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TEMPORAL DISTRIBUTION OF THE 2020 PLOVDIV EARTHQUAKE SEISMIC SEQUENCES

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Studying of the temporal distribution of earthquakes is very important for understanding the physics of the earthquake generation process. In the present study the time distribution of the fore-aftershock sequences before and after the 2020 Plovdiv earthquake, with moment magnitude M_W4.5 is analyzed. Foreshocks are one of the few well-documented precursors of large earthquakes. Aftershocks are defined as seismicity above the background activity following a main shock. The properties of aftershock sequences (distinct cluster in space and time) allow time-dependent prediction of aftershock probabilities. We analyze the temporal pattern of earthquake distribution of the foreshock and aftershock sequences of the main event. The temporal distribution of foreshocks shows non-random features. Although dominated by the classic power law decay in time, the aftershocks suggest the existence of secondary aftershock sequence. The attenuation of aftershock activity is well described by the modified Omori formula. Aftershock sequence is best modelled by the combination of one ordinary and two secondary aftershock sequences. Transition from aftershock activity to background seismicity is observed about 62 days after the main shock.

Keywords: foreshocks, aftershocks, temporal distribution, city of Plovdiv

ВРЕМЕВО РАЗПРЕДЕЛЕНИЕ НА СЕИЗМИЧНИ ПОРЕДИЦИ ПРЕДИ И СЛЕД ЗЕМЕТРЕСЕНИЕТО ОТ 2020 Г. В РАЙОНА НА ГРАД ПЛОВДИВ

Пламена Райкова

Резюме: Земетресението е уникално природно явление, определящо се от голям брой фактори, които не могат да бъдат непосредствено наблюдавани и трудно се контролират. За сеизмично застрашените области (каквато е територията на България) земетресенията са неделима част от природните процеси. Земетресенията са неравномерно разпределени в пространството и времето. Изследването на времевото им разпреде-

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ление е съществено за опознаване на сеизмогенния процес. В сеизмологичния анализ Поасоновият процес се използва за описание разпределението на земетресенията във времето. С него добре се описват сеизмологичните данни, но основният му недостатък като модел на сеизмичния процес е, че не отчита възможността земетресенията да се генерират в групи. Групите от земетресения се разглеждат като съществен неслучаен елемент на сеизмичността. Изявени и разпознаваеми клъстери от земетресения са фор-афтършоковите поредици и сеизмичните роеве. Форшоковите събития са група земетресения, предхождащи по-силното главно събитие. Ако този клъстер може да бъде разпознат, преди да се реализира главното земетресение, то тази група би се превърнала в полезен инструмент за прогнозиране на силни земетресения. Афтършоковите поредици са тези групи от земетресения, които се реализират непосредствено след главното събитие и постепенно затихват и отслабват по сила във времето. Една от феноменалните характеристики на афтършоковия процес е затихването му във времето по обратен степенен закон (модифицирана формула на Omori), докато повечето от физичните процеси затихват експоненциално във времето.

В настоящото изследване е анализирано времевото разпределение на фор-афтършоковата активност преди и след земетресението от 01 май 2020 г. с магнитуд по сеизмичен момент M_W4.5, реализирано в района на град Пловдив, сеизмогенна зона Марица. За оценка на времевото разпределение на събитията от афтършоковата поредицата от 2020 г. е приложена модифицираната формула на Omori. Сравнени са различни модели за разпределение на афтършоковата активност във времето чрез информационния критерий на Akaike. Основен източник на информация за разгледания сеизмичен клъстер са данни от Националната оперативна телеметрична система за сеизмологична информация (НОТССИ). При времевото разпределение на форшоковата активност се открояват две седмици с активност, след което активността намалява и се наблюдава сеизмично затишие преди реализацията на главното земетресение. От честотно разпределение на афтършоковите събития може да се каже, че в първо приближение затихването на афтършоковата активност се описва добре с модифицираната формула на Omori. При честотно-линеаризирано разпределение на афтършоковите събития се наблюдава преминаване от афтършокова активност към фонова сеизмичност около 62 ден след главното събитие. Моделът в най-добро съответствие с наблюденията е моделът с две вторични серии, без магнитуден праг. Получените оценки на параметъра p са над 0.9, което е характерно за районите на Южна България, където афтършоковият процес затихва значително по-бързо.

Ключови думи: форшок, афтършок, времево разпределение, град Пловдив

INTRODUCTION

Modelling of space-time and energy distribution of earthquakes is a major aspect of modern seismological research. Examination of the temporal distribution of earthquakes is of fundamental importance for understanding the physics of the earthquake generation process. The temporal clustering of foreshocks and aftershocks is a dominant non-random element of the seismicity, so when the clusters are removed, the remaining activity can be modelled as a Poisson process (Gardner, Knopoff, 1974). There is still no precise definition for seismic clusters despite of the concept that an earthquake is a key aspect of seismicity that provides key information on earthquake dynamics (Zaliapin, Ben-Zion, 2013). Statistically significant clusters consist of foreshocks, main shocks, and aftershocks.

Foreshocks are one of the few well-documented precursors of large earthquakes. This type of events is observed within a few hours, several months or a year before the main shock (among others Molchan et al., 1999; Papadopoulos et al., 2000). Even if it is not considered a prognostic sign, the foreshocks show stress accumulation in the surroundings before the large earthquake. The nature of this type of sequences is very important for earthquake prediction.

Aftershocks are defined as seismicity above the background activity following a main shock (Liu and Stein, 2011). Aftershocks occur after the main event and their frequency decays over time, typically following a pattern known as the Omori's law, which later is modified by Utsu (1961) and is known as modified Omori's law. The power-low decay represented by the modified Omori relation is an example of temporal self-similarity of the earthquake source process. The duration of aftershock sequences may last months, a few years, or even longer for earthquakes within stable continental interiors (Stein and Liu, 2009). Some authors recognize that the main causes of aftershocks include main shock-induced changes of frictional properties of the fault zone and stress perturbations (e.g. Liu and Stein, 2011).

In this study the temporal patterns of fore – aftershock sequences of the May 1, 2020 earthquake with moment magnitude M_W4.5 (T_0=11:01:38, ϕ=42.26°, λ=24.87° and h=5 km) are examined. The event occurred near the city of Plovdiv, in the Maritsa seismogenic zone. The 2020 M_W4.5 Plovdiv earthquake was felt on the territory of central southern and southwestern Bulgaria. The earthquake was felt (with intensity up to 5.5 MSK64) in the city of Plovdiv and its surroundings.

The contemporary tectonic activity of the area is associated with Maritsa fault system with WNW-ESE direction. The Maritsa fault with its satellites belongs to structures with a long-lasting development, which continues in the neotectonic period. The available historical documents prove the occurrence of destructive earthquakes during the 18th–19th centuries in the Maritsa zone (Glavcheva et. al). In the 20th century the Maritsa zone has experienced two strong earthquakes: the Chirpan earthquake of April 14, 1928 with M_W6.5 and the Plovdiv earthquake of April 18, 1928 with M_W7.1. The 1928 earthquakes destroyed 74000 buildings in the towns of Plovdiv, Chirpan and Parvomay (Kirov, 1945).

The manifold purpose of the study is first to examine temporal pattern of the fore-aftershock distribution in the epicentral zone of the 2020 Plovdiv earthquake. Then to test different statistical models for aftershock occurrence based on the transformation of the time scale t to a frequency-linearized time scale τ. Finally, the Akaike Information Criterion, AIC (Akaike, 1974, 1977) is used to select the best statistical model for aftershock occurrence.

METHOD AND DATA

METHOD

Different studies show that foreshock activity increases approximately as the inverse of time before mainshock (e.g., Mogi, 1969). There are large variations in the distribution of the foreshock's activity. For that, reason it is difficult to find an empirical law describing their occurrence over time before the main event.

In term of occurrence rate, foreshocks are less frequent than aftershocks (Jones and Molnar, 1979). In this study is applied two different models to generate distribution of time intervals between earthquakes (fore and aftershocks) and the main event. For the foreshock a uniform distribution is used while for the aftershock data we used the model obeying a modified Omori's law (Utsu, 1969):

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

where: n(t) is frequency of aftershocks at time t; t is the elapsed time since the occurrence of the main shock, and K, p, c are constants. The most important parameter is parameter p, which characterizes the decay of the aftershock activity.

Based on the assumption that aftershocks are distributed as a non-stationary Poisson process, Ogata (1983) proposed to use the maximum likelihood method for estimating the parameters K, c and p in the modified Omori formula. The intensity function of the Poisson process λ(t) is defined by the relation:

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

Using the modified Omori formula, the intensity function becomes:

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

The maximum likelihood estimates (MLE) of the parameters are those, which maximize function (3) with, the corresponding vector q (Ogata, 1983).

An integration of the intensity function λ(t) gives a transformation from the time scale t to a frequency-linearized time scale t (Ogata, 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 an aftershock sequence can be defined as:

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

The time scale t 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 t should be observed if an appropriate model has been selected. Anomalies in the aftershock activity are more evident on the N (t) plot than on n(t). Thus the t time axis will be used to detect secondary aftershock activity.

To select which model fits the observations better, the Akaike Information Criterion (AIC) (Akaike, 1974) is used. This is a measure of which model most frequently reproduces features like the given observations, and is defined by:

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

A model with the smallest value of AIC is a better fit to the observations.

DATA

We have selected a space-time window to form the data set used in our study. All events recorded by NOTSSI (National Operative Telemetric System for Seismological Information) that are in the vicinity of the inferred rupture zone of the Plovdiv earthquake are included. To estimate the parameters of the distributions of aftershock events with time, a PASKAL software package is developed (Solakov, 2010).

In the present study we analyze the data set of 6 foreshocks and 63 aftershocks of the May 1, 2020 earthquake. To assure a consistency in the locations, we relocated all NOSSI data for the sequence, applying a version of soft were HYPO 71- called DHYPO (Solakov, Dobrev, 1987) which is used in Bulgarian seismological practice. The body P-wave magnitude (Christoskov et al., 2012) was estimated for each event of the compiled data set.

To define time boundaries, we study the frequency-time distribution of the earthquakes located in the considered area from January 2020 to March 2021 (Fig. 1). The data show increasing rate of the seismic activity in the region in April 2020 and stayed relatively high for about 9 months (Fig. 1). The events around Plovdiv are almost uniformly distributed in time before April 2020 and after December 2020. Thus, the data we used for this study were earthquakes located in Plovdiv area from 1 April 2020 to 31 December 2020.

In the present study the compiled data set is divided into two subsets: foreshocks (quakes preceding the main event) and aftershocks (earthquakes following the main event). The two subsets are analyzed separately.

We accept that aftershocks satisfy the space-time criteria introduced by Gardner and Knopoff (1974) and modified by Christoskov and Lazarov (1981) for the Central Balkans:

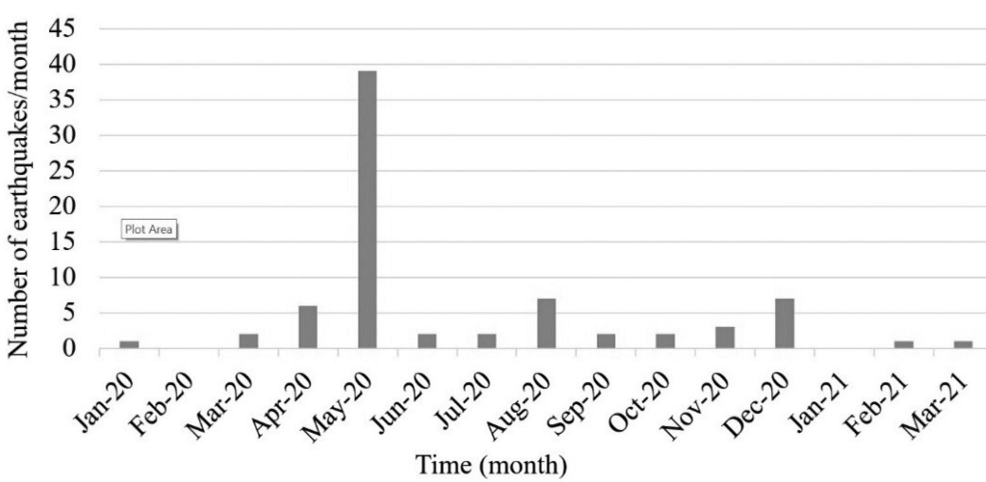

Fig. 1. Frequency-time distribution for the earthquakes in the area of the Plovdiv sequence

$$\log R_a(M_m) = 0.9696 + 0.1243\, M_m$$

$$\log T_a(M_m) = -0.62 + 0.56\, M_m \qquad (M_m < 6.0) \qquad (6)$$

$$\log T_a(M_m) = -5.25 + 2.15\, M_m - 0.137\, M^2_m \qquad (M_m \geq 6.0),$$

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.

RESULTS

The results are presented in Figs. 2-5 and Tab. 1. The temporal distribution of foreshocks is presented in Fig. 2, while for the aftershocks it is presented in Figs. 3-5 and Tab. 1.

The temporal distribution of foreshock sequence is shown in Fig. 2 and indicates that the pre-shocks have an uneven distribution over time. A well-expressed cluster occurred approximately month before the main event. Precursor aseismic gap of 14 days before the main shock are observed in Fig. 2.

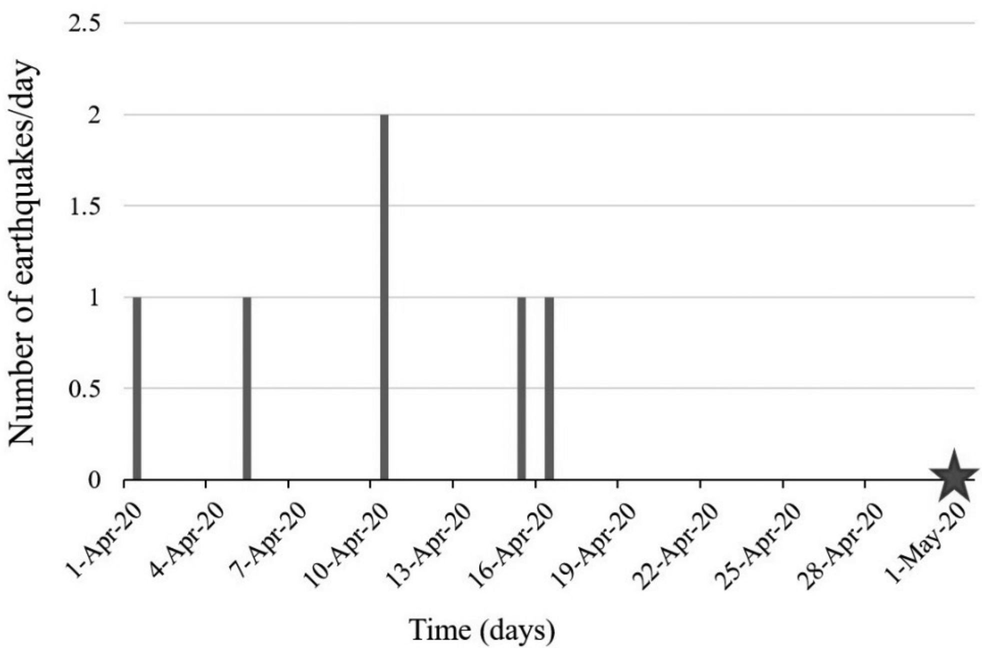

Fig. 2. Temporal distribution of foreshocks - daily distribution of foreshocks before the main event (red star)

In the study, two aftershock data samples are analyzed: the first includes all aftershocks, located inside the area of interest; and the second data set covers all events with magnitude larger than or equal to 2.0, $M_p \geq 2.0$ that are located in the same area. Furthermore, we analyze the aftershock sequence for two different time intervals after the main earthquake. The time interval T_a=80 days is the one calculated value of the elapsed time since the occurrence of the main shock using Eq. 6., and second time interval is T_a=228 days (observed time interval).

The parameters K, c, and p in the modified Omori formula (Eq. 1) are estimated using the maximum likelihood method and presented in Tab. 1.

Table 1

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

Model	**T**	**K**	**p**	**c**	**K_1**	**p_1**	**c_1**	**K_2**	**p_2**	**c_2**	**AIC**
An ordinary aftershock sequence-all aftershock	228	4.77	0.80	0.01							130.02
An ordinary aftershock sequence-all aftershock	80	5.81	1.04	0.06							-7.20
An ordinary aftershock sequence, with threshold magnitude Ma=2	228	3.34	0.99	0.02							42.06
An ordinary aftershock sequence, with threshold magnitude Ma=2	80	3.44	1.02	0.02							2.74
One ordinary and one secondary aftershock sequences-all aftershocks	228	4.44	0.81	0.01	0.43	0.81	0.03				129.46
One ordinary and one secondary aftershock sequences-all aftershocks	80	5.77	1.06	0.06	0.08	1.06	0.01				-15.31
One ordinary and one secondary aftershock sequences, with threshold magnitude Ma=2	228	2.40	1.10	0.02	2.48	1.10	1.06				44.40
One ordinary and one secondary aftershock sequences, with threshold magnitude Ma=2	80	3.34	1.05	0.03	0.08	1.05	0.01				-7.00
One ordinary and two secondary aftershock sequences-all without threshold magnitude	228	4.05	1.04	0.03	1.23	1.04	0.18	44.87	1.04	320.6	132.08

One ordinary and two secondary aftershock sequences-all without threshold magnitude	80	4.94	1.04	0.04	0.21	1.04	0.01	0.07	1.04	0.01	-25.84
One ordinary and two secondary aftershock sequences, with threshold magnitude Ma=2	228	2.17	1.25	0.03	3.80	1.25	1.25	432.0	1.25	4206.7	47.00
One ordinary and two secondary aftershock sequences, with threshold magnitude Ma=2	80	2.17	1.23	0.03	3.62	1.23	1.29	0.02	1.23	0.01	-10.61

The frequency-time distributions of earthquakes for different time intervals are presented in Fig. 3.

The observed distribution is compared to the theoretical distribution, 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 of events will increase linearly with τ. There is a relatively good correlation between the theoretical and the observed distribution for all cases.

The comparison between empirical and theoretical distribution (Fig.3) shows that as a first approximation the temporal distribution of earthquakes in aftershock sequence of the Plovdiv earthquake is well described by the modified Omori formula.

Plots of the cumulative number of events versus frequency-linearized time τ are presented in Fig.4. Figure shows bumps about 2 and 7 days after the main shock. Bumps between 2 and 7 days after the main event are observed in all plots. The aftershock activity decreases around the 2^{nd} day and increases after 7^{th} day. This temporal distribution anomaly could be caused by the occurrence of two of the strongest aftershocks: first on the 2 May 2020 with magnitude M_p2.9 and second on 7 May 2020 with magnitude M_p3.2. Consequently, we reconstructed a model, which considers the effect of a secondary aftershock activity. We tested a model with one or two secondary aftershock sequences after 2 and 7 days and the same p value for the main and secondary aftershocks sequences (Fig.5 and Fig. 6). The model is applied for the two data sets.

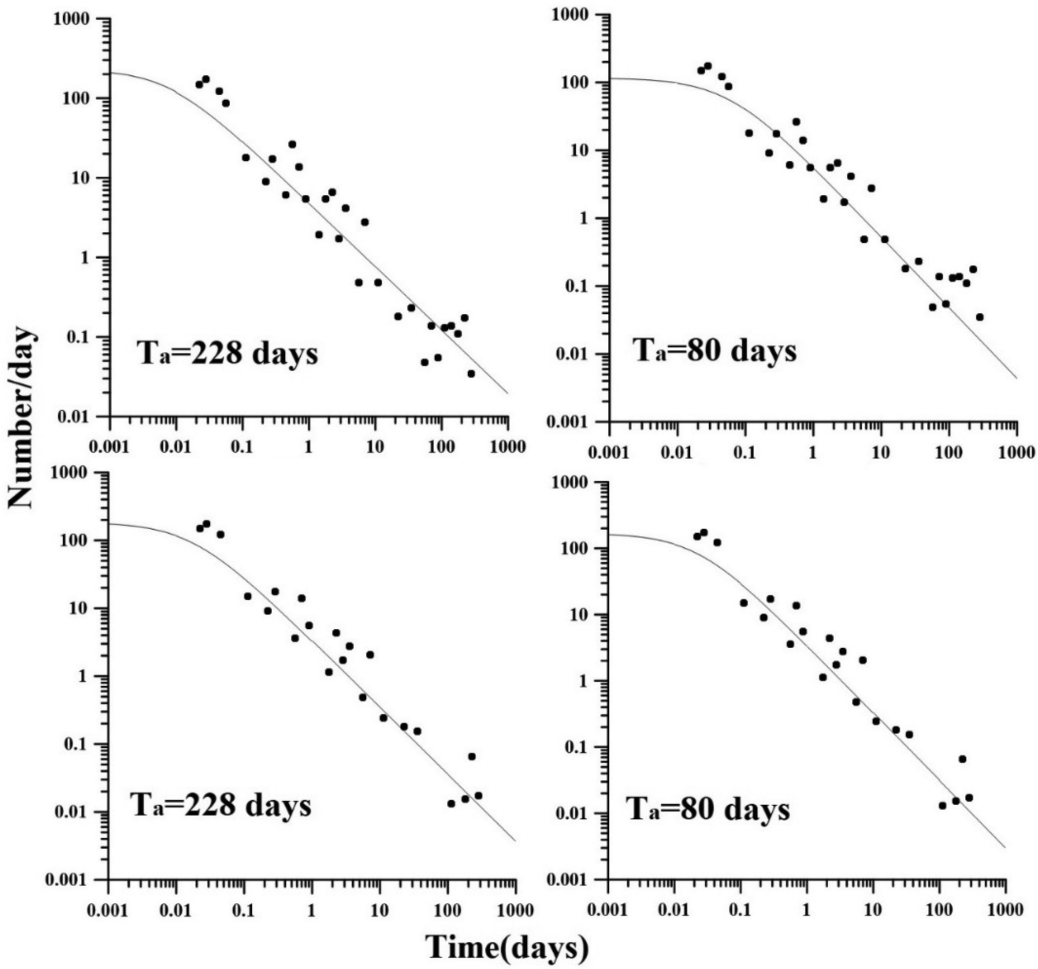

Fig. 3. Frequency-time distributions of aftershocks: a) for a set of data including all aftershocks, for T_a=228 days; b) for a set of data including all aftershocks, for T_a=80 days; c) for aftershocks with magnitude $M_P \geq 2.0$, for T_a=228 days; d) for aftershocks with magnitude $M_P \geq 2.0$, for T_a=80 days

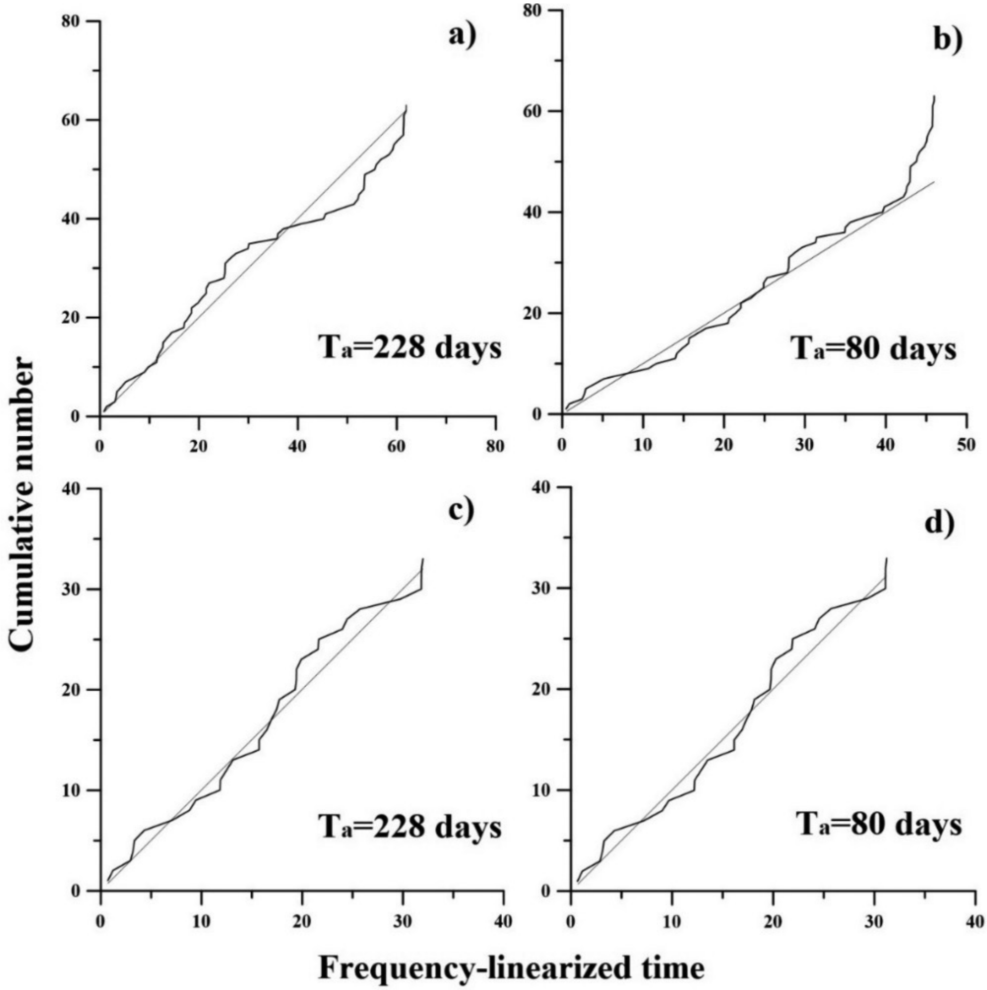

Fig. 4. Plot of the cumulative number of events versus frequency-linearized time τ:
a) for a set of data including all aftershocks, for T_a=228 days; b) for a set of data including all aftershocks, for T_a=80 days; c) for aftershocks with magnitude $M_P \geq 2.0$, for T_a=228 days; d) for aftershocks with magnitude $M_P \geq 2.0$, for T_a=80 days

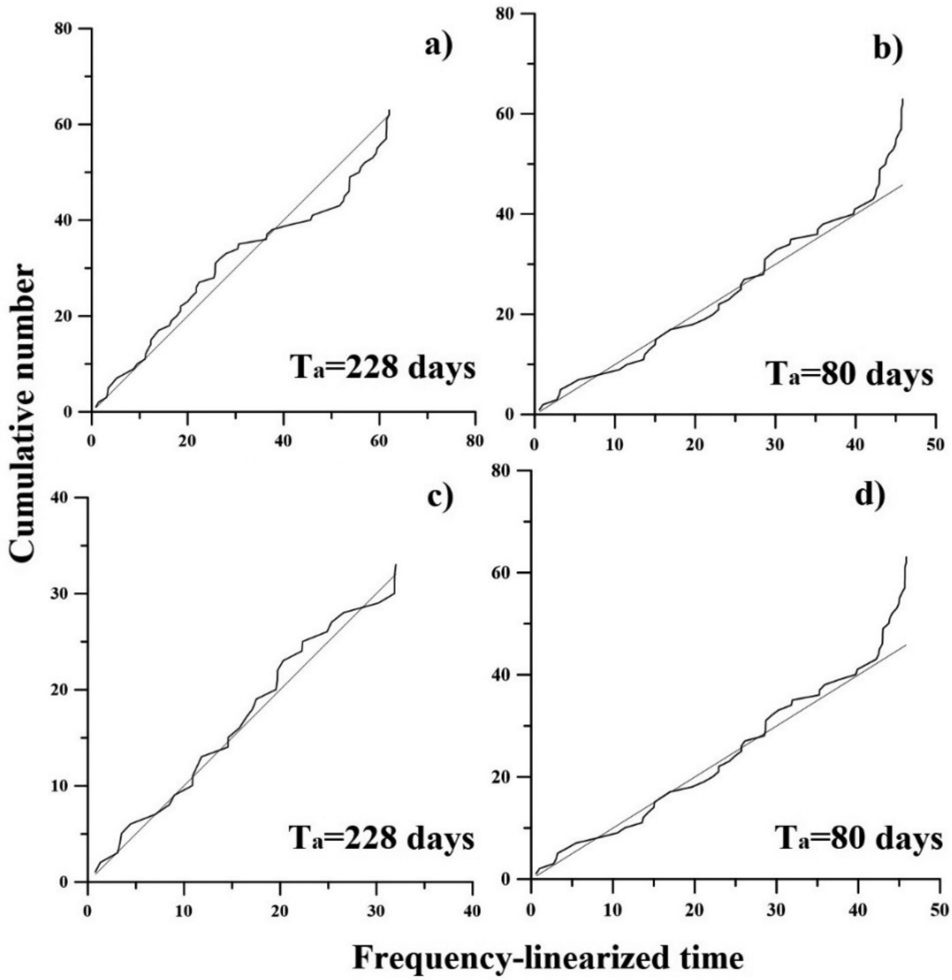

Fig. 5. Plot of the cumulative number of events versus frequency-linearized time τ for one ordinary and one secondary aftershock: a) for a set of data including all aftershocks, for T_a=228 days; b) for a set of data including all aftershocks, for T_a=80 days; c) for aftershocks with magnitude $M_p \geq 2.0$, for T_a=228 days; d) for aftershocks with magnitude $M_p \geq 2.0$, for T_a=80 days

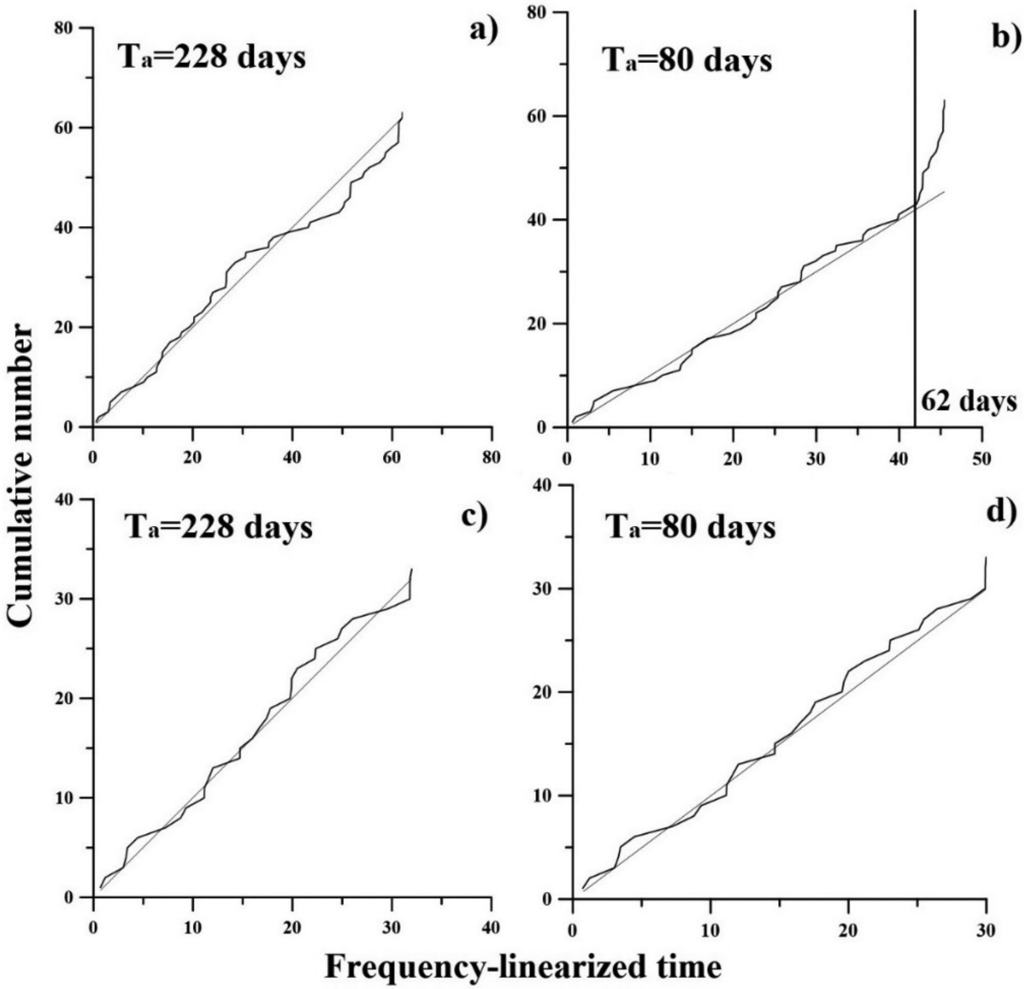

Fig. 6. Plot of the cumulative number of events versus frequency-linearized time τ for one ordinary and two secondary sequences: a) for a set of data including all aftershocks, for T_a=228 days; b) for a set of data including all aftershocks, for T_a=80 days; c) for aftershocks with magnitude $M_p \geq 2.0$, for T_a=228 days; d) for aftershocks with magnitude $M_p \geq 2.0$, for T_a=80 days

The results (Fig. 6 and Table 1) show that the model with one ordinary and two secondary sequences is the best fit between observed and expected distributions for the 2020 Plovdiv earthquake aftershock seismic sequence. The temporal distribution of the aftershocks following the 2020 Plovdiv earthquake is similar to the aftershock sequences in Southern Bulgaria obtained by Simeonova and Solakov (1999) – well expressed secondary aftershock activity and relatively high values of p for the main sequence (p>1) (Simeonova, Solakov, 1999).

Figure 6b shows that a nearly linear trend of aftershock decay continues up to 62 days. About 62 days after the main shock the cumulative number of aftershocks increases rapidly with τ, showing a significant deviation from the prior trend. No large earthquake occurred in the region at that time. Therefore, this change in slope could be treated as a transition from aftershock activity to background seismicity.

CONCLUSIONS

• The temporal distribution of foreshocks shows non-random features. The cluster occurred approximately month before the main event. Precursor aseismic gap of 14 days before the main shock are observed.

• Temporal distribution of aftershocks is well described by the modified Omori formula (as a first approximation).

• The temporal distribution of the aftershocks following the 2020 Plovdiv earthquake is similar to the aftershock sequences in Southern Bulgaria, which is characterized with well-expressed secondary aftershock activity and relatively high values of p for the main sequence ($p>1$) (Simeonova, Solakov, 1999).

• The 2020 Plovdiv earthquake aftershock sequence is best modelled by the combination of one ordinary and two secondary aftershock sequences. Transition from aftershock activity to background seismicity is observed about 62 days after the main shock.

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