DOI: 10.48368/bgs-2025.1.n6

Temporal characteristics of the 17 August 1999 Mw7.5, Turkey earthquake aftershock sequence

Plamena Raykova[1], Dimcho Solakov[1]and Stela Simeonova[1]

[1] National Institute of Geophysics, Geodesy and Geography, Bulgarian Academy of Sciences, Sofia 1113, Bulgaria, praykova@geophys.bas.bg, dimos@geophys.bas.bg, ssimeonova@geophys.bas.bg,

Key words: 1999 Turkey M_W7.5 earthquake, North Anatolian Fault

Summary
Strong earthquake with moment magnitude M_W7.5 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 1999 M_W7.5 earthquake is a part of a seismic sequence along the North Anatolian Fault that started in 1939, causing large earthquakes that moved progressively from east to west over a period of 60 years or more. Studying time distribution of earthquakes is very important for understanding the physics of the earthquake generation process. In the present study temporal pattern of earthquake distribution in aftershock sequence of the 17 august 1999 M_W7.5 Turkey earthquake is analysed. The properties of aftershock sequences (distinct cluster in space and time) allow time-dependent prediction of aftershock probabilities. 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.

Introduction

The Eastern Mediterranean region, is characterized by a complex arrangement of tectonic structures. In the region, 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 (Reilinger and McKlusky, 2011).

The tectonic position of the Anatolian Plate, where Turkey is located is characterise with active neotectonics movement and a long history of devastating earthquakes. The westerly motion of Anatolia with respect to Eurasia and Africa caused 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) of Turkey is a region of high seismicity. Some of the most destructive earthquakes in history have been caused by movement along this fault. It is assumed (Barka A., 2002), that the 17 August 1999 M_W7.5 Turkey earthquake is an earthquake of westward migrating seismic sequence along the NAF. That earthquake sequence started in 1939, causing large earthquakes that moved from east to west over a period of 60 years or more.

In the present study statistical analysis is applied to examine the temporal pattern of earthquakes in the aftershock sequence of the 1999 M_W7.5 (M_d6.7) 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 (Ogata, 1983). The goodness of fit between the aftershock occurrence and different 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 (Akaike, 1974).

Method

The modified Omori formula proposed by Utsu (Utsu, 1969), empirically well describes the occurrence rate 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 elapsed time since 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. The variability of the parameter p value is related to the structural heterogeneity, stress and temperature in the crust (Kisslinger and Jones, 1991) and associated with the tectonics of the region, fault heterogeneity and stress (e.g., Utsu, et.al., 1995). The parameters of the modified Omori formula are estimated using the maximum likelihood method accepting that aftershocks are distributed as a non-stationary Poisson. The following relation defines the intensity function of the Poisson process λ(t):

$$\lambda(t) = \lim_{\Delta \to 0} Prob\{ an\ event\ in\ [t, t+\Delta t]\} / \Delta t \qquad (2)$$

Using the modified Omori formula, the intensity function becomes:

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

An integration of the intensity function λ(t) gives a transformation from the time scale t to a frequency-linearized time scale τ (Ogata and Shimazaki, 1984). On this time axis the occurrence of aftershocks becomes the standard stationary Poisson process if the choice of the intensity function λ(t) (i.e., the parameters K, c and p) is correct.
The frequency-linearized time for a sequence of aftershocks is described by the equation:

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

Thus the τ time axis will be used to detect secondary aftershock activity.
The Akaike Information Criterion (AIC) is used for evaluation of different models, based on the same set of data (Ogata, 1983). The AIC is given by Akaike, 1974:

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

The preferred model is the one with the minimum AIC.

Input data

The data sample of 2898 aftershocks, with magnitude $M_d \geq 2.0$ occurred after the earthquake in the period 1999 - 2004 is compiled on the base of B. U. KOERI-RETMC (Bopazi¸ci 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 North Anatolian Fault, NAF - marked with a red line in Fig. 1).

In Figure 1 aftershocks with $M_d \geq 2.0$ are plotted as circles in different colors and size (both are magnitude, M_d dependent, as presented in the legend of the figure). The figure also shows the faults in the activated part of North Anatolian Fault Zone that are defined in the European project SHARE (Basili et. al., 2013). The identified faults are denoted with red lines.

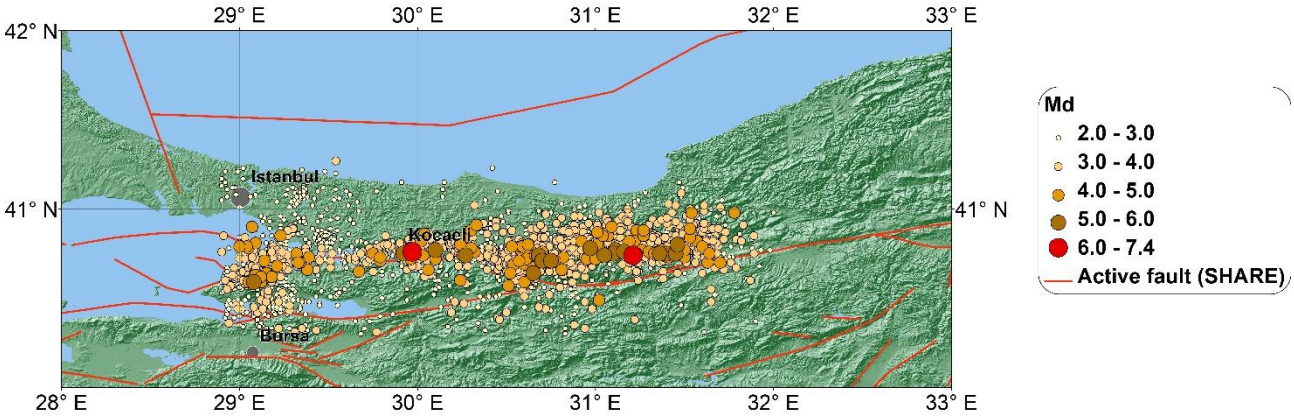


Figure 1. Epicentral map of the aftershocks (with $M_d \geq 2.0$) located in the activated segments of the NAF from 17.08.1999 to 2004

In the following analysis of the temporal distribution of the aftershocks, the use of a complete data set 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 magnitude) based on the assumption of the Gutenberg-Richter (Gutenberg and Richter, 1944) 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 identified as aftershocks. The distribution (illustrated in Fig.2) indicates that the compiled data set (including aftershocks with $M_d \geq 2.0$) is incomplete below $M_d=2.5$.

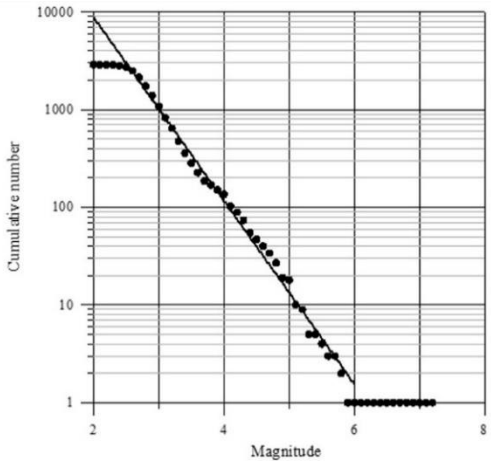


Figure 2. Frequency magnitude distributions for a set of data including all aftershocks with Md≥2.0

Results

The parameters K, c, and p in the modified Omori formula are calculated by the maximum likelihood method, assuming that the seismicity follows a non-stationary Poisson process (Ogata, 1983). If the modelling of the sequence is appropriate, the cumulative number of events will increase linearly with τ. The two models that are tested and the corresponding AIC are presented in Table 1.

Temporal distribution of aftershocks with $M_d=2.5$ occurred about 5 years after the 1999 $M_W7.5$ earthquake is presented in Fig.3. The observed distribution (marked in blue) is compared to the theoretical distribution (red line), based on the selected model. Figure illustrates the cumulative number of events versus frequency-linearized time τ: a) an ordinary aftershock sequence; b) the model with one ordinary and one secondary aftershock sequence with p≠p1.

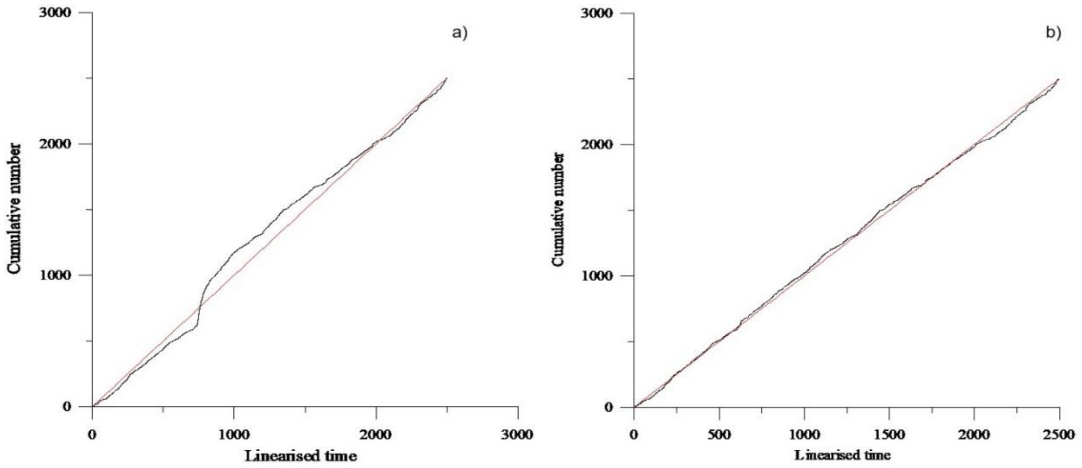


Figure 3. Plot of the cumulative number of events versus frequency linearized time for: a) an ordinary aftershock sequence; b) one ordinary and one secondary aftershock sequence with p≠p1.

Figure 3a) suggests the existence of an obvious discrepancy between observed and expected distributions after the occurrence of the largest aftershocks. Consequently, a model with a secondary aftershock sequence is applicable to the activity after the main event.

The cumulative number of events against the frequency linearized time τ, using MLE`s of the Omori formula parameters for the model with one ordinary and one secondary sequence is plotted in Fig.3b.

The figure illustrates a good fit between observed and expected distributions without evident periods of decaying and activation of the process, and shows that a nearly-linear trend of aftershock decay continues up to 5 years after the main event.

Table 1. Maximum likelihood estimates of the Omori formula parameters and corresponding AIC

Model	**K**	**p**	**c**	**K_1**	**p_1**	**c_1**	**AIC**
An ordinary aftershock sequence, $M_d \geq 2.5$	665.34	1.0	42.67				441
One ordinary and one secondary aftershock sequence	313.25	0.91	30.1	487.84	1.60	3.97	-11.91

Discussion and conclusions

The distribution of earthquakes in the aftershock sequence of the main earthquake shows a complex temporal pattern. 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 1999 Turkey (M_W7.4) earthquake is well modelled by the combination of one ordinary and one secondary sequence. The anomalies observed in the temporal distribution of the aftershocks could be caused by the occurrence of one of the strongest aftershocks on 12 November 1999, with moment magnitude M_W7.2.

More than 200 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 all over the world (e.g., Utsu et.al., 1995). The p-value estimates in the present study are in the range of the published p-value for aftershock sequences in the world.

The public needs to have a better understanding of basic seismic hazard issues, including an awareness of potential hazardous shaking just after the main shock and a damaging aftershock that may occur many months later. Consideration of recent earthquake sequences suggests that aftershocks to large earthquakes although they are still, by definition, smaller events, can be damaging and should be addressed in emergence planning scenarios.

Funding: This study was funded by Partnership Agreement No. 3-51/13.01.2022 under the National Scientific Program "Security and Defense".

References

Akaike , (1974) A new look at the statistical model identification. IEEE Trans. Automatic Control AC-19: 716-723, doi: 10.1109/TAC.1974.1100705.

Barka A (2002) The Surface Rupture and Slip Distribution of the 17 August 1999 Izmit Earthquake (M 7.4), North Anatolian Fault. BSSA 92 (1): 376–386, doi:10.1785/0120000841.

Basili R, Kastelic V, Demircioglu M, Garcia Moreno D, Nemser E., et al. (2013) The European Database of Seismogenic Faults (EDSF) compiled in the framework of 538 the Project SHARE. http://diss.rm.ingv.it/share-edsf/, http://doi.org/10. 539 6092/INGV.IT-SHARE-EDS

Bopazi ̧ci University Kandilli Observatory and Earthquake Research Institute – Regional Earthquake-Tsunami Monitoring Center, available athttp://www.koeri.boun.edu.tr/sismo/2/en/

Gutenberg R, Richter R (1944) Frequency of earthquakes in California. Bulletin of Seismological Society of America34: 185–188

Kisslinger C, Jones L (1999) Properties of aftershock sequences in southern California. Journal of Geophysical Research, 96: 11947-11958

Ogata Y (1983) Estimation of the parameters in the modified Omori formula for aftershock sequences by the maximum likelihood procedure. J. Phys. Earth, 31: 115-124.

Ogata Y, Shimazaki K (1984) Transition from aftershock to normal activity: the Rat Islands earthquake aftershock sequence. Bulletin of Seismological Society of America, 74: 1757-1765.

Reilinger R, McKlusky S (2011) Nubia–Arabia–Eurasia plate motions and the dynamics of Mediterranean and Middle East tectonics. Geophysical Journal International, 186 (3): 971–979.

Sengör AMC. (1979) The North Anatolian transform fault: its age, offset and tectonic significance. J G S, 136: 269 – 282, https://doi.org/10.1144/gsjgs.136.3.0269

Utsu T (1969) Aftershocks and earthquake statistics (I) - Some parameters which characterize an aftershock sequence and their interaction. Journal of the Faculty of Science, Hokkaido Univ., Ser. VII, 3: 129-195.

Utsu T, Ogata Y, Matsu'ura R (1995) The centenary of the Omori formula for a decay law of aftershock activity. Journal of Physics of the Earth, 43: 1-3.