Bulgarian Chemical Communications, Volume 47, Special Issue B (pp. 397–404) 2015

The 2012 M_w5.6 earthquake in Sofia seismic zone and some characteristics of the aftershock sequence

S. Simeonova*, D. Solakov, I. Aleksandrova, P. Raykova, V. Protopopova

National Institute of Geophysics, Geodesy and Geography, Bulgarian Academy of Sciences, Acad. G .Bonchev Str., Bl.3, BG-1113 Sofia, Bulgaria

The seismic sequence of May 2012 was studied using digital data from Bulgarian Seismological Network and macroseismic information available in Sofia municipality. The results favor the idea that the occurrence of the seismic sequence took place at the Pernik-Belchin fault extending in NW-SE direction. In the sequence the temporal distribution of aftershocks is dominated by the classic power law decay in time. More over, the results indicate that seismic energy is released very slowly and is mostly related to normal faulting with small strike-slip component. In the study is shown that for southwestern Bulgaria the seismicity characteristics, focal mechanisms and stress analysis confirm the hypothesis that neotectonics of this region is similar to that of northern Greece with predominant N-S extension.

Key words: seismicity, earthquake spectrum, aftershock activity, fault plane solution, South-Western Bulgaria

INTRODUCTION

The territory of Bulgaria represents a typical example of high seismic risk area in the eastern part of the Balkan Peninsula. The neotectonic movements on the Balkan Peninsula are controlled by extensional collapse of the Late Alpine orogen,and were influenced by extension behind the Aegean arc and by the complicated vertical and horizontal movements in the Pannonian region.

The Sofia seismic zone is located in southwestern Bulgaria - the area with pronounce tectonic activity and proved crustal movement. The capital of Bulgaria - Sofia is situated in the center of the Sofia area that is the most populated (the population is of more than 1.5 mil. inhabitants), industrial and cultural region of Bulgaria that faces considerable earthquake risk. The strongest known event in the region is the 1858 earthquake with intensity I_0=9-10 MSK, caused heavy destruction in the city of Sofia and the appearance of thermal spring. An earthquake of moment magnitude 5.6 hit Sofia seismic zone, on May 22nd, 2012. The earthquake occurred in the vicinity of Pernik city, at about 25 km south west of the city of Sofia. The quake was followed by intensive aftershock activity. It is worth mentioning that the seismic sequence of May 2012 occurred in an area characterized by a long quiescence (of 95 years) for moderate events. Moreover, a reduced number of small earthquakes have also been registered in the recent past.

In the present study we first compiled relevant macroseismic information and estimate macroseismic effects caused by the 2012 M_w5.6 earthquake in the city of Sofia. Than analyze wave forms and find spectral characteristics of the main shock and some of the strongest aftershocks. Additionally, spatial and temporal distribution of aftershocks is studied. Finally, individual focal mechanisms of the main shock and the largest aftershocks are determined. In the study new results of the present state of stress in southwestern Bulgaria from 20 earthquake focal mechanisms are presented.

SEISMICITY IN SOFIA SEISMIC ZONE

The contemporary tectonic activity of the Sofia seismic zone is predominantly associated with the marginal faults of Sofia graben. The boundaries of the graben are represented by fault systems with expressive neotectonic activity. The available historical documents prove the occurrence of destructive earthquakes during the 15th-18th centuries in the Sofia zone. In 19th century the city of Sofia has experienced two strong earthquakes: the 1818 earthquake with epicentral intensity I_0=8-9 MSK and the 1858 quake with I_0= 9-10 MSK. The 1858 earthquake caused heavy destruction in the town of Sofia and the appearance of thermal springs in the western part of the town [1]. During the 20th century the strongest event occurred in the vicinity of the city of Sofia is the 1917 earthquake with $M_S = 5.3$ (I_0=7-8 $MSK64$). The earthquake caused a lot of damages in the city and changed the capacity of the thermal mineral springs

* To whom all correspondence should be sent: stelas@geophys.bas.bg

Fig. 1. Damages caused by the 2012 M_w5.6 earthquake.

in Sofia and surroundings. The earthquake was felt in an area of 50000 km^2 and followed by aftershocks, which lasted more than a year [2] and [3]. Almost a century later (95 years after the 1917 earthquake) an earthquake of M_w5.6 hit Sofia seismic zone, on May 22nd, 2012. No casualties and severe injuries have been reported. Moderate to heavy damages (Fig. 1) were observed in the cities of Pernik and Sofia and their surroundings.

The earthquake is largely felt on the territory of Bulgaria and neighboring countries: northern Greece, FYROM, eastern Serbia and southern Romania (presented in Fig. 2).

Predominantly moderate (grade2,according to [4]) to substantial (grade3, according to [4]) damages were observed in the city of Sofia and surroundings. Distribution of macroseismic effects (generated by the 2012 M_w5.6 earthquake) along the city of Sofia is estimated on the base of documents and reliable information available in Sofia municipality. The

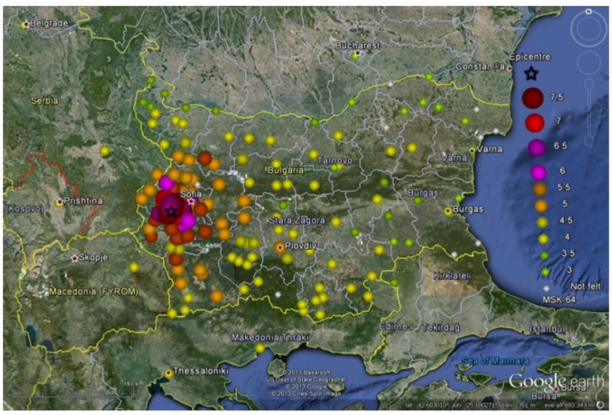

Fig. 2. Intensity field of the 2012 M_w5.6 earthquake.

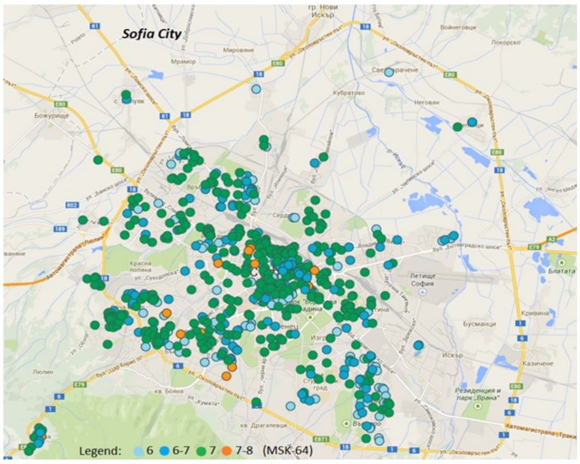

Fig. 3. Observed macroseismic effects (in MSK intensity scale) for the city of Sofia caused by the 2012 M_w5.6 earthquake.

intensity map illustrating the distribution of macroseismic intensity (MSK) along the city of Sofia is presented in Fig. 3. The figure shows that the intensity values range between 6th and more than 7th MSK. The highest intensity values (above 7 MSK) are related to old not well maintained buildings that were not reinforced (marked by orange spots in Fig. 3). Predominant level of damage to buildings in Sofia is 7th MSK concentrated in the central part of the city. Field with impacts of seventh degree grows mainly west of the city center from northwest to south-southeast (described in details in [5]).

SPECTRA ANALYSIS

P wave displacement spectra for the 2012 Pernik earthquake (M_w5.6; T_0=00:00:32 UTC) and two of the strongest early aftershocks (the first - M_w4.7, T_0=01:30:50 UTC; the second m_b4.2, T_0=02:13:28 UTC) are presented in Fig. 4. The spectra are estimated using records at station MPE - at epicentral distance of about 100 km. Both aftershocks occured in the first 3hs after the 2012 earthquake.

The figure shows low frequency content and not expressed spectrum plateau and corner frequency for the main shock while for the two aftershocks comparatively well outline a flat long period displacement spectrum (plateau between 0.7–3.0 Hz) is observed. The specific P wave displacement spectral of the 2012 M_w5.6 earthquake could be assumed as indicative for a very low rupture velocity [6]. The low rupture velocity means slow-faulting, which brings to slow release of accumulated seismic energy.

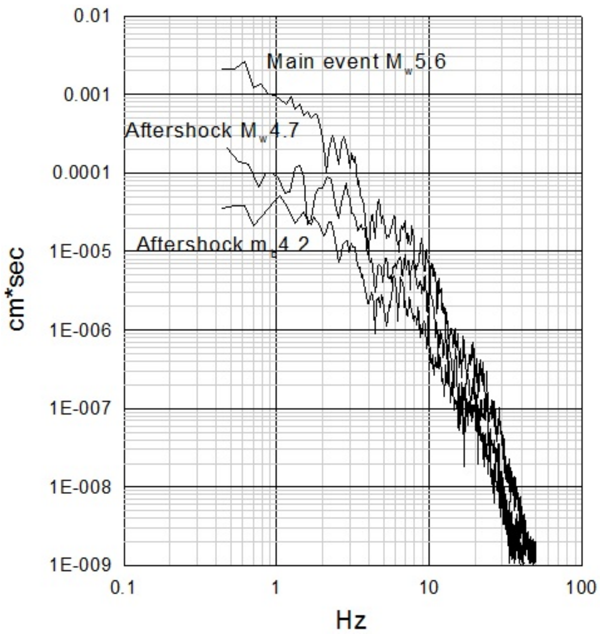

Fig. 4. Displacement spectra of *P* wave for main event and two of the strongest aftershocks.

SPACE-TIME DISTRIBUTION OF AFTERSHOCKS

Examination of the space-time distribution of earthquakes is of fundamental importance for understanding the physics of the earthquake generation process. One challenge in applying statistical methods to study the earthquake occurrence is to distinguish objectively the nonrandom from the random. The spatial and temporal clustering of aftershocks is the dominant non-random element of seismicity.

Spatial distribution of aftershocks

The spatial pattern of aftershock activity of earthquakes varies from event to event. Although the mechanism of aftershock occurrence has not been fully understood yet the spatial distribution of aftershocks seems to provide clues to the mechanical properties of the source region. It is assumed that aftershock area expansion pattern reflects the spatial variation of fault zone properties. On the assumption that the degree of spatial non randomness in the aftershock distribution is associated with the degree of non uniformity of stress in the area, an increased degree of clustering can then be related to an increased non uniformity in stress.

The aftershock patterns for different elapsed time after the 2012 Pernik earthquake are presented in Fig. 5.

Figures show the following characteristics in spatial pattern of aftershock activity:

- The aftershocks (presented in Fig. 5(a)) coincides with Pernik-Belchin fault (identified by Karagjuleva et al. [7] elongated in NW-SE direction;
- The first 3 hrs aftershocks occurred in the NW-SE oriented Pernik-Belchin fault (Fig. 5(a))

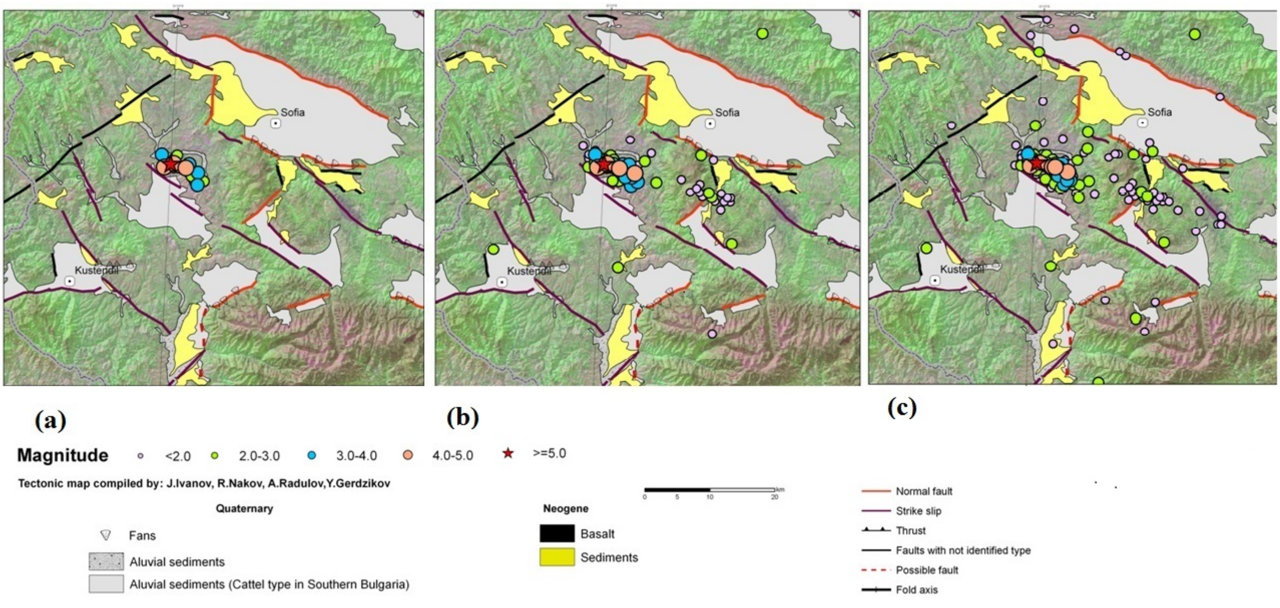

Fig. 5. Spatial pattern of aftershocks: (a)occurred 3 hrs after the 2012 M_w5.6 Pernik earthquake; (b)occurred 14 days after the 2012 M_w5.6 Pernik earthquake; (c)occurred 663 days after the 2012 M_w5.6 Pernik earthquake

and later (for elapsed time 14 days, Fig. 5(b)) aftershock activity migrates towards the fault with NE-SW orientation;
- A high degree of clustering of the strong aftershocks ($M \geq 3.0$) in a comparatively small and slightly elongated NW-SE area;
- A well expressed tendency of aftershock area expansion in time;
- Aftershock area expansion with decreasing of the threshold magnitude.

Temporal distribution of aftershocks

Aftershocks occur after the main shock and their frequency decays through time with approximately the reciprocal of time elapsed since the main earthquake. The occurrence rate of aftershock sequence in time is empirically well described by the modified Omori formula proposed by Utsu in 1961 [8]

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

where t is the elapsed time since the occurrence of the main shock, and K, p, c are constant parameters. The power-low decay represented by the modified Omori relation is an example of temporal self-similarity of the earthquake source process. Aftershock decay rate (parameter p) contains information about the mechanisms of stress relaxation and frictional strength heterogeneity.

On the assumption that aftershocks are distributed as a non stationary Poisson process, Ogata [9] proposed to use the maximum likelihood method for estimating the parameters K, c and p in modified Omori formula. Using the modified Omori formula the intensity function of the Poisson process $\lambda(t)$ is defined by the relation:

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

An integration of the intensity function $\lambda(t)$ gives a transformation from the time scale t to a frequency-linearized time scale τ [9]. On this time axis the occurrence of aftershocks becomes the standard stationary Poisson process if the choice of the intensity function (the parameters K, p, and c) is correct. The time scale τ 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 τ should be observed if an appropriate model has been selected.

The 2012 Pernik earthquake aftershock sequence is analyzed from 0 to $T = 663$ days by fitting it to the modified Omori formula. The maximum likelihood estimates (MLM,s) of the Omori formula parameters are as follows: $K = 15.04$, $c = 0.022$ and $p = 0.89$.

The frequency-time distribution of aftershocks is presented in Fig. 6. Figure 7 illustrate a plot

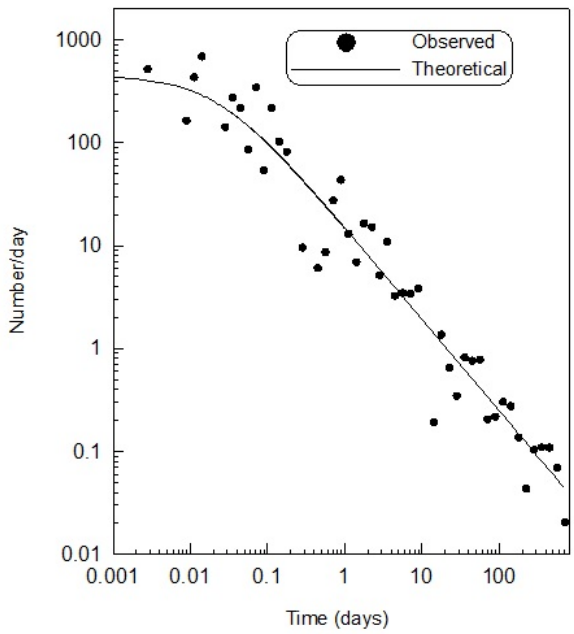

Fig. 6. The frequency-time distribution of 2012 Pernik earthquake aftershocks.

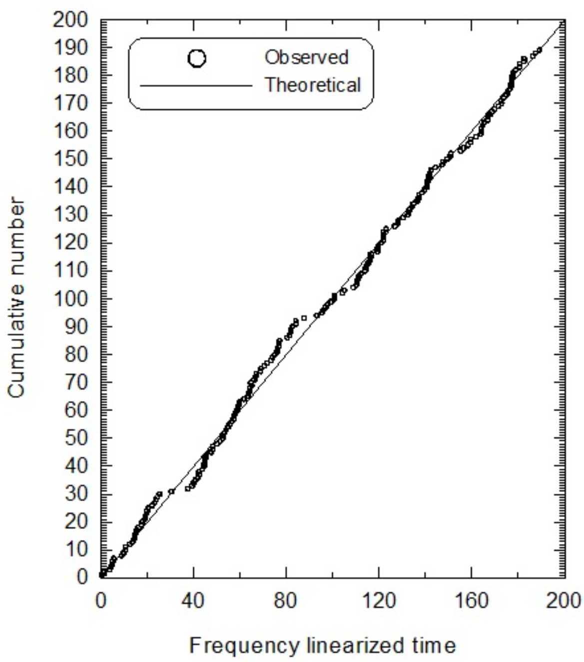

Fig. 7. Plot of cumulative number of events versus frequency linearized time τ.

of cumulative number of events versus the frequency-linearized time τ. In both figures the observed distribution is compared with the distribution (called "theoretical"), which is expected from the selected model (in the case, the model is the modifed Omori formula).

A comparison between empirical with theoretical distribution (Fig. 6 and Fig. 7) shows that as a first approximation the temporal distribution of events in aftershock sequence of the 2012 M_w5.6 Pernik earthquake is well described by the modified Omori formula.

Figure 7 shows that a nearly linear trend of aftershock decay continues up to 663 days; thus the modified Omori formula fits largely the observations up to 663 days after the main shock. The figure also suggests the existence of some discrepancies between observed and expected distributions (S-shaped deviations from the linear trend) – evident periods of decaying and activation of the process. Consequently models that take into account the effect of secondary aftershock activity were constructed. Two models for secondary sequences are test: 1) the first model with one secondary aftershock sequence after 0.5 days and 2) a combination of one main and two secondary sequences – after 0.5 and 53 days. The same p value for the main and secondary aftershock sequences is assumed for both models.

To select which model fits the observations better, the Akaike Information Criterion (AIC) [11] is used. AIC criterion is defined by following equation:

$$\begin{aligned} \text{AIC} = &(-2)\max(ln - \text{likelihood}) \\ &+ 2(\text{Number of the used parameters}) \end{aligned} \quad (1)$$

Results are presented in Table 1.

The maximum likelihood estimate 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 2012 Pernik earthquake is best modeled by one ordinary and two secondary sequences (presented in Fig. 8), although there remain S-shaped deviation from the linear trend – about 80 day after the main shock.

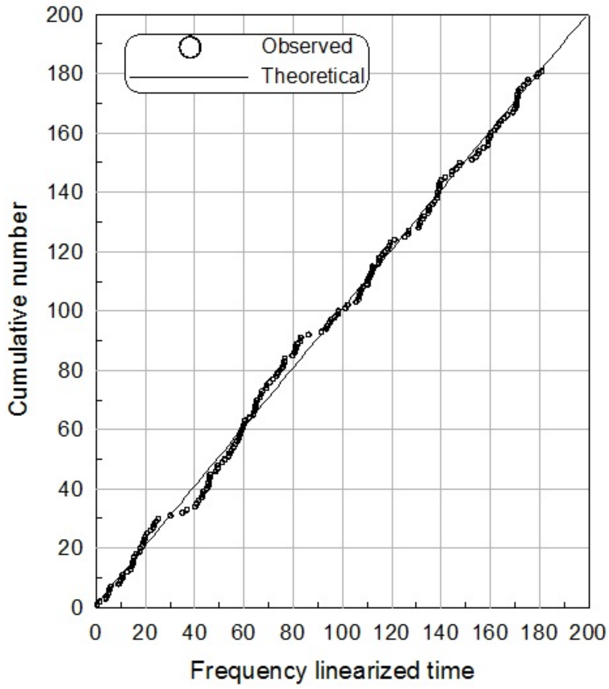

Fig. 8. Plot of the cumulative number of events versus the frequency-linearized time τ (one ordinary and two secondary aftershock sequences with $p = p_1 = p_2$).

The temporal pattern of earthquake distribution in aftershock sequence of the 2012 M_w5.6 Pernik quake that is characterized with slow decay in time $p < 1.0$ (p value of the main and secondary sequences is 0.91) is similar to the temporal distribution of aftershocks in Northern Bulgaria [12]. The results give reason to be assumed that aftershocks are generated in slowly relaxing environment with low heterogeneity. (The same results are reported in [13] where the aftershock sequence is analyzed for 365 days elapsed time after the 2012 Pernik earthquake.)

Table 1. *MLE*'s of the Omori formula parameters and corresponding *AIC*

Model	K	p	c	K_1	p_1	c_1	K_2	p_2	c_2	*AIC*
An ordinary aftershock sequence	15.22	0.91	0.026	–	–	–	–	–	–	97.56
One ordinary and one secondary aftershock sequences, p=p_1	15.15	0.93	0.028	0.44	0.93	0	–	–	–	76.64
One ordinary and two secondary aftershock sequences, p=p_1=p_2	14.09	0.91	0.028	0.40	0.91	0	0.44	0.91	0	74.96

FOCAL MECHANISMS

Earthquake focal mechanisms provide one of the best observational materials for analyzing the current state of stress in the crust. The fault-plane orientations and slip directions of earthquakes can provide important information about fault structure at depth and the stress field in which the earthquakes occur.

Fault plane solutions for the 2012 M_w5.6 Pernik earthquake and 19 aftershocks with $M \geq 3$ are presented in Fig. 9.The focal mechanisms were calculated according to the definitions in Aki and Richards [14] using the polarities of the P wave, azimuth and incidence angle by applying the software FOCMEC [15] (details are presented in [16]).

As it is seen in the figure, the average strike of one of the nodal planes is 311 NW-SE for all estimated focal mechanisms. The predominant nodal plane can be accepted as the activated fault in the considered area. The fault is extending in NW-SE direction dipping (as average) at 50°. The identified seismogenic structure coincides with the well known Pernik-Belchin fault [7]. The faulting is right-literal if the chosen nodal plane of focal mechanisms is the main one. It means that the foot-wall block is on the right side of line Pernik-Belchin fault the so called Golo Burdo and hanging-wall block is on the left side – Pernik graben.

The main shock and all aftershocks, except those mark by numbers 7 and 16 (see Fig. 9), indicate normal right-lateral fault movement with small strike-slip component, faulting along a hidden fault plane, caused by extensional regional tectonic stresses. The aftershock number 7 indicates thrust faulting with small strike-slip component and the quake number 16 is clear strike-slip motion.

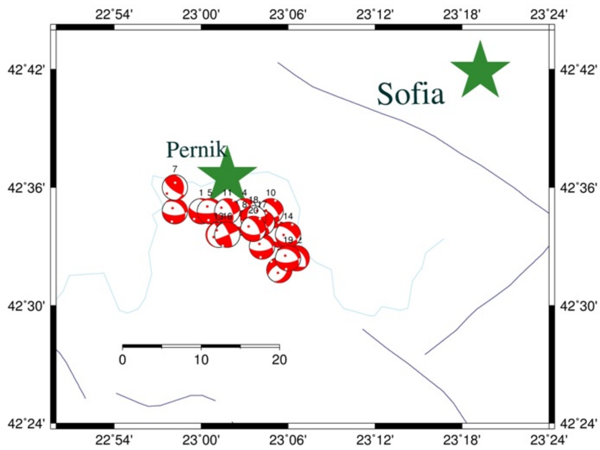

Fig. 9. Fault plane solutions of the 2012 M_w5.6 Pernik earthquake and aftershocks.

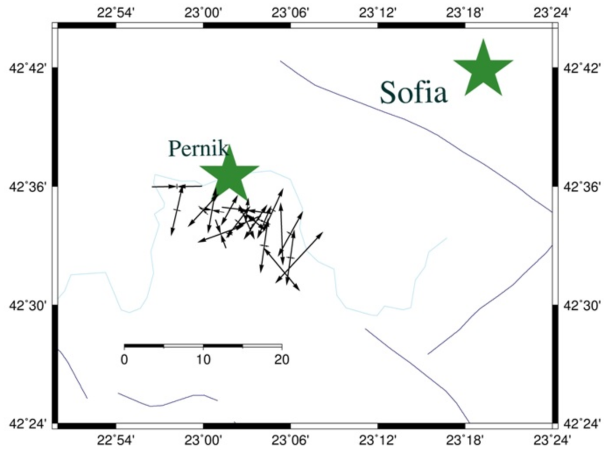

Fig. 10. Individual P and T axes of the 2012 M_w5.6 Pernik earthquake and aftershocks.

Figure 10 displays the horizontal projections of the individual P (pressure) and T (tension) axes of the twenty earthquakes. The axes of compression (P-axes) are orientated predominantly in NW-SE direction and are significantly smaller than the axis of decompression (T-axes) in NE-SW direction. The plunge of P-axes is varying in the range 10°−84°, about 51 in average, and the plunge of T-axes is in predominant sub horizontal orientation (0°-60°), about 15 in average.

The main results from the focal mechanism determination and stress analysis show the prevailing of a normal or extensional stress regime in the considered region (southwestern Bulgaria). Generally, the tension axes are with sub horizontal orientation and large values especially in NE-SW direction.

The observed sub horizontal extensional stresses with predominant NE-SW trend of the T-axes is consistent with the general trend of the regional extensional field of tension axes for southern Bulgaria and surroundings. This stress field corresponds to that found in southern Bulgaria (presented by among others in [17]) and confirms the hypothesis that the neotectonic movements in Balkan Peninsula are the consequence of the long lasting extensional movements in the inner parts of the Aegean region and Central Balkan region.

Acknowledgments*. We are very grateful to anonymous reviewer for his constructive comment and important suggestions, which help to improve the manuscript. We would like to thank employees of* *the Sofia municipality for providing access to all available documentations and reliable information for macroseismic effects caused by 2012 earthquake* (M_w5.6). *The work is supported by PROJECT* $BG051PO001 - 3.3.06 - 0063$. *The project is funded by the Operational Programme "Human Resources Development", co-financed by the European Social Fund of the European Union.*

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ЗЕМЕТРЕСЕНИЕТО (M_W**5.6) ОТ 2012 ГОДИНА, РЕАЛИЗИРАНО В СОФИЙСКА СЕИЗМИЧНА ЗОНА И ПОСЛЕДВАЛАТА ГО АФТЪРШОКОВА АКТИВНОСТ**

С. Симеонова, Д. Солаков, И. Александрова, П. Райкова, В. Протопопова

Национален институт по геофизика, геодезия и география, Българска академия на науките, ул. "Акад. Г. Бончев" бл.3, 1113 София, България

(Резюме)

Софийска сеизмична зона, разположена в централна западна България, е област с висока плътност на населението, индустриален и културен център на България и силна сеизмична уязвимост.

Наличните исторически документи свидетелстват за разрушителни земетресения в зоната през 15-ти и 18-ти век. През 19-ти век в близост до град София, разположен в централната част на сеизмичната зона, са реализирани две силни земетресения: през 1818 г. с интензивност $I_0 = 8$–9 МШК и през 1858 г. с $I_0 = 9$–10 МШК. Земетресението от 1858 г. е нанесло сериозни щети в град София и е довело до появата на термални извори в западната му част. В началото на 20-ти век, през 1905 г., в околностите на град Трън, разположен в западната маргинална част на зоната, е реализирано силно сеизмично събитие с $M_S = 6.5$, последвано (през 1917 г.) от умерено силното земетресение (M_s =5.3 и $I_0 = 7.8$ МШК), локализирано в близост до град София. Земетресението е усетено в област с площ около 50000 km^2 и е последвано от афтършокова серия продължила повече от година. Почти век по-късно (95 години) на 22 май 2012 г., земетресение с магнитуд $M_w = 5.6$ ($I_0 = 8$ МШК) се реализира в околностите на град Перник, на около 25 км югозападно от град София. Земетресението е усетено в голяма част от територията на България (до приморските градове Бургас и Варна) в западна Македония, северна Гърция и Турция. Няма жертви и сериозно ранени. Установените щети в градовете София, Перник и Радомир (най-близко разположените градове) са предимно леки до умерени и в единични случи умерено силни. Събитието е последвано от интензивна сеизмична активност.

В настоящата работа са оценени въздействията от земетресението, реализирано на 22 май 2012 г., върху територията на България и околностите ѝ. Специално внимание е отделено на установените щети в град София. Анализирани са спектралните характеристики на главния удар и на най-силните афтършокови събития (M>4.0). Изследвано е пространствено-времевото разпределение на афтършоковите събития. На базата на решенията на механизмите е установено, че преобладаващият вид разломно движение в зоната е с нормален разседен фокален механизъм (в 19 случая от 20 решения на механизмите). Най-общо осите на максимална компресия (P-осите) на локалните напрежения са в направление СЗ-ЮИ.