Space-temporal distribution of earthquakes in the three swarms occurred in Bulgaria

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Abstract
Studing of the space-temporal distribution of earthquakes is very important for understanding the physics of the earthquake generation process. In the present study we examine the space - temporal pattern of earthquake distribution in the three swarms occurred on the territory of Bulgaria. The first cluster is the 1997-1999 swarm occurred in the Rila Mountain, the second one is the April 2009 cluster occurred near the city of Kardzhali, and the last is the 2014 swarm occurred in the region of the city of Plovdiv from January to February 2014. The seismic clusters were analysed using digital data recorded by the Bulgarian Seismological Network.

Пространствено-времево разпределение на три роя реализирани на територията на България

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Резюме
Наличието на различни поредици от събития, оказва съществено влияние върху разпределението на земетресенията в пространство и времето. Необходимо е да се познават статистическите характеристики на различните серии и винаги да се отчита тяхното влияние при общите изследвания върху сеизмичността. В настоящото изследване е представено пространствено-времевото разпределение на три роя: поредицата от 1997-1999 г., в района на Рила; поредицата от април 2009 в близост до град Кърджали; третата поредица е от януари – февруари 2014 г., в района на град Пловдив. Основни източници на информация за разгледаните земетресения са използвани данни от Националната Оперативна Телеметрична Система за Сеизмологична Информация (НОТССИ).

Introduction

Swarms are earthquakes that are clustered in space and time, and are not associated with an identifiable main shock, as opposed to foreshock and aftershock sequences, which are usually associated with the occurrence of a main shock (Kanamori, 1972). The majority of swarms occur in volcanic regions. However, they also occur in tectonic boundaries and intracontinental areas. This type of seismic activity may proceed days, weeks or months. The highly heterogeneous character of an area explains the occurrence of this type of seismicity, and/or weakened areas of the earth's crust, unable to withstand the stress applied (Mogi, 1963).
The swarms have been studied in the regions of Western Bohemia since the middle Ages (Fischer, et al. 2014) and in Bulgaria since 19th century (Watzof, 1902). Nowadays, swarms are extensively studied in the areas, where this type of clusters is very characteristic.
The b-value of the Gutenberg–Richter law reflects the state of stress and the level of heterogeneity in the Earth's crust (Gutenberg and Richter, 1944; Schorlemmer, et. al, 2005). Some studies show (among others Sykes, 1970 and Ibs-von Seht, 2008) the existence of b-value differences for volcanic ($b > 1$ are presented in Sykes, 1970) and continental rifts zones (the b-value ranging from 0.8 to 1.0 in Ibs-von Seht, 2008).
In the present study statistical analysis is applied in order to examine the space - temporal pattern of swarms on the territory of Bulgaria.

Data and Method

In this analysis, as a swarm are considered earthquakes that clustering in time and space. A swarm is not characterized by a main event, and the frequency-time distribution of the sequence cannot be modelled with a modified Omori formula.

The data we used for the study are earthquakes clustering in three swarms located on the territory of Bulgaria from 1997 to 2014. The events were recorded by Bulgarian Seismological Network (NOTSSI). The body P-wave magnitude M_P after Christoskov et al (2012) using the maximum amplitudes of body P waves of local earthquakes (up to 10º) recorded on the broadband seismographs was estimated for each event of the considered data sample. The analysis was carried out based on the standardized data files, including 578 earthquakes.
The first cluster is the 1997-1999 swarm occurred in the Rila mountain (Kresna seismogenic zone), which includes 240 earthquakes occurred in the period of about one and the half year. The second is the April 2009 cluster located in the vicinity of the city of Kardzhali (seismogenic zone Eastern Rhodopes), including 291 earthquakes that were generated in the period less than a month. The last cluster is the 2014 swarm located near the city of Plovdiv (Maritsa seismogenic zone), with includes 47 events occurred in the period of more than a month.
The magnitude-frequency distribution is important for predicting the number of earthquakes in a certain magnitude interval for a certain period of time, supposing that the process is stationary over time.
In practice, most commonly are used two methods for estimating the b-value: the least squares method and the maximum likelihood method (MLM). In the present study MLM is applied.
On the assumption that $\boldsymbol{m_1}$**=∞** - unilaterally cutoff distribution (Utsu, 1965; Aki, 1965) applying the MLM, the estimation for the b-value is defined by:

$$b = \frac{1}{\ln(10)(\overline{M} - M_0)}, \quad (1)$$

where $\overline{M}$ is the average magnitude of the sample and M_0 - the lower limit of the distribution.
For bilateral cutoff distribution (Page, 1968) applying the MLM, the estimation for the b-value is defined by:

$$b = \frac{1}{\ln(10)\cdot(\overline{M} - \frac{M_0 - M_1 e^{-\beta\Delta M}}{1 - e^{-\beta\Delta M}})} \quad (2)$$

where β=bln(10).

Results

Space distribution

1997-1999 swarm in the Rilla Mountain

The spatial distribution of earthquake in the swarm located in the Rila Mountain that occurred from 1997 to1999 is presented in Fig. 1. The figure illustrates 240 earthquakes with magnitude in the interval $1.0 \leq M_p \leq 3.7$ (where M_p is P-wave magnitude, specified in Christoskov et. al, 2012) occurred in the time period of 822 days.
The spatial distribution of the earthquakes includes three small subs clusters clearly distinguishable over time. Figure 1, plots a); b) and 1 c) show the spatial distribution of the three sub-clusters separately while Fig. 1, plot d) illustrates the spatial distribution of all events in the swarm.
The earthquakes are clustered close to an identified structure. Generally, the swarm is realised in the east-west direction and the fault structure is moved to the northeast-southwest. The first in-time subs-cluster (Fig. 1, plot a), including the strongest events (18 earthquakes with M_p> 3.0) was realised in the eastern part of the activated area. The second and third in-time subs-clusters (Fig. 1, plots b and c), including earthquakes with a magnitude M_p<3.0, mark the western and eastern peripheries of the swarm, respectively.

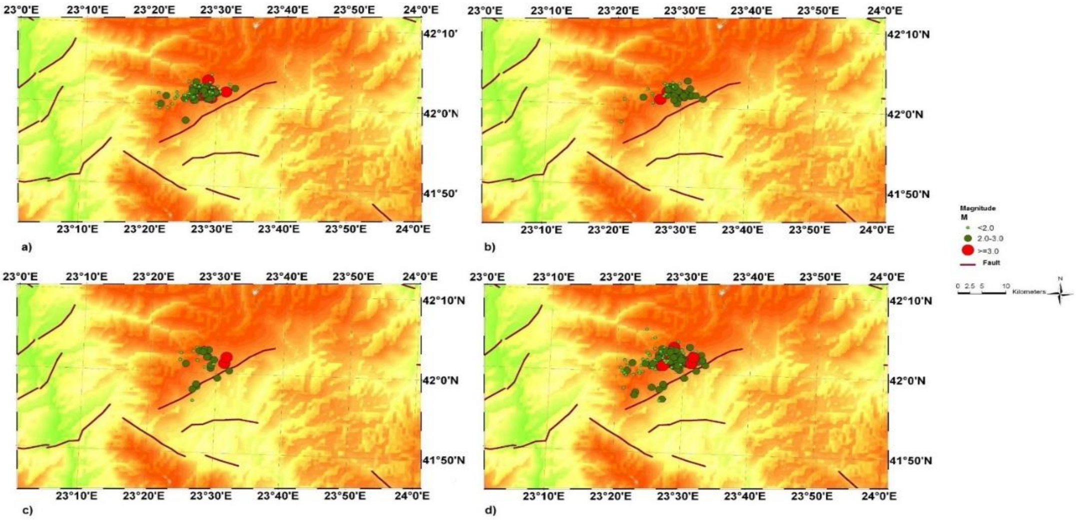

Fig. 1. Spatial pattern of swarm activity: a) earthquakes occurred in the time interval June – December 1997; b) earthquakes occurred in the time interval 16 – 23 January 1999; c) earthquakes occurred in the time interval 7 – 27 August 1999; d) all events in the period from June 1997 to August 1999. The identified faults (modified from the Neotectonic map compiled by J. Ivanov, R. Nakov, A .Radulov, Y. Gerdzikov presented in Report of Geoph.Inst.-BAS, 2008) are denoted by dark red lines.

08-30 April 2009 swarm located in the vicinity of the city of Kardzhali

The spatial distribution of the earthquakes in the April, 2009 swarm is presented in Fig. 2. This sequence includes 291 events, occurred in the time period of 22 days (08-30 April 2009). Only 27 earthquakes have magnitude estimates, the rest of the events (264) are small and were recorded only at KDZ station, which is the nearest to the activated area station (at about 18 km epicentral distance). The figure illustrates spatial distribution of the 27 earthquakes with magnitude in the range $1.0<M_p\leq4.1$.
The figure shows that the earthquakes occurred in a relatively small area, which area cannot be associated to a defined fault structures.

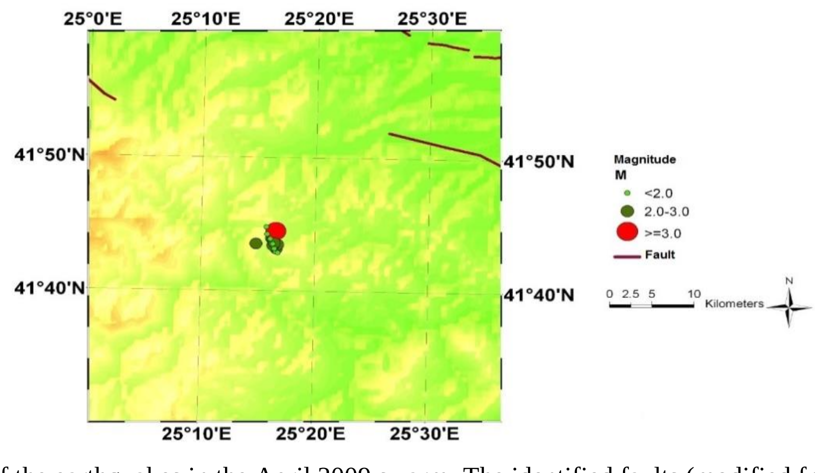

Fig. 2. Spatial pattern of the earthquakes in the April 2009 swarm. The identified faults (modified from the Neotectonic map compiled by J. Ivanov, R. Nakov, A .Radulov, Y. Gerdzikov presented in Report of Geoph.Inst.-BAS, 2008) are denoted by dark red lines.

January – February 2014 swarm located near the city of Plovdiv

The cluster includes 47 earthquakes with magnitude ranging between $1.1\leq M_p\leq3.4$. The time span of this swarm is slightly more than 30 days. The spatial distribution of the sequence that occurred near the city of Plovdiv is presented in Fig. 3. The figure shows that the earthquakes occurred in a relatively small area, which area cannot be associated to a recognised fault structure.

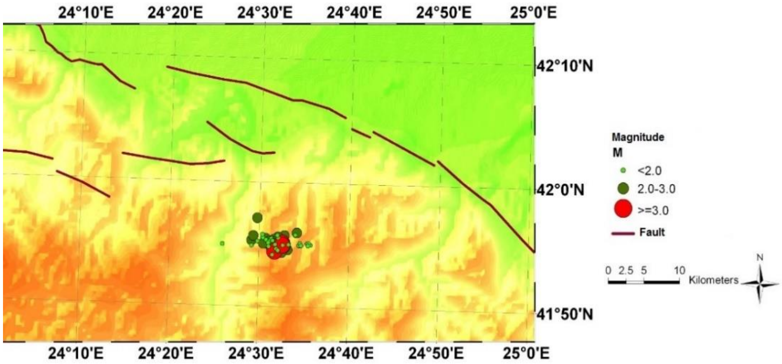

Fig. 3. Spatial pattern of the earthquakes in the January – February 2014 swarm. The identified faults (modified from the Neotectonic map compiled by J. Ivanov, R. Nakov, A .Radulov, Y. Gerdzikov presented in Report of Geoph.Inst.-BAS, 2008) are denoted by dark red lines.

Temporal Distribution

Temporal distribution of seismicity in the Rilla Mountain for the period 1996 – 2002 is presented in Fig.4a.
The figure shows temporal distribution of earthquakes with magnitude ranging between 1.0 and 3.5 in the 1997-1999 swarm that is located in the Rilla Mountain.
The three sub-clusters of the swarm are well illustrated in the Fig.4a. The first sub-cluster (which is the largest one) includes 133 events occurred from June to December 1997, other 127 events occurred in the following 21 months (up to the end of the 1998). The next two sub-clusters are clearly expressed in the figure - 46 earthquakes (the second sub-cluster) and 36 events (the third sub-cluster) occurred in January 1999 and August 1999, respectively.
The Gutenberg–Richter law (Gutenberg and Richter, 1942): log N = a – bM, defines the magnitude-frequency distribution of earthquakes.
In our study values of the Gutenberg–Richter law parameter b are calculated applying the maximum likelihood method (MLM) by using the Utsu (Utsu, 1965) and Page (Page, 1968) relations (given by formulas 1 and 2). The results for each sub-cluster and for the whole swarm are presented in Tab.1
The results show variations of the b-value with no obvious tendency to increase over time through Page relation and obvious tendency to increase over time through the Utsu relation. For the swarm, the b-value is close to the average of the values for the sub-clusters.

Sequence (period)	Utsu	σ (Utsu)	Page	σ (Page)
I (June ÷December 1997)	0.74	0.09	0.56	0.07
II (January 16 ÷ January 23, 1999)	0.92	0.17	0.76	0.14
III (June 07 ÷August 27, 1999)	0.94	0.23	0.71	0.17
Swam (from 1997 to 1999)	0.82	0.07	0.69	0.06

Tab. 1. Estimated b -values and the calculated errors for the 1997 - 1999 swarm located in the Rilla Mountain.

The temporal distribution of earthquakes in the swarm is characterized by the rapid activation (increasing the number of the events) and quick attenuation after the strongest events occur. After each of the sub-clusters and the swarm as a whole, the activity returned to the levels of the background seismicity. The well-pronounced slope at the beginning of the three sub-cluster is almost the same as at the end of each of them.
Temporal distribution of seismicity in the Kardzhali region for the period 2008-2011 is presented in Fig.4b. The figure shows temporal distribution of 291earthquakes with magnitude ranging between 1.0 and 4.0 in the April 2009 swarm located in the vicinity of the city of Kardzhali. The earthquakes are unevenly distributed in time. At the very beginning of the swarm 185 events are realized in 4 days (from April 8 to April 11, 2009). The strongest earthquakes with magnitude larger than 3.0 are generated in the first 4 days. The earthquake rate of occurrence decreases with time thus 108 events occurred in the period April 12 to April 30, 2009. After April 30, 2009 the activity returned to the levels of the background seismicity.
Figure 4c illustrates the temporal distribution of years of seismicity near the city of Plovdiv during the period 2010-2016, which includes the activity in 2014 (for a period of 38 days). The swarm activity in 2014 stands out very clearly - a quick increase in the number of occurred earthquakes over a short period of time (several days). The time

distribution of the events (slope of the curve) before the activation of the swarm (at the beginning of 2014) is very close to the observations after the activity (after February 2014).
This swarm is characterised by a strong activity from two days in January and a low but more stable activity in February 2014. In January, the activity occurred over four days, in which 27 events with magnitudes of 1.5-3.4 were registered. In February, the events were small (20 events with a magnitude in the interval 1.0-2.7) and were more evenly distributed over time. After February a transition to the background seismicity was observed.

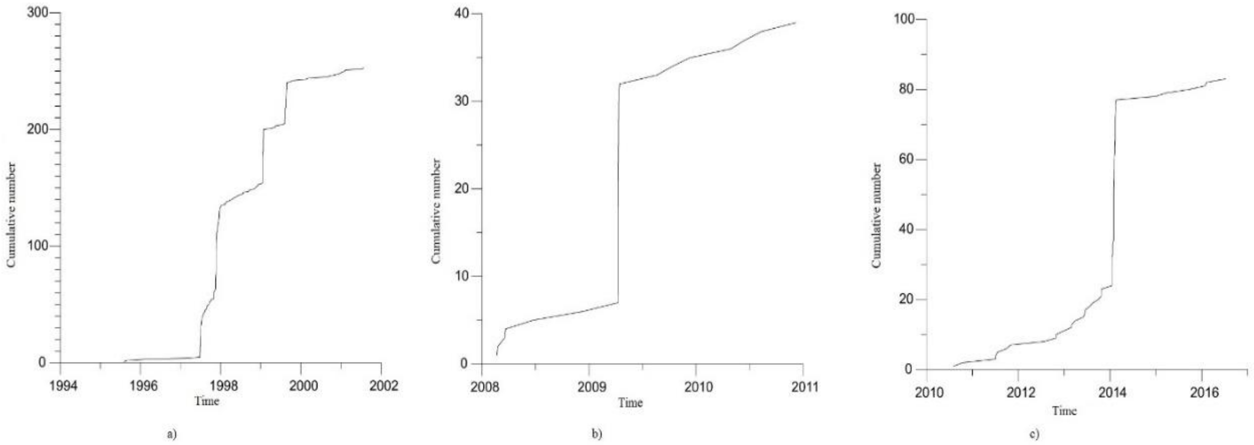

Fig. 4. Temporal distribution of seismicity (in years): a) in the Rilla Mountain for the period 1996 – 2002; b) in the Kardzhali region for the period 2008-2011; c) near the city of Plovdiv for the period 2010 – 2016.

Conclusions

We can summarize the finding from our study of the space-temporal distribution of earthquakes in the three swarms occurred in Bulgaria as follows:

- The earthquakes in 2009 (near the city of Kardzhali) and 2014 (in the region of the city of Plovdiv) swarms are clustered in a very small area which cannot be associated with a defined fault structure;
- The events in the 1997-1999 swarm (in the Rila Mountain) that are divided into three sub-clusters over the time were clustering near a defined fault structure;
- The temporal distribution of earthquakes in the three swarms indicates unevenly distribution over time - rapid activation (increasing the number of the events) and quick attenuation after the strongest events occur. After each of the swarms, the activity returned to the levels of the background seismicity. The well-pronounced slope at the beginning of the three clusters is almost the same as at the end of each of them;
- The b-value variation over time is observed for the 1997-1999 swarm (in the Rila Mountain). Estimates of the parameter for the swarm confirms the hypothesis that in continental rifts the b-value of seismic swarms is less than 1.0.

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