

Short-Term Seismic Activity in Vrancea. Inter-Event Time Distributions

Bogdan Felix Apostol^{*,1} and Liviu Cristian Cune²

⁽¹⁾ National Institute for Earth Physics, Călugăreni Street, 12 Magurele, Ilfov, Romania

⁽²⁾ National Institute of Physics and Nuclear Engineering, Magurele, Ilfov, Romania

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Abstract

Short-term seismic activity in Vrancea is analyzed by means of the inter-event magnitude distributions (distributions of the next seismic event following a conditional seismic event). This seismic activity in Vrancea is fitted by Omori-type time-power laws, with possible correlations over a range of 20–25 days, for magnitudes $M < 4-5$. Such temporal patterns can be employed in seismic hazard and risk estimation, providing the data set is statistically significant.

Keywords: inter-event time distributions; next-earthquake time-magnitude distributions; Omori law.

1. Introduction

The general goal of the statistical analysis of short-term seismic activity, especially the inter-event time distributions (next-earthquake, inter-occurrence, waiting time distributions), is to reveal possible regular patterns of earthquake occurrence (see, for instance, Bak et al., 2002, Lindman et al., 2005, Corral, 2004, 2005, and, especially, de Arcangelis et al., 2016 and References therein). Needless to say, such information is of relevance for seismic hazard and risk estimation. Short-term earthquake forecasting models were put forward [Reasenber and Jones, 1989, 1994; Ogata, 1988, 1998; Gerstenberger et al., 2005; Omi et al., 2016, de Arcangelis et al., 2018], where universal scaling laws [Bak et al., 2002, de Arcangelis et al., 2016] have been discussed, possibly with a limited validity [Lindman et al., 2005], clustering and time-decreasing sequences governed by Omori-type power laws, or stochastic point-processes [Ogata, 1988, 1998]. We report herein upon similar statistical distributions for short-term seismic activity in Vrancea, focusing especially on their temporal behavior over short times. A general statistical analysis of the seismic activity in Vrancea has been reported previously [Apostol, 2006a, 2019].

A geometric-growth model has been introduced for energy accumulation in the focal region by Apostol [2006a]. Making use of this model, time, energy and magnitude distributions of earthquakes have been derived, in particular the well-known magnitude distribution law $\beta e^{-\beta M}$. These results have been applied to a set of 1999 earthquakes with magnitude $M \geq 3$, which occurred in Vrancea between 1974 and 2004. This statistical analysis provided the value $\beta=1.89$. The analysis has been updated recently to 3640 Vrancea earthquakes with $M \geq 3$, corresponding to the period 1981-2018 [Apostol, 2019].

2. General considerations upon temporal distributions of earthquakes

It is generally accepted that earthquakes may conveniently be divided into background earthquakes and earthquakes accompanying main seismic shocks, as aftershocks and foreshocks. The background earthquakes are characterized by a mean recurrence time, depending on their energy (magnitude). The mean recurrence time has been interpreted as a failure time in a brownian-motion model [Matthews et al., 2002]. Poisson-like random processes may also be employed for the temporal distributions of the background earthquakes, as for rare events. They exhibit the well-known Gutenberg-Richter magnitude distribution $\beta e^{-\beta M}$, where M denotes the magnitude, which is well documented for various types of seismic activities, periods and regions. A typical value $\beta = 1.17$ is provided for parameter β by an isotropic point-like seismic focus model [Apostol, 2006 a,b], though different values are also known, like, for instance, $\beta = 1.89$ for Vrancea seismic region [Apostol, 2006a]. Similarly, data given by Bullen [1963], indicate $\beta = 1.38$ for a large set of global earthquakes. Variations in these parameters were reported, depending on the magnitude threshold [Godano et al., 2014]. The value $\beta = 1.89$ corresponds to a geometric-growth model of an approximate faulting geometry for Vrancea focal region [Apostol, 2006 a,b]. Also, tectonic-style variability for this parameter has been reported for various seismic regions [Wiemer and Wyss, 2002; Giulia and Wiemer, 2010].

Background earthquakes represent a distinct seismic activity over long times. When a main shock is present, the seismic activity over short time is dominated by accompanying seismic events. Their temporal distributions are power laws of Omori type [Omori, 1894; Utsu, 1961], like $1/t$, where t is time measured with respect to the main shock, both in the future, as for aftershocks, and in the past, as for foreshocks (usually with a cutoff time). It is assumed, on theoretical grounds, that the accompanying seismic activity is symmetric under time reversal with respect to the main shock [Papazachos, 1978; Kagan and Knopoff, 1978; Jones and Molnar, 1979], although, in practical realizations, the past and future wings of these distributions are often unbalanced [Kazemian et al., 2015]. The pair distributions used here for our next-earthquake analysis are symmetric by their definition. The assumption that the analysis of the foreshock activity may shed light upon the occurrence of the main shock is questionable [Sornette et al., 1992; Sornette and Sammis, 1995; Sornette 1998; Helmstetter and Sornette, 2002, 2003; Felzer et al., 2004; Lippiello et al., 2012a, 2017; Seif et al., 2018]. Omori laws may arise from a self-replication phenomenon underwent by an original, exponential generating distribution [Apostol, 2006c], the aftershocks and foreshocks being distributed by a Gutenberg-Richter law in magnitude, as suggested previously [Vere-Jones, 1969]. Generating exponential distributions for the accompanying seismic activity have also been used to analyze Bath's law [Bath, 1965; Console et al., 2003; Helmstetter et al., 2004].

If the accompanying seismic activity is viewed as a relaxation process [Apostol, 2006 a, b], its time distribution can be written as

$$\frac{dp}{d|t|} \sim e^{-\alpha|t|} \quad (1)$$

where t is the time measured with respect to the moment of the main shock and α is a positive-valued coefficient of relaxation. The distribution given by equation (1) is symmetric in the parameter α and the statistical variable $|t|$. Therefore, we may assume that the parameter α is also a statistical variable, and we may set $\alpha = \gamma r$, where gamma is a positive constant and r is a statistical variable. This corresponds to an ETAS model [epidemic-type aftershock sequence, Ogata 1988, 1998; Zhuang et al., 2011] with a continuous branching range, governed by r . Therefore, we have a two-variable distribution P , which can be written as

$$\frac{d^2P}{drd|t|} \sim e^{-\gamma r|t|} \quad (2)$$

whence, by integrating with respect to r , we get

$$\frac{dp}{d|t|} \sim \int_0^\infty dr \cdot e^{-\gamma r|t|} = \frac{1}{\gamma|t|} \quad (3)$$

which is Omori power law. This is another derivation of Omori law, which is equivalent with the derivation that makes use of the self-replication process described by Apostol [2006c].

Omori's law represents only a particular pattern in the short-term seismic activity accompanying a main seismic shock, the seismic activity over a short-time scale being more complex. The scarcity of data regarding the foreshocks (i.e. the poor statistics) and the difficulty of identifying the aftershocks may render Omori's law of little practical use. In general, it is still missing a practical, reliable method of disentangling the truly accompanying seismic activity from other, background seismic activity, which may have not a direct relationship with the main shock, especially for the long tail of Omori's law (declustering problem). In addition, the short-time seismic activity may exhibit a more complex pattern, of a multiple-branch character, indicating a superposition of Omori-type distributions. The short-time seismic activity may be described by a set of independent statistical variables, like, for instance, magnitude, time, location, etc., in a stochastic point-process approach, correlations included. Such short-term earthquake forecast models have been introduced in the fundamental works of Ogata, 1988, 1998. A parameter-decoupling scheme was used in the short-term sequence-clustering forecast model proposed for California [Gerstenberger et al., 2005; Reasenber and Jones, 1989, 1994; Omi et al., 2016; de Arcangelis et al., 2018], which introduced a probability $P(M,t,r) \sim e^{-\beta M} \cdot \frac{1}{t_c+t} \cdot \frac{1}{(r_c+r)^2}$ for earthquakes characterized by magnitude M , occurrence time t , and location r , and written own this probability like a product of Gutenberg-Richter magnitude distribution and Omori-type distributions, where t_c and r_c are time and spatial cutoff parameters, respectively (for an isotropic spatial distribution). Such a probability law is fitted to empirical data, and employed for short-term prediction of daily rates of earthquakes. For a particular earthquake sequence the evolution parameters may be updated in real time, and employed for the next-day prediction.

3. Next-earthquake correlation functions

In view of the complexity of the statistical behavior of the short-term seismic activity, more general approaches may be convenient. Such approaches should be of more practical relevance, without resorting too much to patterns established statistically on general sets of data. From the practical standpoint the most relevant question in short-term earthquake forecasting seems to be "what happens next?". The general approach described herein is focused on this main question. It is based on inter-event time distributions employed for statistical analysis of short-term seismic activity. Suppose that an earthquake occurs at time t_0 and the next one occurs at some time t measured with respect to t_0 . Then we may define a distribution $P(t)$ of these next earthquakes, and determine it from a set of relevant statistical data. Once determined, it may be used for estimating the time probability of occurrence of the next earthquake, based on the principle "what happened will happen again". Characteristic scale time or size, or correlation range could be identified from the statistical analysis of such functions, providing the statistical set of data is large enough, which may shed light on the statistical patterns of a seismic activity. The statistics is rather poor, in general, precisely for that range of characteristic parameters where the estimation of the seismic hazard and risk is most interesting, like, for instance, for high values of magnitude M . The inter-event time distribution approach is applied here to earthquakes occurring in Vrancea, in order to illustrate its predictive capabilities and limits.

Temporal correlations exhibited by inter-event time distribution functions are described by gamma distributions, which imply power laws multiplied by exponentials [Corral, 2004, 2005]. Magnitude correlations have been demonstrated by a more elaborate model of dynamic scaling [Lippiello et al., 2008, 2012b; see also Stallone and Marzocchi, 2019]. Also, deviations from gamma distributions are reported [Bottiglieri et al., 2010; Lippiello et al., 2012c]. In general, the correlations involved in the short-term seismic activity are similar with those pertaining to accompanying seismic activity, which makes reasonable an Omori-type law for the former distributions.

4. Brief characterization of Vrancea earthquakes

The seismic area that is analyzed here is Vrancea, one of the most active intracontinental seismic areas in Europe. The earthquakes occur here within a volume with lateral extent $\sim 30 \times 70 \text{ km}^2$ in the depth range 60-180 km. The rate of the seismic moment release is about $1.2 \times 10^{12} \text{ Nm/yr}$ [Apostol, 2006 a,b]. Vrancea seismic region

exhibits mainly middle-depth earthquake (~80 km to ~200 km), and occasionally crustal, or surface, small earthquakes. Strong earthquakes occur sometimes in Vrancea, as, for instance, $M=7.4$, March 4, 1977, depth 94 km, or $M=7.1$, August 30, 1986, depth 131 km. Nine earthquakes with magnitude $M>7$ have been recorded in Vrancea in the past two centuries. Although several tectonic models, spanning a large range of geodynamic scenarios, have been advanced to explain the characteristics of this undercrustal seismicity, the nature and mechanisms for earthquake generation are still subjects of debate. The statistical analysis of the associated distribution functions may provide information on the time and size patterns of earthquake occurrence if the statistical data set is large enough. A set of 1999 earthquakes with magnitude $M\geq 3$, occurred in Vrancea between 1974 and 2004 has been analyzed by using magnitude distribution of the type $\beta e^{-\beta M}$ and exceedance rate, with $\beta=1.89$ and a total seismicity rate $1/t_0=10^{4.21}$ per year, on average [Apostol, 2006a]. The basic data set used for the statistical analysis reported here (magnitude step $\Delta M=0.1$) includes 3640 earthquakes with (moment) magnitude $M\geq 3$ recorded between 1981 and 2018 (38 years) [ROMPLUS Catalog, 2018]. The magnitude distribution of these Vrancea earthquakes has been analyzed by using the Gutenberg-Richter law [Apostol, 2019], with $\beta\cong 2.1$ and $1/t_0\cong 10^{4.92}$ [error $\cong 10\%$, Apostol, 2019].

5. Inter-event time distributions for Vrancea

For the sake of simplicity we neglect here the geographical and depth distribution of the earthquakes in Vrancea, because, on one hand, these earthquakes do not exhibit a large variability with respect to location coordinates, and, on the other hand, their inclusion may reduce considerably the size of the data set. Therefore, the generic parameter used in the analysis of the inter-event time distributions is the magnitude M . Seismic activity of the intermediate-depth source of region Vrancea (Romania) is analyzed here in terms of inter-event time-magnitude distributions. The data considered are seismic events with moment magnitude $3.0 \leq M$ (3640 events), which occurred during about four decades (since 1981 to 2018, 38 years). For this time interval and magnitude threshold, the ROMPLUS Catalog has been used [ROMPLUS Catalog, 2018].

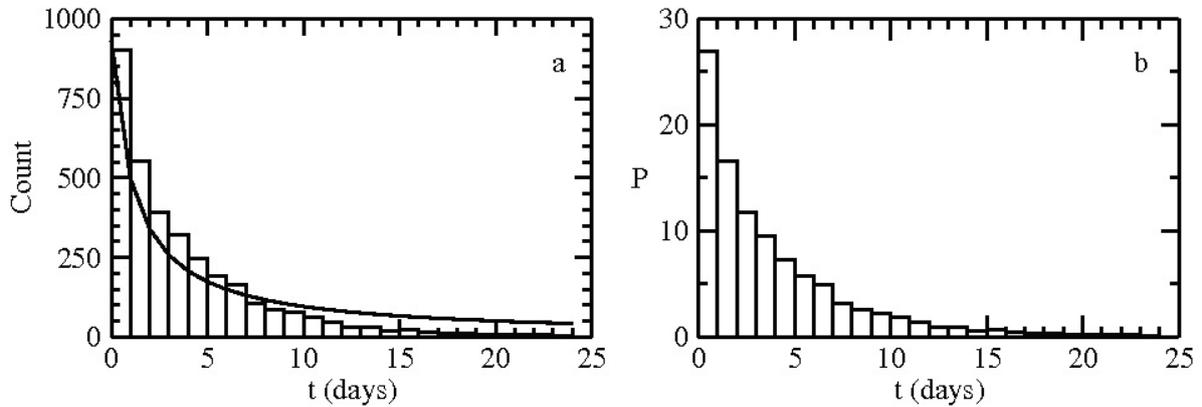


Figure 1. Inter-time distribution of seismic events in Vrancea 1981 – 2018 (3640 events, $M_0, M \geq 3$, panel a) and probabilities $P = P(t)$ (in %, panel b). The fitting curve in panel a is $1066.45/(1.15+t)$ (determination coefficient 0.96).

The seismic events with $M\geq 3$ are distributed in Figure 1 on the inter-event time (panel a); the corresponding probabilities $P(t)$ (in %), calculated from the frequency of the events, are shown in Figure 1 panel b (time is measured in days on the abscissa). We have taken all the earthquakes with magnitude $M\geq 3$ and have read from data how many days elapsed from each such earthquake to the next earthquake with magnitude $M\geq 3$ (a next-earthquake pair distribution). We can see that the rate of occurrence per day of the next earthquake follows a power-law time dependence similar to Omori's law, over a time window of about 25 days. The distribution is fitted with the law $a/(b+t)$, where $a=1066.45$, $b=1.15$ and t denotes the time (coefficient of determination $R=0.96$; the coefficient of

determination is defined as $R^2 = 1 - \sum (d_i - f_i)^2 / \sum (d_i - \bar{d})^2$ where d_i are the data, \bar{d} is the mean value of the data and f_i are fit values). The mean time for $P(t)$ is cca 5.89 days, and the variance is $\sigma=9.55$ days. We note the presence of the characteristic time b , which indicates a deviation from the gamma distribution, as pointed out recently [Lippiello et al., 2012c]. A fitting function $\sim \frac{1}{t^\alpha}$, $t > 1$, $\alpha=0.25$, has been used previously by Apostol et al. [2008], for Vrancea, $M \geq 3$, time interval 1974-2004 (1999 earthquakes), with similar results. In a refined fit a decreasing exponential can be included, to account for the small values of the distribution tail. The data in Figure 1 have also been fitted with $Ae^{-\gamma t} / t^\alpha$, where $A \approx 683.3$, $\alpha \approx 0.12$, $\gamma \approx 0.22$. All these fits are of the same high quality. To check whether the results are biased by the aftershock sequences of the strongest seisms of the investigated time period (four earthquakes with moment magnitude ≥ 6.0), two shorter time intervals have been considered: 1991-2018, avoiding the aftershock sequences of three events with $M > 6.0$ (occurred on August 30, 1986, $M=7.1$, May 30, 1990, $M=6.9$, and May 31, 1990, $M=6.4$), and 2005-2018, when no earthquake larger than 5.6 moment magnitude occurred. The results show very similar forms of next-earthquake probabilities of occurrence, in all three cases ($a=881.85$, $b=1.25$, $R=0.94$ for 1991-2018 and $a=492.6$, $b=1.16$, $R=0.93$ for 2005-2018).

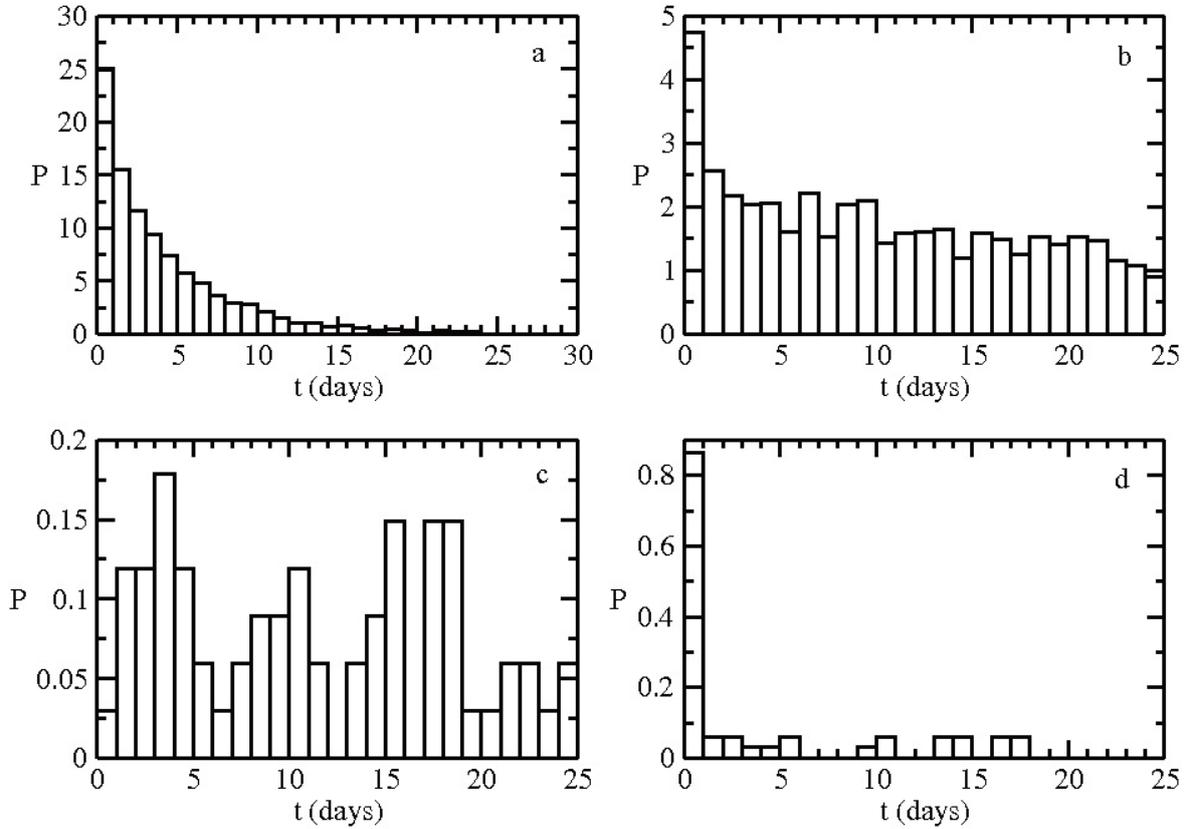


Figure 2. Inter-event time distributions $P = P(M, t)$ (in %) for Vrancea 1981-2018 for $M_0 \geq 3$ and $3 \leq M < 4$ (panel a), $4 \leq M < 5$ (panel b), $5 \leq M < 6$ (panel c) and $6 \leq M$ (panel d).

The probabilities $P(M, t)$ for $M_0 \geq 3$ for Vrancea are shown in Figure 2 for $3 \leq M < 4$, $4 \leq M < 5$, $5 \leq M < 6$, and $6 \leq M$ (panels a, b, c and d, respectively). First, we note that the inter-event distributions $P(M, t)$ for Vrancea exhibit a characteristic decrease in time, with the highest probability of next-earthquake occurrence in the same day as the reference earthquake, at least for small magnitudes ($M < 5$). Then, we note the decreasing maximum values of these probabilities ~ 22.7 for $3 \leq M < 4$, ~ 2.75 for $4 \leq M < 5$, while the probability $P(M, t)$ vanishes practically for $M \geq 5$. This result agrees with the magnitude correlations discussed recently for conditional probability distributions [Lippiello et al., 2008, 2012b; Stallone and Marzocchi, 2019].

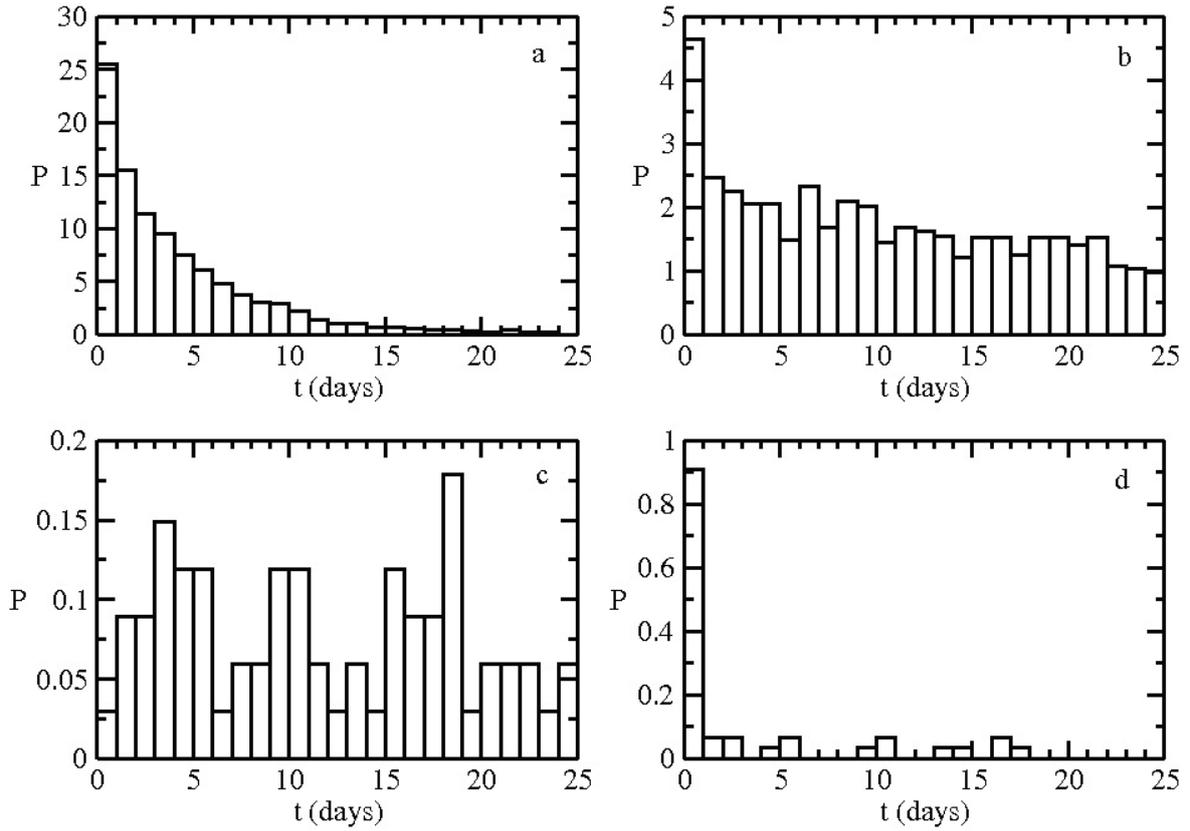


Figure 3. The inter-event time (conditional) probability $P = P(M, t | M_0)$ (in %, Vrancea) for $3 \leq M_0 < 4$ and $3 \leq M < 4$ (panel a), $4 \leq M < 5$ (panel b), $5 \leq M < 6$ (panel c) and $6 \leq M$ (panel d).

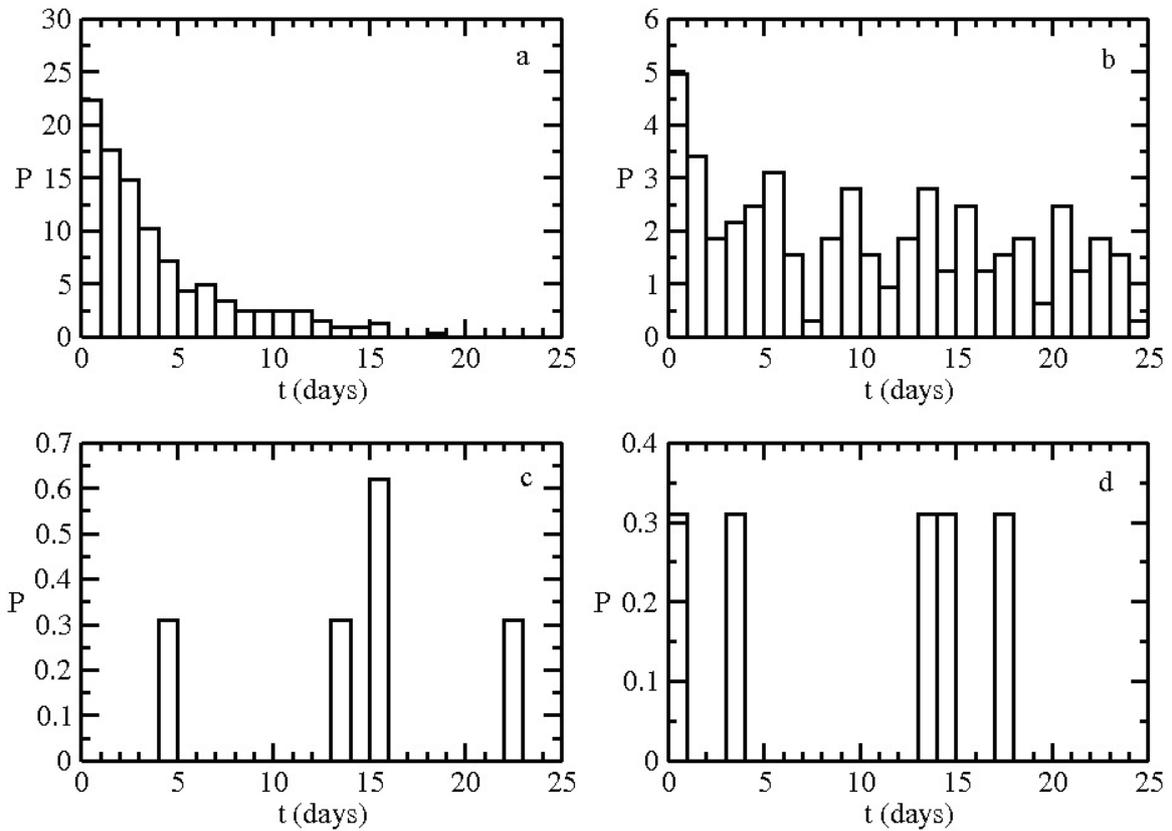


Figure 4. Same as in Fig. 3 for $4 \leq M_0 < 5$.

Also, it is worth noting that $P(t)$ and $P(3 \leq M < 4, t)$ are similar, obeying, Omori-type power laws, at least for short times, while the distributions become gradually irregular, exhibiting large fluctuations on increasing magnitude above $M=4-5$. The statistics becomes poor for higher magnitude ($M > 5$), as expected. A correlation time of 20-25 days can be estimated, after which the probabilities decrease appreciably (below 1), as well as a size correlation of cca $M=4-5$, above which the distributions acquire very small values, and are very irregular.

The conditional probabilities including the magnitude M_0 of the former earthquake $P(M, t | M_0)$ are shown in Figures 3-5 for $3 \leq M_0 < 4$ (Figure 3), $4 \leq M_0 < 5$ (Figure 4) and $5 \leq M_0 < 6$ (Figure 5). The first observation is that distributing the time-magnitude events with respect to the former earthquake magnitude M_0 does not change practically the characteristic time-decreasing behavior of the next-earthquake activity for small magnitudes.

It can be seen in Figure 2 (panel *a*) and Figure 3 that $P(M, t)$ and $P(M, t | 3 \leq M_0 < 4)$ are very similar, while considerable differences appear for $P(M, t | 4 \leq M_0 < 5)$, even for small magnitudes $3 \leq M < 4$. This reflects again the size correlation $M=4-5$, and indicate large fluctuations for higher-magnitude distributions. Higher-order correlation functions (as well as higher-magnitude analysis, or enlarging the magnitude gap $\Delta M = 1$) reduce considerably the statistical set, thus exhibiting a poor confidence.

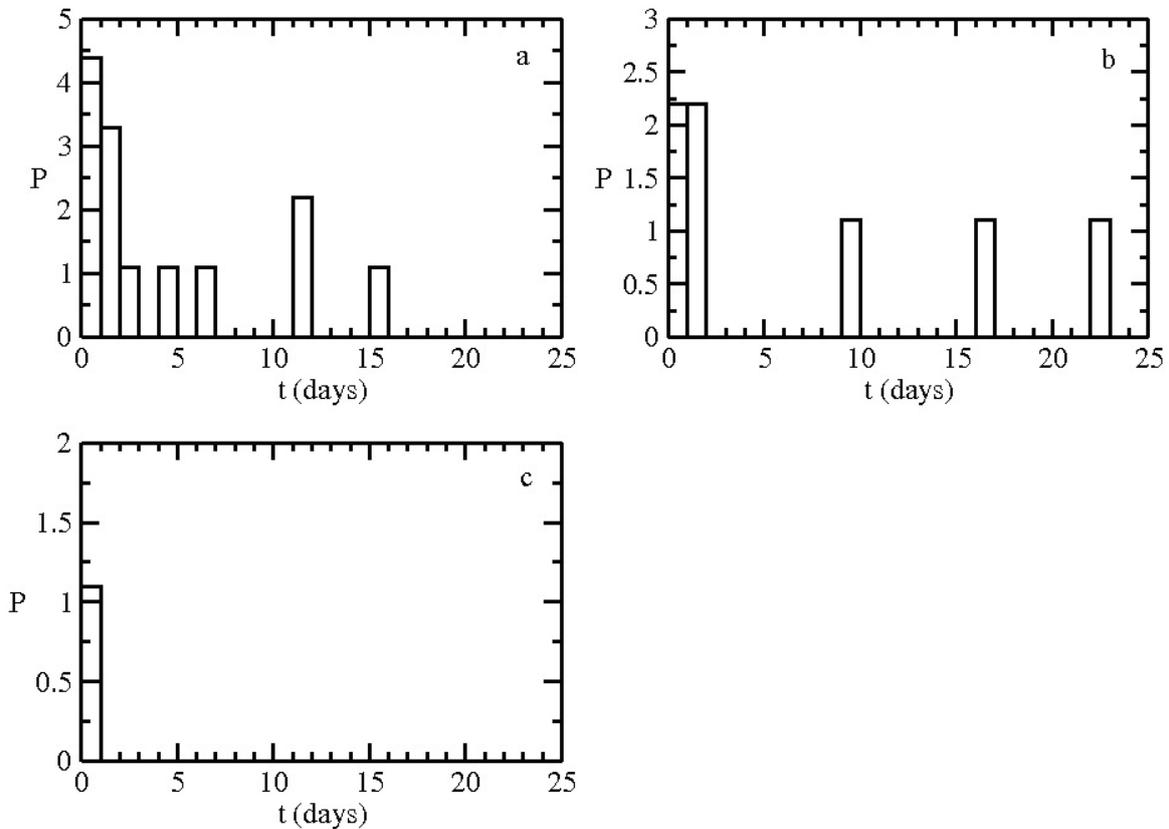


Figure 5. Same as in Figs. 3 and 4 for $5 \leq M_0 < 6$.

6. Conclusions

The inter-event time distributions are analyzed here for short-term seismic activity in Vrancea. The main distribution function is the time-magnitude probability $P(M, t | M_0)$ of the next earthquake of magnitude M occurring at time t elapsed from the occurrence of the former with magnitude M_0 (inter-event time distribution). It may be viewed as a two-point correlation function, or a conditional probability. This distribution is obtained by analyzing 3640 earthquakes with (moment) magnitude $M \geq 3$ recorded in Vrancea over the last 38 years [since 1981 to 2018, ROMPLUS Catalog, 2018]. The results show a characteristic time-decreasing behavior of the

occurrence of the next earthquake, at least for small magnitudes. Correlations are identified for lower-magnitude earthquakes ($M, M_0 < 4-5$), extending roughly over 20-25 days. Statistics becomes poor for stronger earthquakes ($M > 5$), preventing any confident estimation. The results of the present report show that the inter-event time distributions can be employed for estimating the short-term seismic hazard and risk for moderate earthquakes ($M < 5$) in Vrancea. For instance, from Figure 2 we read the probability 0.047 for occurring an earthquake with magnitude between 4 and 5 the same to the next day after one with magnitude $M \geq 3$ has occurred. In general, the approach can be useful for those seismic activities, periods and regions of interest, characterized by rich statistics (as, for instance, crustal, or surface, moderate earthquakes).

Data and sharing resources: <http://www1.infp.ro/realtime-archive>

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***CORRESPONDING AUTHOR: Bogdan Felix APOSTOL,**

National Institute for Earth Physics,

Călugăreni Street, 12 Magurele,

Ilfov, Romania

e-mail: apostol@infp.ro

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