) active fault of Turkey; b) historical earthquakes across Turkey and the surrounding region from BC 2000 to AD 1900; c) recent seismicity across Turkey during the period 1900 to 2012 [11]

Anatolian Fault Zone are shown [11].

The 2023 $M_W 7.8$ ($M_L = 7.5$) earthquake was largely felt on the territories of Turkey and Syria and in the Balkan countries: Greece, Bulgaria, Romania and Croatia. The main shock triggered destructive aftershock within the same fault zone, at a distance of 100 km further north with moment magnitude $M_W 7.5$ ($M_L = 7.4$). These earthquakes caused extensive primary and secondary effects on the environment including surface ruptures, ground cracks, liquefaction phenomena, and hydrological anomalies causing extensive impact on networks and infrastructure [12].

In the present study statistical analysis is applied to examine the temporal pattern of earthquakes in the aftershock sequence of the February 6, 2023 Turkey earthquake. The maximum likelihood method is used for estimating the parameters (K , c and p) in the modified Omori formula for the aftershock sequence. The goodness of fit between the aftershock occurrence and different statistical models has been tested using a transformation from the time scale t to a frequency-linearized time scale τ . Finally, to select the best statistical model for aftershock occurrence the AKAIKE Information Criterion [13] is used.

Method. Aftershocks occur after the main shock and their frequency decays in time with approximately the reciprocal of time elapsed since the main earthquake. Among different models, the modified Omori law is one of the most effective approaches. Aftershock time series analyzed in this study are all well fit with the modified Omori model. The occurrence rate of aftershock sequence in time is empirically well described by the modified Omori formula proposed by Utsu [2].

The frequency $n(t)$ of aftershocks at time t is estimated using the modified Omori formula [2]:

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

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

K -value is controlled by the total number of the aftershocks in the sequence. The parameter depends on the total number of aftershocks and the threshold magnitude [14]. The value of the parameter c is a controversial quantity [14] and it is strongly affected by incomplete detection of small aftershocks in the early stage of sequence [14].

Among these three parameters, p -value is the most important and defines the mode of aftershock decay as a function of time on frequency. The variability of the characteristic parameter p -value is related to the structural heterogeneity, stress and temperature in the crust [14] and may be associated with the tectonics of the region, fault heterogeneity and stress [14]. Many estimates of p -value with a scatter from 0.6 to 2.5 and a median of 1.1, have been published for aftershock sequences in different parts of the world [14].

Based on the assumption that aftershocks are distributed as a non-stationary Poisson process, OGATA [15] proposed to use the maximum likelihood method for estimating the parameters K, c and p in the modified Omori formula.

The following relation defines the intensity function of the Poisson process $\lambda(t)$:

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

Using the modified Omori formula, the intensity function becomes:

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

An integration of the intensity function $\lambda(t)$ gives a transformation from the time scale t to a frequency-linearized time scale τ [16]. On this time axis the occurrence of aftershocks becomes the standard stationary Poisson process if the choice of the intensity function $\lambda(t)$ (i.e., the parameters K, c and p) is correct.

The frequency-linearized time for a sequence of aftershocks, for time interval s , is described by the equation:

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

The time scale τ is used for testing the goodness of fit between the aftershock occurrence and the selected model.

A linear dependence between the observed cumulative numbers of aftershocks (N) and τ should be observed if an appropriate model has been selected. Anomalies in the aftershock activity are more evident on the $N(\tau)$ plot than on $n(t)$. Thus the τ time axis will be used to detect secondary aftershock activity.

The Akaike Information Criterion (AIC) [13] is used for evaluation of different models, based on the same set of data [15]. The AIC is a measure of which model fits better the observations, and is given by:

$$(5) \quad AIC = 2k - 2 \ln(\text{maximized value of the likelihood function}),$$

where k is the number of estimated parameters. The preferred model is the one with the minimum AIC.

Input data. The earthquake data used in the study are from B. U. KOERI-RETMC [17] (Bopaziçi University Kandilli Observatory and Earthquake Research Institute, available at <http://www.koeri.boun.edu.tr/sismo/2/en/>).

In the present study, as aftershocks, we accept all events that are located in the inferred rupture zone (activated segments of the East Anatolian Fault Zone – the area marked with a light green contour in Fig. 2 a). Thus, we compile a sample of 3386 aftershocks, with magnitude $M_L \geq 3.0$ occurred 176 days after the February 6, 2023 $M_W 7.8$ earthquake.

The aftershocks with $M_L \geq 3.0$ are plotted as circles in different colours in Fig. 2a. The size of the circles is magnitude, M_L dependent (as presented in the legend of Fig. 2). Figure 2 also shows the active faults in the considered region that are defined in the European project SHARE (Seismic Hazard Harmonization in Europe [18]). Black lines denote the identified faults.

In the analyses of the space-time-magnitude distribution of the aftershocks, the use of complete data set for all magnitude levels is essential for reliable results. To ensure a complete data sample the minimum magnitude of completeness $M_{\min}$ (the so-called the minimum magnitude of complete reporting-threshold

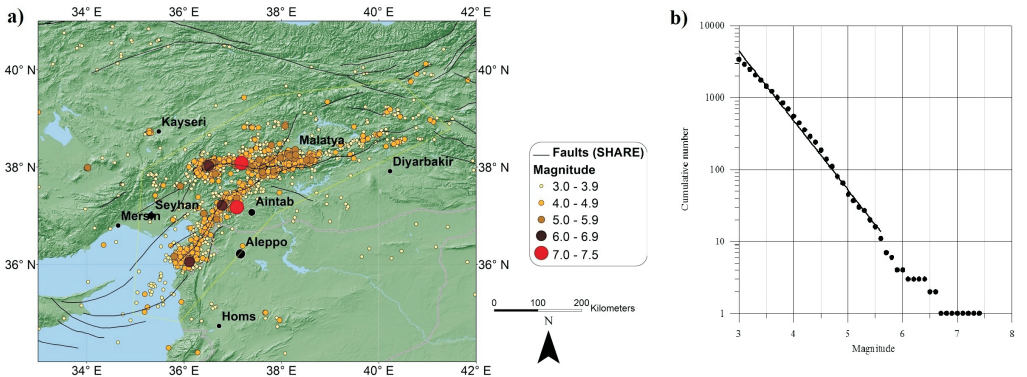


Fig. 2. Set of data including all aftershocks with $M_L \geq 3.0$: a) space distribution; b) frequency magnitude distributions

magnitude) based on the assumption of the Gutenberg–Richter [19] power law distribution of magnitudes can be estimated.

We use the magnitude frequency distribution (known as Gutenberg–Richter law) to test the completeness of the events located in the selected area. Figure 2 b) illustrates the cumulative magnitude–frequency of aftershock sequence.

The distribution (illustrated in Fig. 2b) indicates that the compiled data set (including aftershocks with $M_L \geq 3.0$ of the $M_W 7.8$ Turkey 2023 earthquake) is complete for $M_L \geq 3.5$.

In the present study two data samples with different threshold magnitude ($M_{\min}$) are considered. The data samples with $M_{L\min} = 3.5$ and $M_{L\min} = 4.0$ include 1441 and 554 aftershocks, respectively.

Results. The value of the threshold magnitude ($M_{\min}$) varies systematically in space and time across different networks and catalogues. Temporal variations in that parameter can potentially cause incorrect p -value estimation.

To test the reliability of the estimated p and c values for the aftershock sequence, we considered the effects of different $M_{\min}$. The parameters K , c , and p in the modified Omori formula (for $T = 176$ days) are calculated accurately by the maximum likelihood method, assuming that the seismicity follows a non-stationary Poisson process [15]. The estimated parameters are presented in Table 1.

The results in Table 1 show that the p -value slightly varies (from 1.15 to 1.16)

T a b l e 1

Maximum likelihood estimates of the Omori formula parameters and corresponding AIC (for $T_a = 176$ days)

Model	K	p	c	K_1	p_1	c_1	k_2	p_2	c_2	AIC
An ordinary after-shock sequence, $M_L \geq 3.5$	323.12	1.15	0.44							−8016.01
One ordinary and one secondary aftershock sequences	144.73	1.09	0.18	106.89	1.09	0.33				−8039.30
One ordinary and two secondary aftershock sequences	145.01	1.10	0.12	102.73	1.10	0.32	3.55	1.10	0.01	−8090.62
An ordinary after-shock sequence, $M_L \geq 4.0$	108.87	1.16	0.24							−2453.95
One ordinary and one secondary aftershock sequences, $M_L \geq 4.0$	47.92	1.07	0.08	29.22	1.07	0.07				−2498.30
One ordinary and two secondary aftershock sequences, $M_L \geq 4.0$	46.38	1.08	0.06	29.02	1.08	0.06	0.85	1.08	0.00	−2534.30

with variation of $M_{\min}$ while c -value changes between 0.44 and 0.24 (or decreases with increasing of $M_{\min}$). The presented results support the concept that the p -value is nearly independent of $M_{\min}$, but the c value strongly depends on the $M_{\min}$ of the input data (among others in [14] and [20]).

The frequency-time distribution of aftershocks with $M_{L\min} = 3.5$ and $M_{L\min} = 4.0$ occurred in 176 days after the main event is presented in Fig. 3a. Figure 3b illustrates the cumulative number of events versus frequency-linearized time τ , for the two threshold magnitudes: $M_{L\min} = 3.5$ and $M_{L\min} = 4.0$.

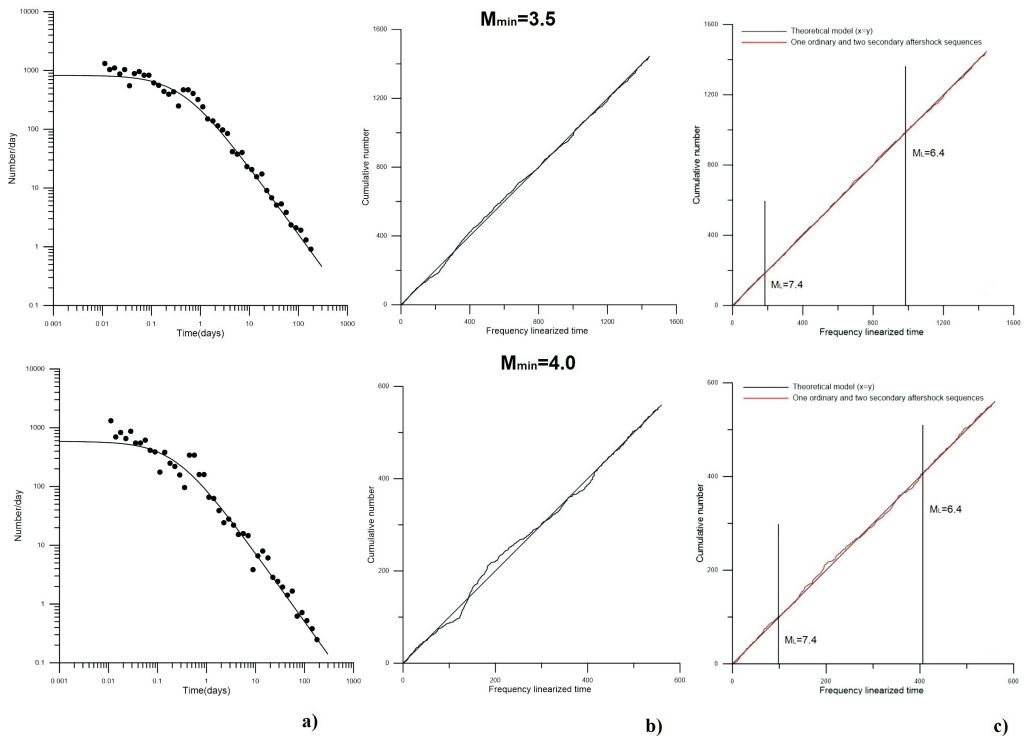


Fig. 3. Temporal distribution of aftershocks for the two threshold magnitudes: $M_{L\min} = 3.5$ and $M_{L\min} = 4.0$: a) frequency-time distribution; b) cumulative number of events vs. frequency-linearized time τ ; cumulative number of events vs. frequency-linearized time τ for the best model

The cumulative number of events is plotted against the frequency-linearized time τ , using the estimated parameters K , p , c (Fig. 3b). The observed distribution (in blue colour) is compared to the theoretical distribution (in black colour), based on the selected model (in this case, the model is the modified Omori formula). If the modelling of the sequence is appropriate, the cumulative number should increase linearly with time τ .

The data presented in Fig. 3b suggests the existence of some discrepancies between observed and expected distributions, i.e., the modified Omori formula

does not fit the observational data. The distribution for different magnitudes, $M = 3.5$ and $M = 4.0$ presented in Fig. 3b shows bumps about nine hours and 14 days after the main shock in the two plots. The anomalies observed in the temporal distribution could be caused by the occurrence of two of the strongest aftershocks: first on February 6, 2023 with magnitude $M_W 7.5$ ($M_L 7.4$ occurred nine hours after the main event) and the second one with magnitude $M_W 6.4$ ($M_L 6.4$) that is generated on February 20, 2023.

Consequently, we reconstructed models which take into account the effect of secondary aftershock activity. We tested models with one and two secondary aftershock sequences with the same p -value for the main and secondary aftershock sequences. The models that are tested and the corresponding AIC are presented in Table 1.

The AIC values for the models with secondary aftershock activity are smaller than those for the ordinary aftershock sequences for the two data samples with different threshold magnitude (Table 1).

The best model (with the smallest AIC value) for the February 6, 2023 $M_W 7.8$ Turkey aftershock sequence is a combination of one ordinary and two secondary sequences.

In Fig. 3c are plotted the cumulative number of events against the frequency – linearized time τ , using MLE's of the Omori formula parameters for the best models (denoted by a red line) for the two threshold magnitudes: $M_{L\min} = 3.5$ and $M_{L\min} = 4.0$.

Figure 3c illustrates a good fit between observed and expected distributions without evident periods of decaying and activation of the process. Additionally, Fig. 3c shows that a nearly linear trend of aftershock decay continues up to 176 days after the main event (for all three data samples).

The finding of our study is consistent with the result presented in [21] – the best model for the temporal distribution of the aftershocks occurred 27 days after the $M_W 7.8$ Turkey earthquake is one ordinary and two secondary sequences.

Conclusions. We can summarize the principal findings from the study of the 2023 $M_W 7.8$ ($M_L 7.5$) Turkey earthquake aftershock sequence as follows:

The p -value estimates in the study are nearly close to median p -value (1.1) published for aftershock sequences in the world. The p -value is nearly independent of the minimum magnitude threshold while the c -value strongly depends on the $M_{\min}$ of the input data.

The earthquakes distribution in the aftershock sequence of the 2023 $M_W 7.8$ ($M_L 7.5$) Turkey earthquake shows a complex temporal pattern. Two secondary aftershock sequences are recognized.

The maximum likelihood estimates of the parameters in the modified Omori formula, and the selection of a statistical model based on AIC, show that the aftershock sequence of the 2023 Turkey ($M_W 7.8$,) earthquake is best modelled by the combination of one ordinary and two secondary aftershock sequences which

corresponds to the results presented in [21].

The anomalies observed in the temporal distribution could be caused by the occurrence of two of the strongest aftershocks: the first on February 6, 2023 with magnitude $M_W 7.5$ (occurred nine hours after the main event) and the second one with magnitude $M_W 6.4$ that is generated on February 20, 2023.

Moreover, we guess that there is still a need for increased appreciation of large aftershock potential. 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.

Finally, it should be stated that more and new studies on aftershock sequences will help the decision makers to master complicated situations after major earthquakes.

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