

TEMPORAL DISTRIBUTION OF THE AFTERSHOCKS AFTER THE FEBRUARY 14TH, 2023, M_w 5.4 ROMANIA

Plamena Raykova^{1✉}, Luminita Ardeleanu², Dimcho Solakov¹,
Stela Simeonova¹

Received on July 30, 2025

Accepted on October 28, 2025

Abstract

We apply statistical analysis to study the temporal pattern of earthquake occurrence in the aftershock sequence of the 2023 Romania M_w 5.4 earthquake. The temporal clustering of aftershocks is a dominant non-random element of the seismicity, so that, when the clusters are removed, the remaining activity can be modelled as a Poisson process (as first approximation). The maximum likelihood method was 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 then been tested using a transformation from the time scale t to a frequency-linearized time scale τ . It is assumed that on this time axis the aftershocks are distributed in time as a standard stationary Poisson process if the choice of the parameters K , c and p is correct. We further used the Akaike Information Criterion as a measure for selecting the best among competing models. The aftershock sequence of the February 14th, 2023, M_w 5.4 Romania earthquake is best modelled by the combination of one ordinary and one secondary sequence.

Key words: aftershocks, temporal distribution, February 14th, 2023, M_w 5.4 Romania earthquake

Introduction. The space distribution of aftershock sequences observed after the occurrence of a main event, is characterized by great diversity, because a strong

This study was funded by Partnership Agreement No. 3-51/13.01.2022 under the National Scientific Programme “Security and Defense”.

<https://doi.org/10.7546/CRABS.2025.12.11>

mainshock can produce a large number of aftershocks in a short time and in a small region. The aftershock area is located in and around the fault rupture region of the mainshock. The largest aftershocks are not generally forecastable, and they have a potential for structural damage [1]. Space-temporal distribution of aftershocks provides valuable insights regarding the geometry of fault structures, and the stress distribution associated with the earthquake. Additionally, these distributions help in understanding the physical properties of materials within the fault zone, and in underlying the characteristics of the seismic sources responsible for large earthquakes [2].

Temporal distribution of aftershocks is a dominant non-random element of seismicity; if clusters are removed, the remaining activity can be modelled as a Poisson process as a first approximation [3]. Aftershock activity is usually considered to be the seismicity that occurs after a main event and is above background activity. The frequency of aftershocks decreases with time, usually following a pattern known as Omori's law. The aftershock activity can last months, a year, or even longer for earthquakes in stable continental interiors [4].

In the present study the temporal distribution of the aftershocks of February 14, 2023, Romania earthquake (with magnitude M_W 5.4) is analyzed.

Romania is well-known as a European territory with high level of seismic risk. The seismic hazard for almost half of the country is mainly controlled by the intermediate-depth Vrancea earthquakes, which are located beneath the southern Carpathian Arc. The Vrancea region is characterized by rather high rate of occurrence of large earthquakes in a narrow focal volume in the depth range from 70 km to 160 km [5]. Several areas of shallow seismicity in Romania are considered seismically dangerous. Low-to-moderate crustal seismicity is distributed throughout almost the entire territory, mainly along the Carpathians and in the Pannonian depression: in front of the Eastern Carpathians bend, in the Fagaras Mountain area, in the Danubian area, in the Banat, Crisana, Maramures, and North Dobrogea regions [6]. The area related to February 14th, 2023, M_W 5.4 Romania earthquake is tectonically complex.

It is situated at the contact between the Getic Depression, to the South, and the South Carpathians, to the North [7, 8]. The seismicity of this area is part of the overall seismicity characterizing the contact of the Moesian Platform and the South Carpathians orogen. The considered seismic zone is characterized by shallow seismicity with depths of events in the range 5–33 km, with increased frequency between 5–10 km [6].

The main event was largely felt in Romania and neighbouring countries: a relatively wide felt area included Oltenia, Banat, Hunedoara regions, as well as the north-eastern part of Serbia and the north-western part of Bulgaria. The intensity of the ground motion was estimated at VI degrees on Mercalli scale in the epicentral area. Minor to moderate damages were recorded especially in the epicentral area. The fault plane solution of the main event indicates normal faulting

with rupture plane oriented in ENE–WSW direction [9]. Five months after the main earthquake, the aftershock sequence included more than 3000 seismic events with magnitudes in the range 1.2–4.6.

In the present paper statistical analysis is applied to study the temporal pattern of earthquakes in the aftershock sequence of the February 14th, 2023, M_W 5.4 earthquake.

The maximum likelihood method is applied for estimating the parameters (K , c and p) in the modified Omori formula for the aftershock sequence [10]. 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, to select the best statistical model for the aftershock occurrence, the Akaike Information Criterion (AIC) is used [11].

Method and data. The frequency $n(t)$ of aftershocks at time t is well described by the modified Omori formula [12]:

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

where t is the elapsed time since the occurrence of the main shock, and K , p , c are constants. The key parameter p characterizes the decay of the aftershock activity.

OGATA [10] proposed to estimate the parameters of the modified Omori formula via maximum likelihood method, accepting that aftershocks are distributed as a non-stationary Poisson process.

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:

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

An integration of the intensity function $\lambda(t)$ gives a transformation from the time scale t to a frequency-linearized time scale τ [13]. The aftershocks occurrence on this time axis is transformed into a standard stationary Poisson process if the choice of the intensity function $\lambda(t)$ (i.e. the parameters K , c and p) is accurate.

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

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

Time scale τ was used for testing the goodness of fit between the observed aftershock distribution and the selected statistical model. It is possible that the

chosen model reflects ordinary aftershock activity or suggests the presence of secondary aftershock sequences.

If the model is appropriate, a linear dependence between the cumulative numbers of aftershocks N , and τ should be observed. Anomalies in the aftershock sequences are more obvious on the $N(t)$ plot than on $n(t)$, and the τ time axis was used to identify secondary aftershock activity.

The Akaike Information Criterion (AIC) [11] was applied to select a model that best matches the observed distribution of aftershock events. This is a measure indicating which model most frequently reproduces features similar to the given observations, and is defined by:

$$(5) \quad \text{AIC} = (-2) \max(\ln \text{likelihood}) + 2(\text{Number of parameters}).$$

A model with a smaller value of AIC was considered a better fit to the observations.

The aftershock sequence of the M_W 5.4 Romania earthquake was compiled on the base of earthquake data presented in Romanian Earthquake Catalogue (ROMPLUS) [14].

We accepted that aftershocks satisfy the space-time criteria introduced and modified for the central Balkans by CHRISTOSKOV and LAZAROV [15]:

$$(6) \quad \begin{aligned} \log R_a(M_m) &= 0.9696 + 0.1243M_m, \\ \log T_a(M_m) &= -0.62 + 0.56M_m \quad (M_m < 6.0), \end{aligned}$$

where M_m is the magnitude of the main event, R_a is the largest distance between the main event and an aftershock, and T_a is the greatest elapsed time since the occurrence of the main shock.

Spatial distribution of the considered aftershocks was illustrated in Fig. 1. It shows the distribution of aftershocks, as well as the main earthquake, which was with a magnitude of M_W 5.4.

The data sample of 3501 aftershocks, with magnitude $M_W \geq 1.2$, which occurred within 533 days after the February 14th, 2023, M_W 5.4 earthquake, is compiled.

To test the completeness of the data sample and to estimate the minimum magnitude of completeness (the so-called threshold magnitude) the magnitude–frequency distribution the Gutenberg–Richter law [16]) was used. The cumulative magnitude–frequency distribution of aftershocks is shown in Fig. 2.

The distribution indicates that the compiled data sample is incomplete below $M_{\min} = 1.8$.

Results. To test the reliability of the estimated p -values for the aftershock sequence, we considered the effects of different $M_{\min}$. We estimated parameters in the modified Omori formula for three different $M_{\min}$ ($M_{\min} = 1.8, 2.0$, and 2.5).

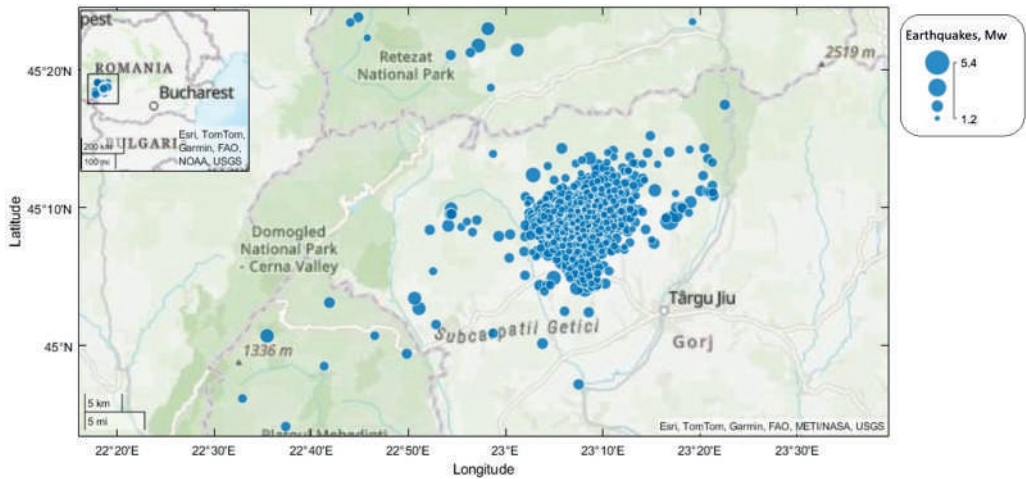


Fig. 1. Space distribution of aftershocks of February 14, 2023, Romania M_W 5.4 earthquake

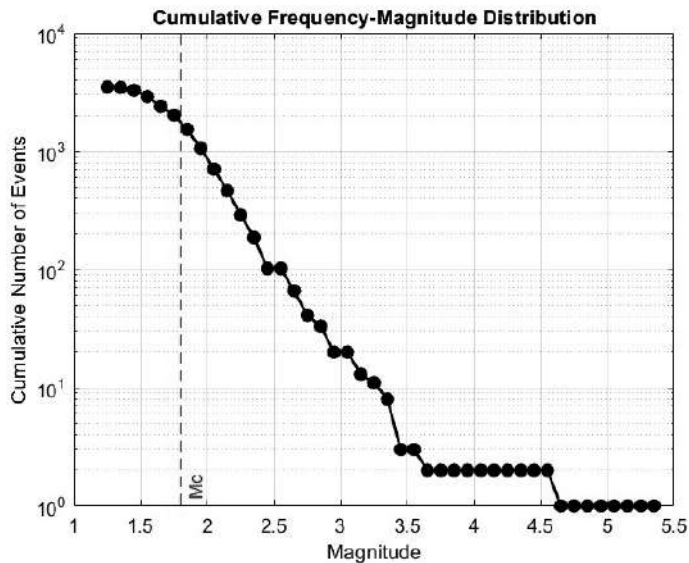


Fig. 2. Frequency–magnitude distribution for 3501 aftershocks with $M_W \geq 1.2$

The results (presented in Table 1) show that the p -value varies slightly from 0.92 to 1.01 with variation of $M_{\min}$.

The parameters K , c , and p of the modified Omori formula (for $T = 553$ days) are calculated by the maximum likelihood method, assuming that the seismicity follows a non-stationary Poisson process. The estimated parameters for the three data samples are presented in Table 1.

The observed aftershock distributions are plotted in blue colour, and the theoretical (model-based) distributions in black, in Fig. 3b, c.

T a b l e 1

Estimates of the parameters of Omori formula and corresponding AIC (for $T_a = 533$ days)

	K	p	c	K_1	p_1	c_1	AIC
An ordinary aftershock sequence, $M \geq 1.8$	186.21	1.01	0.11				-6899.49
An ordinary aftershock sequence, $M \geq 2.0$	76.18	1.00	0.05				-2514.31
An ordinary aftershock sequence, $M \geq 2.5$	8.76	0.92	0.02				85.26
One ordinary and one secondary aftershock sequences, $M \geq 1.8$	184.78	1.04	0.12	9.29	1.04	0.02	-7084.47
One ordinary and one secondary aftershock sequences, $M \geq 2.0$	75.30	1.02	0.05	2.95	1.02	0.01	-2587.54
One ordinary and one secondary aftershock sequences, $M \geq 2.5$	8.69	0.94	0.02	0.49	0.94	0.03	83.50

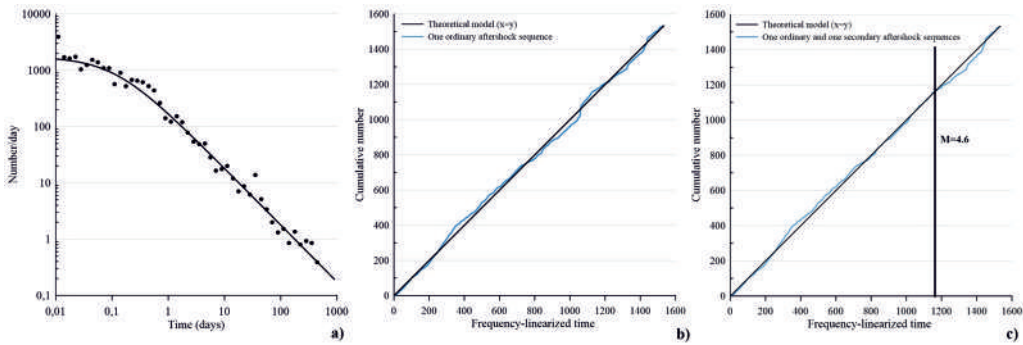


Fig. 3. Temporal distribution of aftershocks for the threshold magnitude $M_{\min} = 1.8$: a) frequency-time t (days) distribution; b) cumulative number of events vs. frequency-linearized time τ for an ordinary aftershock sequence; c) cumulative number of events vs. frequency-linearized time τ for a combination of one ordinary and one secondary sequence

The results for the data set with threshold magnitude $M_{\min} = 1.8$ are displayed in Fig. 3. Figure 3a illustrates frequency-time t (in days) distribution of earthquakes. Figure 3b, c presents the cumulative number of events against the frequency-linearized time τ , using the estimated parameters K , p , c . If the modelling of the sequence is appropriate, the cumulative number of events will increase linearly with τ .

Figure 3a and b suggests the existence of some discrepancies between observed and expected distributions, i.e., the modified Omori formula does not fit the observational data. Figure 3a shows a bump about 34 days after the main shock. This temporal distribution anomaly could be caused by the occurrence of

the strongest aftershocks on March 20, 2023, with magnitude $M_W = 4.6$. Consequently, we tested the model with one ordinary and one secondary aftershock sequences, with the same p -value for both (main and secondary) sequences.

Figure 3c shows the cumulative number of events against the frequency-linearized time τ , using the MLEs of the Omori formula parameters for this model. A good fit between observed and expected distributions can be noticed, without evident periods of decaying and activation of the process. A nearly linear trend of aftershock decay, up to 533 days after the main event, is observed.

All tested models with their corresponding AICs are presented in Table 1.

Discussion. Aftershock decay rate (parameter p in modified Omori's law) contains information about the mechanisms of stress relaxation and frictional strength heterogeneity. The variability in the characteristic p -values is related to the structural heterogeneity, stress and temperature in the crust [18].

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 in different parts of the world [18]. The p -value estimated in the present study is very close to the p -value assessed in GHITA et al. [19] for February 14th, 2023, M_W 5.4 Romania earthquake. Ghita et al. [19] applied an approach based on the modified Omori formula to study the 2023 aftershock sequence, testing several relatively short time periods (hours to one day). The p -value about 1.0 is in the middle of the p -value range obtained for aftershock sequences in Bulgaria and surroundings, $0.71 \leq p \leq 1.17$ [20], and it is in the lower part of the interval obtained for aftershock sequences in Greece, i.e. $0.83 \leq p \leq 1.86$ [17].

Our results confirm the results in the work of UTSU [17] that the p -value is independent of $M_{\min}$, of the input data.

The earthquakes distribution in the aftershock sequence shows a complex temporal pattern. The AIC values for the models with secondary aftershock activity are smaller than those for the ordinary aftershock sequences, for all three data samples. The best model (with the smallest AIC value) is a combination of one ordinary and one secondary sequences for the considered three data sets with different threshold magnitude.

Consideration of recent earthquake sequences suggests that the aftershocks of large earthquakes, although they are, by definition, smaller events, can be very damaging, and should be addressed in emergence planning scenarios. Because of factors such as location and radiation pattern, and the cumulative nature of building damage, aftershocks can cause additional severe damages to those already produced by the mainshocks.

The large aftershock potential needs further assessment. Society should have more knowledge of earthquake seismic hazard issues, including an awareness of potential hazardous shaking just after the main shock, as well as the occurrence of a damaging aftershock several months later.

Conclusion. The aftershock sequences, occurred within 533 days after February 14th, 2023, M_W 5.4 Romania earthquake comprise 3501 aftershocks. Based on the analysis the following conclusions can be drawn:

- A high degree of clustering in the aftershock activity is observed, as well as a well-expressed tendency of expansion of the aftershock area in time as the magnitude decreases.
- A modified version of Omori's law well describes the temporal distribution of the 2023 event in Romania. The p -value, estimated for the aftershock sequence, is in the p -value range that has been estimated for aftershock sequences in different parts of the world. The aftershock sequence of the earthquake is best modelled by the combination of one ordinary and one secondary aftershock sequence.

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.

Acknowledgments. The authors thank the anonymous reviewer for his/her constructive comments, which helped us improve our manuscript.

REFERENCES

- [1] ZHANG S., G. WANG, W. SA (2013) Damage evaluation of concrete gravity dams under mainshock–aftershock seismic sequences, *Soil Dyn. Earthquake Eng.*, **50**, 16–27, <https://doi.org/10.1016/j.soildyn.2013.02.021>.
- [2] ANSARI S. (2017) Aftershocks properties of the 2013 Shonbe M_w 6.3 earthquake, central Zagros, Iran, *J. Asian Earth Sci.*, **147**, 17–27, <https://doi.org/10.1016/j.jseaes.2017.07.042>.
- [3] GARDNER J. K., L. KNOPOFF (1974) Is the sequence of earthquakes in southern California, with aftershock removed, Poissonian?, *Bull. Seism. Soc. Am.*, **64**(5), 1363–1367.
- [4] LIU M., S. STEIN (2011) Aftershocks. In: *Encyclopedia of Solid Earth Geophysics* (ed. H. Gupta), Springer Dordrecht, Netherlands, 192–194.
- [5] WENZEL F., M. ONCESCU, M. BAUR, F. FIEDRICH (1999) An early warning system for Bucharest, *Seismol. Res. Lett.*, **70**(2), 161–169.
- [6] BALA A., V. RAILEANU, C. DINU, M. DIACONESCU (2015) Crustal seismicity and active fault systems in Romania, *Rom. Rep. Phys.*, **67**(3), 1176–1191.
- [7] ZAHARIA B., A. MIHAI, R. DINESCU et al. (2025) Seismic tomography in the Târgu Jiu region (Romania): Relationships with seismic velocity anomalies and fault activity, *Appl. Sci.*, **15**(11), 6084, <https://doi.org/10.3390/app15116084>.
- [8] CRAIU A., M. DIACONESCU, M. CRAIU et al. (2023) Stress field in Targu Jiu seismotectonic area (Romania): Insights from the inversion of earthquake focal mechanisms. In: *23rd International Multidisciplinary Scientific GeoConference SGEM*

- 2023, Conference paper, **22**(1.1), <https://doi.org/10.5593/sgem2023/1.1/s05.72>.
- [9] RADULIAN M., C. IONESCU, A. BALA et al. (2023) Seismic sequence in Southern Carpathians, Gorj area, Romania. Preliminary analysis. In: *Insights of Geosciences for Natural hazards and Cultural Heritage* (ed. F. Chitea), ISBN 978-606-537-637-3.
 - [10] OGATA Y. (1983) Estimation of the parameters in the modified Omori formula for aftershock frequencies by the maximum likelihood procedure, *J. Phys. Earth*, **31**(2), 115–124.
 - [11] AKAIKE H. (1974) A new look at the statistical model identification, *IEEE Trans. Automatic Control*, **19**(6), 716–723, <https://doi.org/10.1109/TAC.1974.1100705>.
 - [12] UTSU T. (1969) Aftershocks and earthquake statistics (I): Some parameters which characterize an aftershock sequence and their interaction, *J. Fac. Sci., Hokaido Univ., Ser. VII (Geophys.)*, **3**, 129–195.
 - [13] OGATA Y., K. SHIMAZAKI (1984) Transition from aftershock to normal activity: The Rat Islands earthquake aftershock sequence, *Bull. Seismol. Soc. Am.*, **74**, 1757–1765.
 - [14] POPA M., A. CHIRCEA, R. DINESCU et al. (2022) Romanian Earthquake Catalogue (ROMPLUS), Mendeley Data, V2, <https://doi.org/10.17632/tdfb4fggghy.2>.
 - [15] CHRISTOSKOV L., R. LAZAROV (1981) General considerations on the representativeness of the seismological catalogues with a view to the seismo-statistical investigations, *Bulg. Geoph. J.*, **3**, 58–72, (in Bulgarian).
 - [16] GUTENBERG B., C. F. RICHTER (1944) Frequency of earthquakes in California, *Bull. Seism. Soc. Am.*, **34**(4), 185–188.
 - [17] UTSU T., Y. OGATA, R. S. MATSU'URA (1995) The centenary of the Omori formula for a decay law of aftershock activity, *J. Phys. Earth*, **43**(1), 1–33.
 - [18] KISSLINGER C., L. JONES (1991) Properties of aftershock sequences in southern California, *J. Geophys. Res.*, **96**, 11947–11958.
 - [19] GHITA C., B. ENESCU, A. MARINUS et al. (2025) Aftershock analysis and forecasting for the crustal seismicity in Romania, *Earth Planets Space*, **77**, 48, <https://doi.org/10.1186/s40623-025-02174-0>.
 - [20] SIMEONOVA S., D. SOLAKOV (1999) Temporal characteristics of some aftershock sequences in Bulgaria, *Ann. Geofis.*, **42**(5), 821–832.

¹*National Institute of Geophysics, Geodesy and Geography,
Bulgarian Academy of Sciences,
Akad. G. Bonchev St, Bl. 3, 1113 Sofia, Bulgaria
e-mails: plamena.raikova@gmail.com, dimos@geophys.bas.bg,
ssimeonova@geophys.bas.bg*

²*National Institute for Earth Physics, P. O. Box MG-2, 12 Calugareni St,
RO-077125 Magurele, Ilfov, Romania
e-mail: ardel@infp.ro*