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Seismicity and nowadays movements along some active faults in SW Bulgaria

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Some results from the seismic, geodetic and extension-metric monitoring of the seismoactive Krupnik source zone in SW Bulgaria during the last 33 years are presented. Special attention is paid to the seismological analysis and fault plain modeling of the stronger earthquakes as a seismic activity investigation. Some extension-metric data and geodetic analysis using present-day GPS data are used in order to constrain the nowadays geodynamics of this region.

Key words: seismicity, earthquake, fault, Krupnik

The South Western part of the Bulgarian territory is the most seismoactive region in Bulgaria and Krupnik seismic zone is the most active part in it. Krupnik seismogenic area is well known by its high seismicity: since I century BC at least 10 events with magnitude M $\geq$ 6 have been occurred on its territory and the adjacent lands. The strongest known event is the earthquake of April 4, 1904 with a magnitude Ms 7.8 [1]; it occurred in the Krupnik source zone, which is nearby the present-day contact area between Southwestern Bulgaria and FYR of Macedonia. Since that time the seismic activity is relatively moderate and scarce along this region. A very complex fault structure characterizes this part of Bulgaria [2]. Several main fault structures build this region. The Krupnik and Struma faults are the most significant of them (Fig. 1).

The geology of the research area is rather complex and is associated with the here situated Pirin, Rila and Vlahina mountains, and first of all with the local structure of the Struma lineament. In fact the Struma lineament is an S-SE oriented asymmetric graben which present view is formed by the Post Alpine activation. Several important faults cross this zone – the subject of our paper is connected with the most significant of them- Krupnik fault lineament (N-NE oriented), which is assumed to be the most active fault structure in Bulgaria. During the Neotectonic stage, the realized vertical movement along this fault is estimated as 3400 m [3]. Some seismotectonics problems of this zone have been discussed in

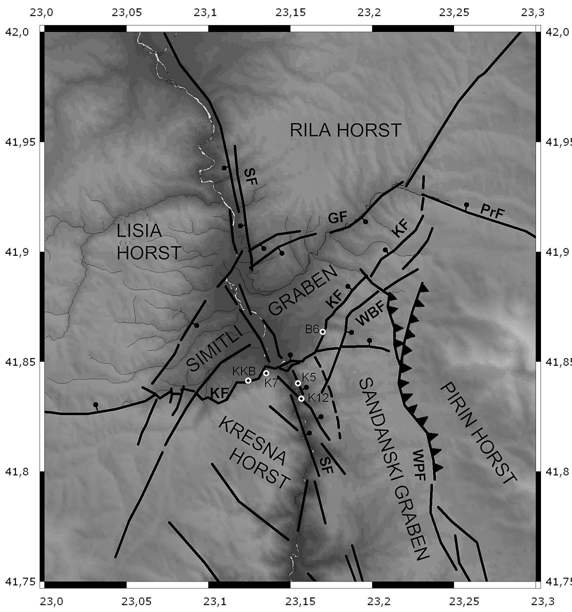

Fig. 1. Simplified sketch of the Simitli graben and adjacent area [4]. The map shows the main tectonic structures, faults and observation points. The main faults are as follows: KF, Krupnik Fault; GF, Gradevo Fault; SF, Struma Fault Zone; WPF, West Pirin Fault (mostly reverse); PrF, Predela Fault; WBF, West Brezhani Fault. The extension monitoring points localities are shown, KKB is the Seismic Station Krupnik.

some previous papers of the authors [4–6] and others. In this paper an attempt to elucidate more detailed the lasts seismic manifestations of the fault structures and to identify the geometry and the movements along the main active faults and their relations to the earthquakes is made. To approach to this main goal first of all we analyze the epicentral, magnitude and depth distribution of the earthquakes and their fault plane

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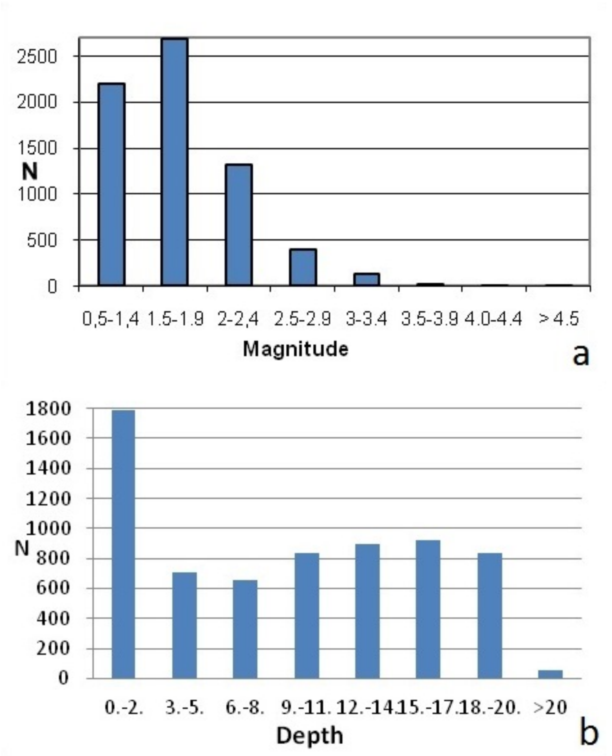

Fig. 3. Magnitude (a) and depth (b) distribution of the seismic events.

mechanisms in the region with coordinates $\varphi = 41.7 - 42.1$ N; $\lambda = 22.7 - 23.4$ E for the period of working of National seismological network NOTSSI (1981–2013), as well as the surface geodetic and extensionmetric manifestations of some satellites of Krupnik fault lineament.

Because of the small number of instrumentally recorded strong earthquakes, the investigation of the well recorded relatively weak seismicity in the last 33 years is required to overcome the existing laps. Conditions for detailed investigations of the weak seismicity around the Krupnik source zone are created after 1980 with the starting of NOTSSI operation. In such a way for the period 1981-2013 in this area more than 6800 earthquakes are recorded in a magnitude interval M = 0.5 – 4.8 (Fig. 2). The magnitude-frequency distribution for the entire data set in Fig. 2a shows that the number of localized events increases with the magnitude decreasing: for M = 4.5–4.9 is 1 event, for M = 4.0–4.4 are 4 events, for M = 3.5–3.9 are 26 events, for M = 3.0–3.4 are 134 events, for M = 2.5–2.9 – 400, for M = 2.0–2.4 – 1326 and so on. The abrupt diminishing of the number of earthquakes in the first two intervals ($M < 1.5$) in Fig. 2a determines also the registration power of the seismic stations network. Taking the latter into account, it can be supposed that the magnitude sample for levels with $M > 1.5$ is comparatively closer to the reality for this part of the Bulgarian territory.

The picture of the depth distribution in Fig. 2b shows that the majority of events occur down to 20 km depth. It is possible the established predominating depth (from 0 to 5 km) to be also due to the presence of unidentified industrial explosions. In the same time the number of events in the interval 11-20 km is comparative with this one. The magnitude distribution of the events in depth (Fig. 3) permits to note some differentiation of depth "floors" with the increase of magnitude – some tendency of formation of some maximums can be traced out for the depth intervals of 10 and 20 km.

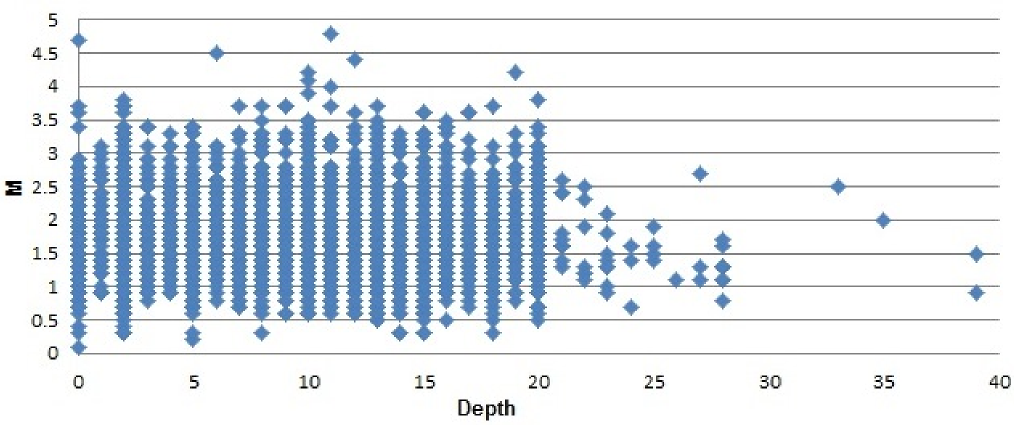

Fig. 3. Magnitude-depth distribution of the seismic events.

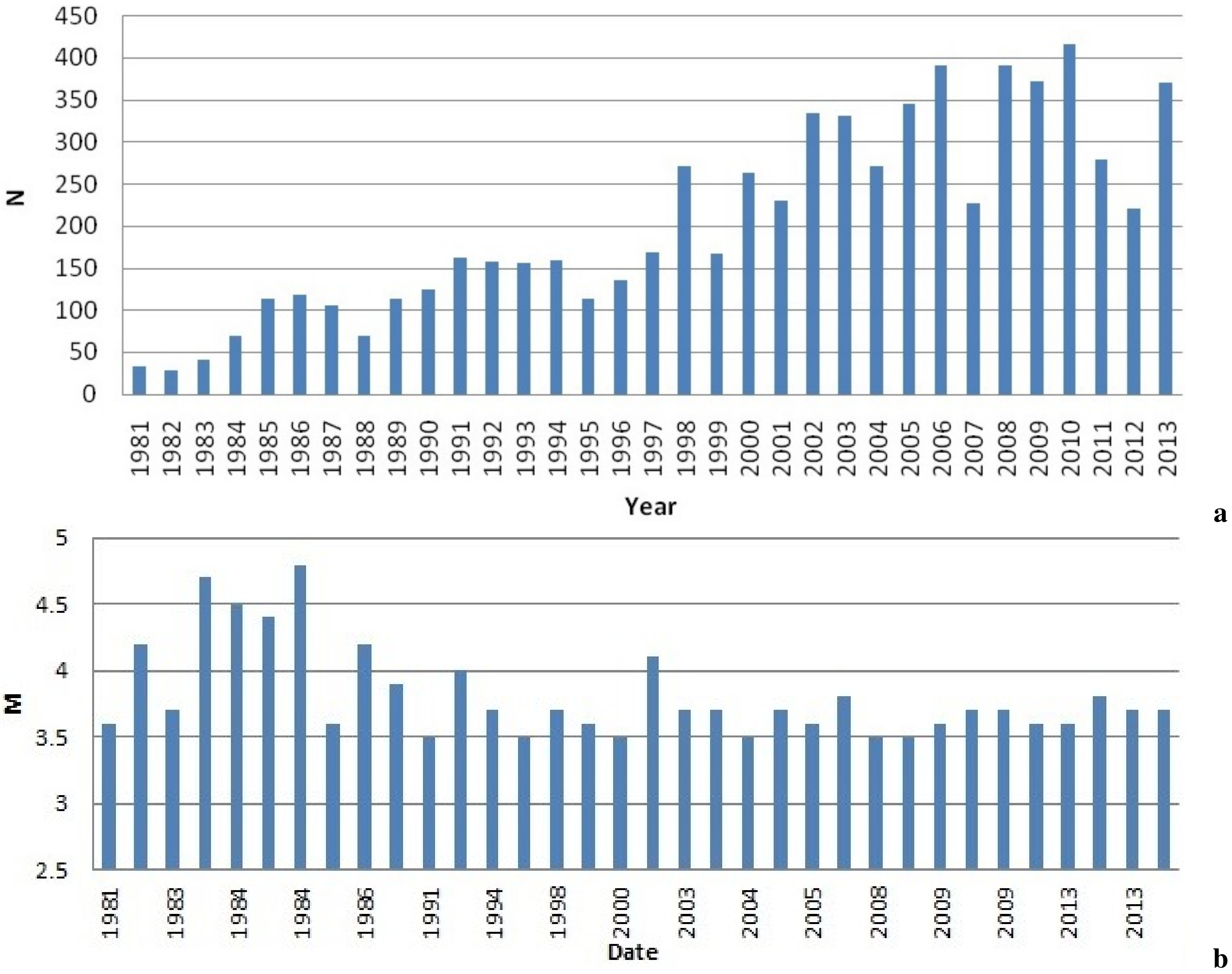

Fig. 4. Time (a) and Magnitude-time (b) distribution of the seismic events.

Fig. 4a illustrates the distribution of seismicity in time according to the number of events per years. The biggest earthquake's amount is displayed in 2010, when about 400 earthquakes occurred – mainly because of local Krupnik fault's earthquake activity. The lowest earthquake quantity is in 1981 and 1982, when about 40 events occurred. Fig. 4b shows the energy release in time through the earthquake magnitude-time distribution. It suggests that in the beginning of 1984, when enough small number of events occurred, is the maximum of energy release. Some other strongest events occurred in 1982 and in 2001. The released high energy amount in the first half of the whole period of study compensates the large number of low magnitude events during the second half of the time period. The low number of small earthquakes in the beginning of the investigated period could be associated with some low registration peculiarities of the network during the beginning of its operation.

The epicenter distribution for the data described above is shown in Fig. 5. The magnitude of the earthquakes is differentiated in five groups – as it is mentioned in Legend of the figure below. From this figure it is clear, that there is no significant number of earthquakes with magnitude $M > 2.$ in the NW and SE parts of the region of interest. The present seismological data demonstrate some grouping of earthquake epicenters. The biggest earthquake density is observed in the NE part of the investigated region, as well as in the SW part (with smaller number of events). It is remarkable that there is no some background of the everywhere space distribution. So, two relatively outlined zones of grouping of the epicenters can be marked, but the zone of concentration of seismic events in east-west direction in the NE part

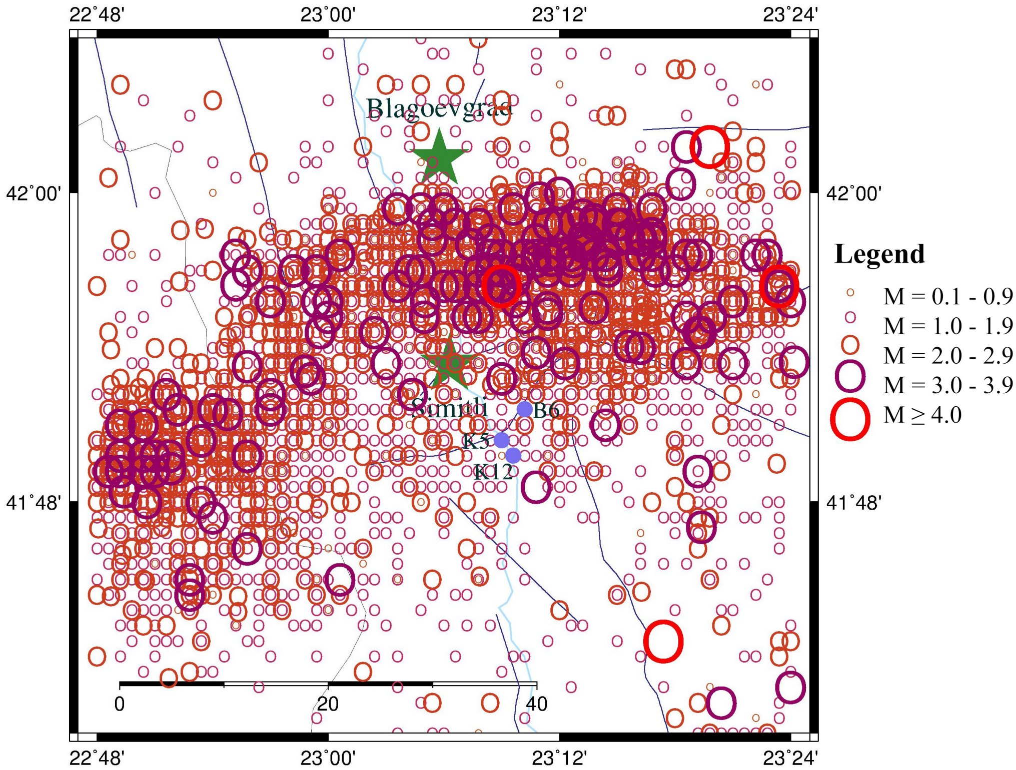

Fig. 5. Epicenter distribution of the seismic events (The Generic Mapping Tools - http://gmt.soest.hawaii.edu/home, the tectonic map is compiled after [7] and [8]).

is more active. This zone can be related with the manifestation of the namely Krupnik fault and its NE branch - West Brezhani fault, as well as with Gradevo fault (Fig. 1). In fact the most significant part of the epicenters is concentrated to the NorthWest from the Krupnik faults lineament with an ENE – WSW direction of the maximum density. The strongest earthquakes for the period of investigation (with magnitude M = 4.4 and M = 4.8) has occurred in one of the same place here during the beginning of 1984. The distribution of the epicenters northern of the Simitli graben can be explained only with the bigger depth of these shocks. The strongest earthquakes are about 10 and 20 km depth and this fact allows us to associate them with the depth activity of the steeple Krupnik-Brezhani fault lineament.

To the SW corner of the territory of interest it can be seen the grouping of epicenters northward from the continuation of the Krupnik fault rupture. More of these earthquakes are located with big depth, which confirm the NW dipping of the fault plane. Having in mind this big hypocentral depth (averaged about 10 km) a hidden penetration of this fault lineament (Pehchevo lineament) to the N-NW direction could be assigned. In such a way this identification may be considered as a manifestation of a particular seismotectonic structure without surface expression, but with an association to well known active fault in around (Krupnik fault). From the picture of Fig. 5 it is clear, that in general, the obtained territorial distribution of the earthquakes shows some agreement with the depth structure of the all shown morphotectonic dislocations, confirming the decisive role of the Krupnik fault system, associated with the surface ruptures from 1904. Only one group of epicenters located to the SE from the maximum concentration could be associated with the influence of the western border of Predela fault - with discordance direction to the Kroupnik system. In this paper the present activity of this eastern faults (with strongest earthquakes with magnitude M = 4.2 and M = 4.0) is out of our interest.

As in the most tectonic region in Bulgaria, the earthquakes in Krupnik source zone are confined to the upper part of the crust, suggested that the depth seismic activity is connected with the depth distribution of morphotectonic dislocations. The orientation of the dislocations and the tectonic stresses in depth in the present work are investigated additionally [9, 10]

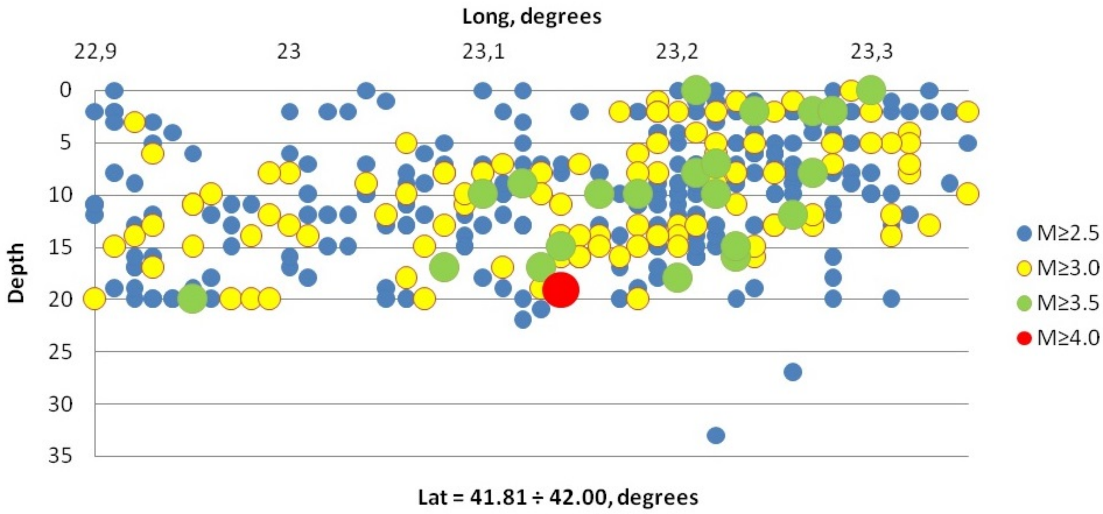

Fig. 6. Depth distribution along a longitudinal profile for the events in NE part.

by means of analysis of the morphotectonic and depth manifestations of the main active faults during the last years. Because of some inaccuracies in the bulletin coordinates for the period 1981–1984, the more precise profile depth distributions were especially made for the events with magnitude $M > 2.5$ (Fig. 6 and Fig. 7). Concerning the depth parameters of the investigated earthquakes with $M > 2.5$, approximately uppersrustal distribution is marked. In fact almost all earthquakes (in depth interval between 0 km and 20 km) are located in the upper crust (or so called "granite" layer) of the region, where the crust thickness varies down to 40 or 45 km depths. In general, it could be confirmed, that the depth distribution of the epicenters of the weak earthquakes at the present, as well as the depth distribution of the stronger earthquakes since the beginning of the century, are located mainly to the depth of 20 km, suggesting the relatively small thickness of the seismogenic layer in the investigated region.

From a geotectonic point of view, the projection of the depth distribution of the seismic events on vertical cross sections is of significant interest – to clarify the seismic structures in depth. To get an idea about the

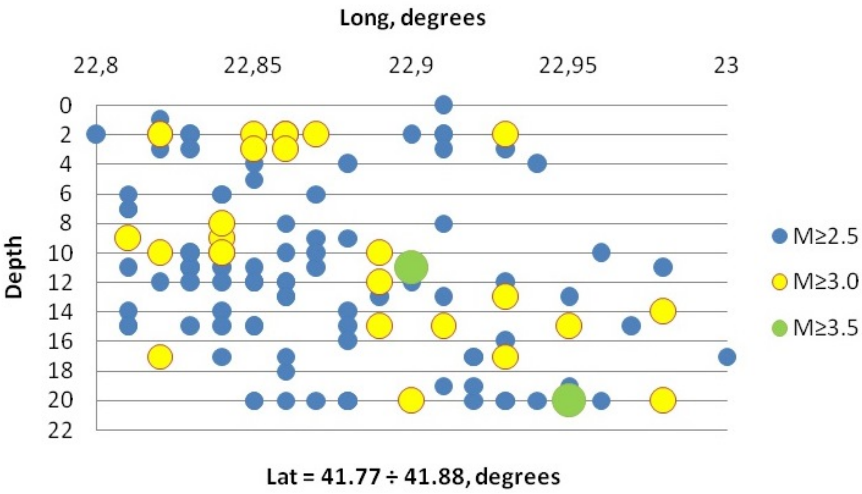

Fig. 7. Depth distribution along a longitudinal profile for the events in SW part.

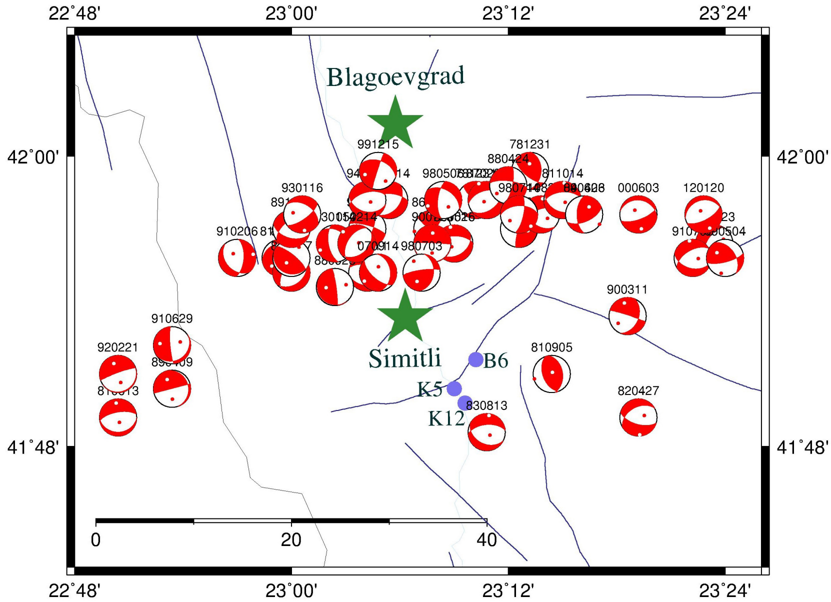

Fig. 8. Fault plane solutions of the stronger events (1981-2013).

distribution of these structures in depth, two vertical cross sections are presented in Fig. 6 and Fig. 7. To present the data more adequately the region of interest is divided into two parts: NE part, including the all area associated with the Krupnik and Gradevo faults (from $\lambda = 22.90$ to $\lambda = 23.35$ and from $\varphi = 41.81$ to $\varphi = 42.00$), and SW one, including almost all earthquakes associated with the depth manifestation of the western part of the Krupnik fault system – Pehchevo lineament (from $\lambda = 22.80$ to $\lambda = 23.00$ and from $\varphi = 41.77$ to $\varphi = 41.88$). The depth distribution of the events is presented by two transversally vertical cross sections with longitudinal directions for each separated parts.

In Fig. 6 it can be seen the depth distribution of the all events from the NE part projected along a longitudinal profile (E-W direction). The vertical cross section reveals stronger seismicity in the deeper layers, which can be generally related to the depths between 6 and 20 km. The level of seismicity in the upper layers is significant lower – there is no one event with magnitude in the interval M = 3.5–3.9 or more. In general it can be seen that the strongest earthquakes are released beneath the central part of the profile. It is interesting to mark some dipping of the seismicity from East to West towards to the central part. To the West from the central part a very slight dipping of the seismogenic layer goes on. The dipping of seismicity in the western part of the profile could be associated with the deep structural influence of older Struma lineament which crosses here transversally the profile.

The depth distribution of the data for SW part of the all region under investigation is presented in Fig. 7. Almost all these earthquakes could be generally related to the hidden manifestation of the E-NE oriented satellite of the western part of Krupnik fault system. The seismicity here is rather weak, but involves the whole surficial 20 km depths. The level of seismicity beneath of 10 km depth is higher - all events with magnitude $M > 3.0$ are concentrated here. The strong shocks gravitate predominantly towards the eastern end of the profile, but not so abrupt increasing of the depth of the earthquakes towards eastern part is observed. In fact, all differentiated by magnitude groups of earthquakes go deeper to the east situated Struma lineament. This is consistent with the hypothesis of the hidden deep influence of the older Struma fault satellites.

The fault plane solutions of the stronger events (magnitude $M > 3.5$) are presented on Fig. 8. More than 80% of the focal plane solutions are with normal dip-slip component and the predominant orientation of the nodal planes is 70° to 90°. This prevailing plane direction coincidence with the orientation of the Krupnik fault sistem. The most relevant evidence for this zone is the almost horizontal orientation of the T-axes in the NNW – SSE direction. There is no clear predominant trend of the P-axes, but mainly for the

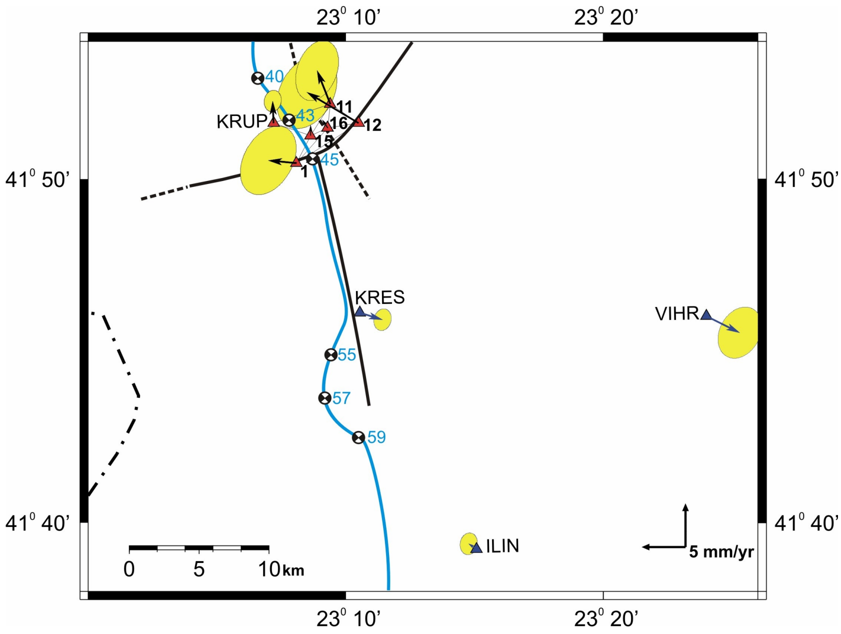

Fig. 9. Extension regime in the Krupnik region by geodetic data.

cases of subhorizontal axes, the ENE – WSW direction dominates. In many of these cases a strike-slip mechanism of faulting (with relevant normal dip component) could be recognized. The plunge angle of the P-axes is larger in comparison with that of T-axes. In general, the calculated focal mechanisms of the earthquakes show that the earthquakes are caused by the tectonic activation of predominantly normal faults, situated around the Krupnik source zone. As well as the Krupnik zone is the zone with the biggest regional significance in SW Bulgaria, special multidisciplinary investigations have been performed namely here by National Institute of Geophysics, Geodesy and Geography (NIGGG) and Geological Institute (GI) of Bulgarian Academy of Sciences (BAS). Special attention is paid to the complex analysis in order to constrain the geodynamics of this region using present-day GPS and extension-metric data.

The local geodetic network in the Krupnik region is designed for monitoring the horizontal crustal block motion [11]. The original configuration consists of 16 points with and the first GPS measurements are performed during the period 1984-1992, but horizontal motions are not revealed. Higher precise GPS measurements started in 1995 by means of many times measuring of the classical points and correlations with other measurements until now. For monitoring of horizontal motions after careful estimation of the tectonic settings and access to the points' state, six of them – two on the southern side and four from the northern side of the Krupnik fault are chosen for GPS observations One idea about the geodetic network and the distribution of geodetic points of measurements in this part of SW Bulgaria could be assumed by the picture in Fig. 9. Geodetic data constrained the recent crustal motions along the Krupnik fault and confirmed its tectonic activity. They also show that the region is undergoing the extension and are in agreement with the seismological and geological information. The field of seismotectonic deformations is generally characterized by predominance of NW-SE horizontal extension. From NE to SW the direction of extension changed gradually to WNW-ESE.

To detect the real rates of fault movements along the fault in the region of interest one extension-metric monitoring at many points in and around the Krupnik region have been organized by GI of BAS [4–6, 12] and others. The obtained results confirmed the decisive role of the Krupnik fault - the main extension movements have been observed for the points K5, K12 and B6 (Fig. 8) which are located very closed to the Krupnik-Brezhani fault surface line. The most expressive results have been obtained along the Krupnik fault for the monitoring site B6. In Fig. 10 some unpublished results for this point during the period

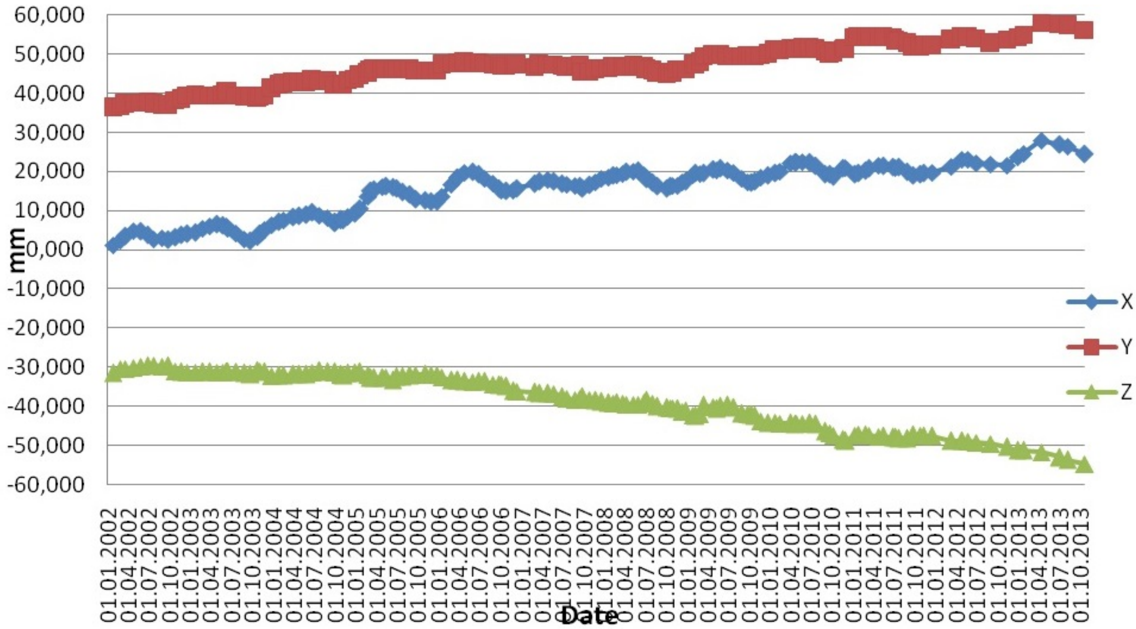

Fig. 10. Displacements found at point B6.

Jan. 2002 – Dec. 2013 are presented. Concerning horizontal movements, varying periods of compression and extension at fault are established. The deformation accumulated so far is impressive. The total displacement till now – after 11 years of monitoring, shows about 30 mm of sinistral displacement, and about 27 mm of thrusting. The permanent trend of extension of about 2 mm/a, left-lateral slip of about 2.7 mm/a and a reverse slip of about 2.5 mm/a is preserved like one reliable tendency for many years. In comparison with seismological data (Fig. 11) some very general correlations are obvious - the horizontal displacements change their directions as if following the picks and gap in the seismic activity.

As a conclusion it could be emphasized that the realized weak seismicity in the region of interest dur-

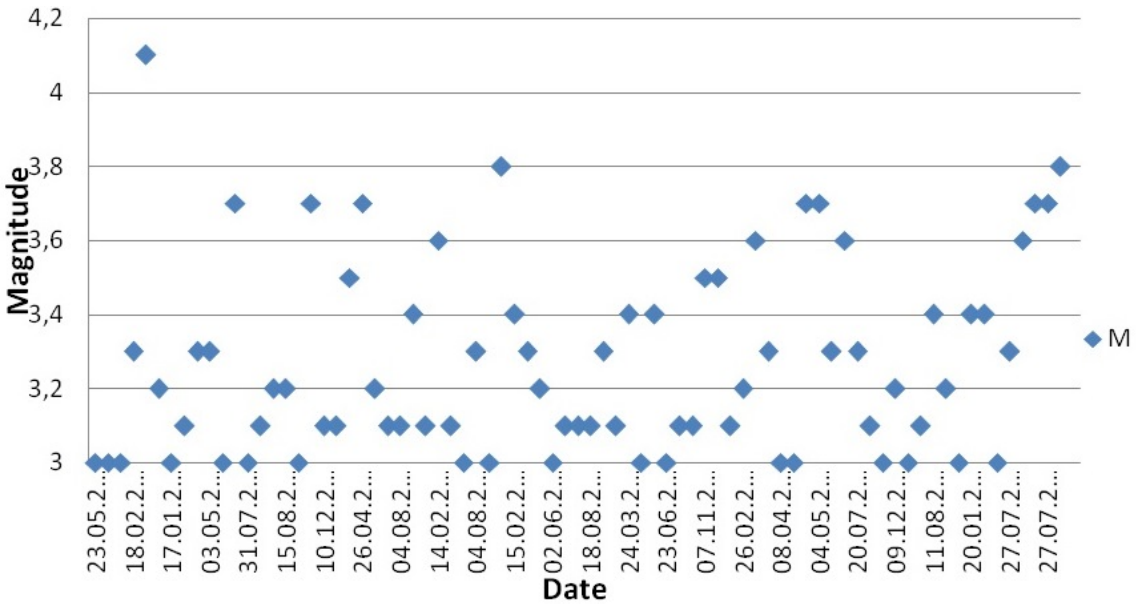

Fig. 11. Magnitude-time distribution of the strongest events during the extension monitoring time.

ing the last 33 years confirms the decisive role of the Krupnik fault lineament, associated with the E-NE oriented surface ruptures caused by the very strong 1904 earthquakes. Distribution of the epicenters shows obvious activity in NE direction. The depth distribution of earthquakes probably marks a prevailing activity of the northern boards of Simitli graben and some depth influence of Struma lineament. The main result of fault plane solutions modeling is that the seismological results confirmed the geological hypothesis of the extensional regime of the Krupnik region in SW Bulgaria. Orientation of the extension is S-SE, perpendicularly to the Krupnik fault. According to geodetic data at the same time the all territory of SW Bulgaria is moving towards S-SE with velocity of about 2–3 mm/yr relative to stable Europe. The good correlation between the geodetic and seismological investigation is a reliable evidence for the identity of the deformation of the crust and the seismic activity of this seismogenic area, where the regional tectonic stress are released periodically by activation of normal faulting. The extension-metrics monitoring shows also very quiet contemporary extensional deformations associated with the Krupnik fault. All this leads to the conclusion that the crust around the Krupnik source zone is relatively homogeneous in strength, according to regional point of view. On the base of the complex analysis of the contemporary seismicity, fault plane solutions, geodetic and geological modeling, it could be conclude that the present seismotectonic activity in the Krupnik region is associated very well with the main geodynamic processes in the central part of Balkan region.

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СЕИЗМИЧНОСТ И СЪВРЕМЕННИ ДВИЖЕНИЯ ПО АКТИВНИ РАЗЛОМИ В ЮГОЗАПАДНА БЪЛГАРИЯ

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(Резюме)

В настоящия доклад се предлага детайлна информация за параметрите на сеизмичността през последните 30 години в Югозападна България – района южно от Благоевград. Чрез интерпретация на механизмите на земетресенията се анализира поведението на активните разломи и статуса на тектонските напрежения в района като част от Струмската, Пределската и Крупнишката разломна система (известна с едно от най-силните корови земетресения на територията на Европа за последните 200 години). Представени са и резултатите от дългогодишните екстензометрични измервания на скоростите на тектонските движения около трите разломни системи. Проведен е комплексен сеизмотектонски анализ на представените резултати и са установени известни корелационни зависимости между отделните геодинамични параметри на изявените разломни системи в изследваната част на Югозападна България.