4.6.1. ON THE SEISMIC SOURCE REGIONS IN MACEDONIA-BULGARIA BORDER AREA

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4.6.1.1. Introduction

Two devastating series of earthquakes developed in Macedonia-Bulgaria border region (Balkan Peninsula) during the XXth century. They occurred in Pehcevo-Kroupnik (1904) and Valandovo (1931) seismic zones. Their strongest events were coupling in pairs (magnitudes classically determined are known as 7.1, 7.8 and 6.0, 6.7 respectively). When similar seismic violence has been once experienced in a certain region, this is a signal one to be especially attentive. The goal of this study is to improve the knowledge about state-of-the-art of the source regions of these two earthquake series and their adjacent areas. The long-term seismicity in the region is reviewed, after involving recent catalogue renovations. For the series in 1904 and 1931 especially, a comprehensive study of the initial datasets is anew undertaken applying appropriately formulated criteria. The analysis on the basis of the historical and nowadays seismicity suggests a new outlook on the seismogenesis in each of the considered zones.

4.6.1.2. Long-term seismicity

The acquaintance with the long-term seismicity is of prime importance to reliable hazard and seismic risk assessment. It is well known how much inconveniences the political and any kind of administrative boundaries may cause to the investigation of earthquake influence distribution. In this study we make an attempt to present the latest outlook on the long-term seismicity in the Macedonia-Bulgaria border region. To this goal the catalogues by Shebalin et al., (1974), Grigorova et al., (1978), Hadzievski (1976 a, b, c) renovated by materials of later publications are used. Some of these recent publications emphasize on how fully and how far critically the information sources were exploited, i.e. they are steps towards improvement of the supporting dataset (data from which the earthquake parameters are evaluated) quality. After checking the authenticity of the strong events in the cited catalogues, especially of these proceeding from a very poor dataset like the historical ones, some key catalogue events were clarified. Thus, it was shown that the careless reading of initial records had provided false entries in the catalogue as the 1866 magnitude 7 event in the middle Strouma valley (Glavcheva, 1999) and the 1759 magnitude 6.3 event in the Pirin mountain massif (Glavcheva, 2000); in result, similar events were omitted from the catalogues. Others, previosly unknown events, like those from the Ambraseys' database of earthquakes (BEECD – App. F2, 1998) are involved to contribute to the revised seismicity pattern. For the territory of R. Macedonia papers based on the recent seismicity investigation (Hadzievski, Pekevski, 1985, Jordanovski, Pekevski et. al, 1998) give additional (revised) information and are also used.

On the basis of the above materials a map of the earthquakes distribution from ancient times (since 375 A.D.) till 1980 is drawn up (Fig. 4.6.1.1.). All known damaging events

(maximum intensity of 6 or higher degree according to the Medvedev-Sponheuer-Karnik [MSK] scale) are presented being marked by the epicentral intensity (Io) or a documented site intensity (Imax). Most severe earthquakes are known to have been occurred in Marvinci-Valandovo area – 1st-2nd Cent.? (9 MSK), in Stobi – 400 AD (9 MSK), in Ossogovo mountain – 1641 (the town of Kyustendil, 9 MSK), in Kroupnik-Pehchevo area – 896 and 1904 (9 and 10 MSK, respectively), and in Valandovo area – 1931 (10 MSK).

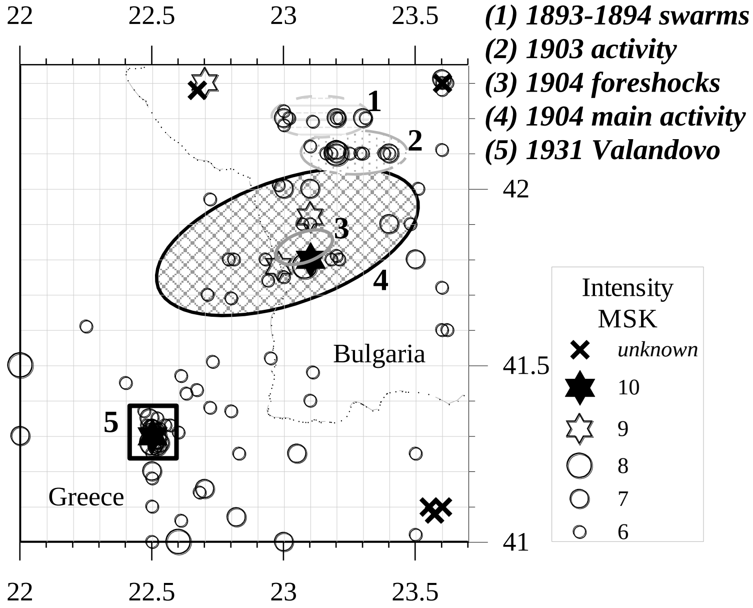

Fig. 4.6.1.1. Long term seismicity in the study region (375 AD – 1980): only earthquakes which caused damages (I≥6 MSK) noted by their Io or Imax reported; the areas outlined show seismogenic process development in the Kroupnik-Pehcevo area

The accent of this study is put on the 1904 and 1931 earthquake sequences and then activated Earth's crust space. Availability of rich macroseismic material stored during the XXth century favors the analysis. The nowadays seismicity investigation serves to clarify important seismogenic features of the study region.

4.6.1.3. Seismicity of the Kroupnik-Pehcevo region in 1904

1904 was the year of occurrence of two catastrophic earthquakes in the nowadays Macedonia-Bulgaria border region, the Kroupnik-Pehcevo area. At that time the regional seismology was at its non-instrumental stage. Descriptive reports on earthquake effects and collaborators' intensity assessments being gathered through well developed correspondents' networks (meteorological observatories, telegraph-postal services, railway station officials, municipal offices and people's teachers) were regularly published by J. Mihailovic for Serbia and S. Watzof for Bulgaria in macroseismic compilations (1907 and 1905-1907, respectively). Much later, catalogue solutions were made based on these datasets. Going through the available catalogues the time-space development of the seismogenic process in the area can be traced (Fig. 4.6.1.1.). It is obvios, that ten years before the 1904 devastation, in 1893-1894, a swarm-kind earthquake activity took place at about 30 km northwards from the central spot of the future giant seismic source. The latest serious pre-activity of seismic nature (November 1903) was in immediate vicinity of the 1904 excited zone.

Concerning the 1904 seismic activity, one can easily understand that no full inventory of the initial dataset has been made before this study. On this reason we undertook the macroseismic analysis under appropriate rules formulated on purpose. As a result, a new comprehensive energy catalogue was compiled. It has provided quite important new information about the seismic activity during the earliest stage of the rupture process. Some main steps at the initial data processing are presented in the next rows.

Two specific problems in dealing with the documentary database have to be mentioned: (i) the difficulties created by the Rossi-Forel scale itself and the "personal scale" of the correspondents' intensity assessments; (ii) absence of information or reports from the territory with significant consequences on buildings, communications and on the psychic state of the people themselves, for several days after the greatest earthquakes occurrence on 4 April 1904. To overcome these inconveniences the only output is the compilation of an energy catalogue according to appropriately formulated criteria.

For distinguishing events according to their "absolute" time in circumstances of lack of unified timing over the territory of the country, the "relative differences" are used:

$$t_A(abs) = t_M(abs) - [t_M(i) - t_A(i)] \qquad (1)$$

where $[t_M(i)-t_A(i)]$ indicates the difference between the moments of the main shock $t_M(i)$ and of a concrete aftershock $t_A(i)$ reported from the same locality "i", and $t_M(abs)$ is the "real time" of the main earthquake according to the Balkan Catalogue (Shebalin et al., 1974). In such a manner it is decided whether the information refers to a given event *A*.

While evaluating the excitation distribution all the available data was used. Intensity maps are drawn for all the earthquakes felt at epicentral distances surpassing those to which the mainshock's area of I≥8 MSK had spread (to about 50-80 km). The earthquake magnitude (M) is evaluated using the felt area size. The application of such an approach does not need precise hypocentre location when the macroseismic field periphery is far enough. In the study case this approach is the only way out. The following equations obtained for the territory of Bulgaria (Glavcheva, 1997) are used:

$$\begin{aligned} (2) \qquad & MLH = (2.36 \pm 0.26) \log R_3 \\ & MLH = (2.45 \pm 0.24) \log R_4 + (0.49 \pm 0.43) \end{aligned}$$

where R_3 and R_4 are the mean isoseismal radii of 3 and 4 MSK respectively (correlation coefficients r=0.90 and 0.92). After tracing out the reports from two meteorological stations situated within the pleistoseismal area, Rila Monastery and Borovetz, where the observation continued without interruption for many days, it turned out that the earthquakes with M≥4.5 during the first two days after the catastrophe could have been identified without any omissions.

After distinguishing the individual shocks by time and energy, it became evident that the seismic source maximal activity was in the interval between the two catastrophic earthquakes. That is why this very period presents the most curious stage of the rupture process, unfortunately the least familiar till now.

Taking into account the new catalogue completeness in relation to the earthquakes of M≥4.5 (as mentioned above), the value M=4.5 is fixed as the lower threshold while plotting the energy-time distribution (Figs. 4.6.1.1. (a), 4.6.1.1. (b)).

The elastic energy released is calculated for each shock, proceeding from the macroseismic magnitude, through the empirical correlation for Bulgaria (Grigorova, Christoskov, 1968):

$$\log E\,[J] = 2.23+2.23M-0.055\,M^2$$

The sample derived from the new energy catalogue shows significant changes of the energy releasing in time (Fig. 4.6.1.2. (b)) in comparison with the corresponding data from the latest Bulgarian catalogue (Grigorova et al., 1978) (Fig. 4.6.1.2. (a)). It is obvious that immediately after the first catastrophic earthquake (M=7.1) the source region is very active for around 10 minutes. During the time rest, till the second catastrophic earthquake (M=7.8), strong aftershocks are lacking and the average energy released per single event is reduced almost 20 times comparing with the first part of the interval between the two biggest earthquakes. In the same time, the earthquake frequency inbetween the two biggest earthquakes is keeping almost constant (Fig. 4.6.1.2. (c)), only the energy level is quite lower.

The anomaly established could be considered as a seismic precursory phenomenon.

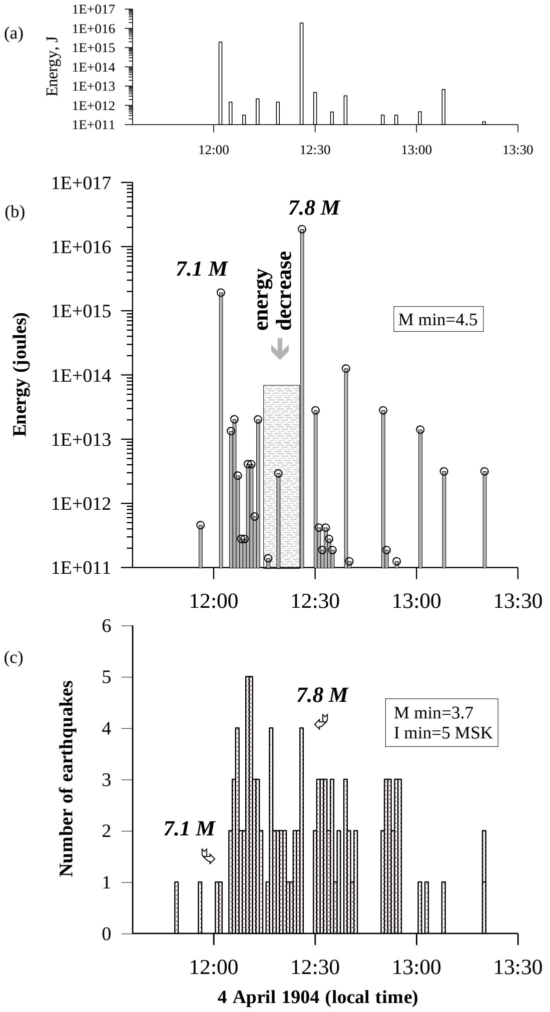

Fig. 4.6.1.2. Earliest stage of seismic activity, 1904: energy-time distribution according to Grigorova et al., (1978) (a) and this study catalog (b); earthquake frequency, this study (c).

4.6.1.4. Nowadays seismicity in Kroupnik-Pehcevo region

Many investigations on earlier earthquakes showed that the historic seismic activity in the Kroupnik-Pehcevo region was usually realized along a subequatorial seismogenic direction (eg Fig. 4.6.1.1.) crossing through the first order Strouma morphotectonic lineament system. The subequatorial orientation was also clearly manifested by the highest intensity fields of the catastrophic 1904 earthquakes, so as by macroseismic fields of smaller earthquakes (Shebalin, 1974, Glavcheva, 1993). The weak earthquakes distribution in this region, based on recent years registrations by high sensitive seismographs, also shows that the seismogenic structures are subequatorially (transversally) oriented in the ENE direction (Fig. 4.6.1.3.). The seismicity in the Kroupnik-Pehcevo region and its adjacent areas for the period 1990-2004 (registrations and earthquake parametrization according to Bulgarian national seismological survey NOTSSI) will be considered below.

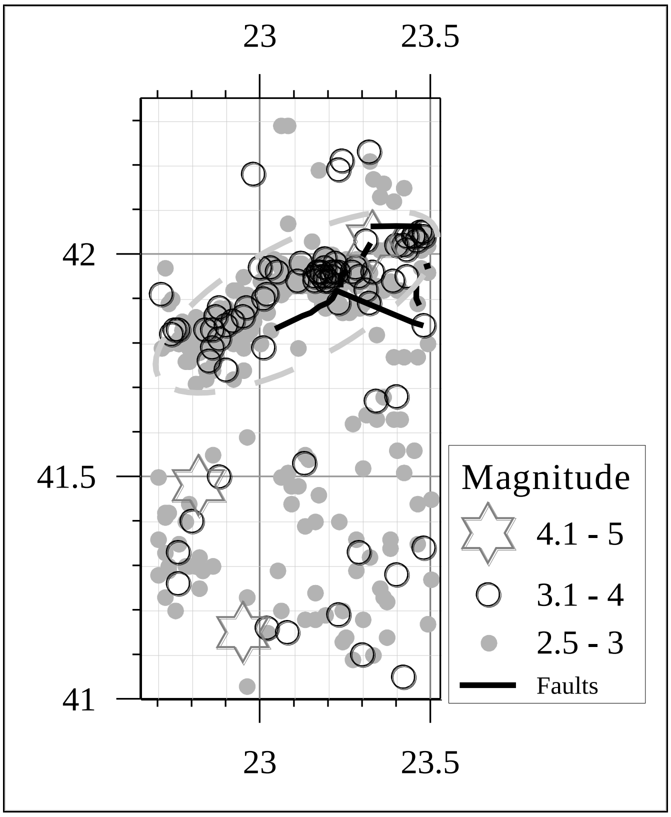

Fig. 4.6.1.3. Nowadays seismicity (period: 1990-2004; M≥2.5)
in Kroupnik-Pehcevo region (area outlined) and its adjacent areas - registrations and earthquake parametrization according to Bulgarian national seismological survey

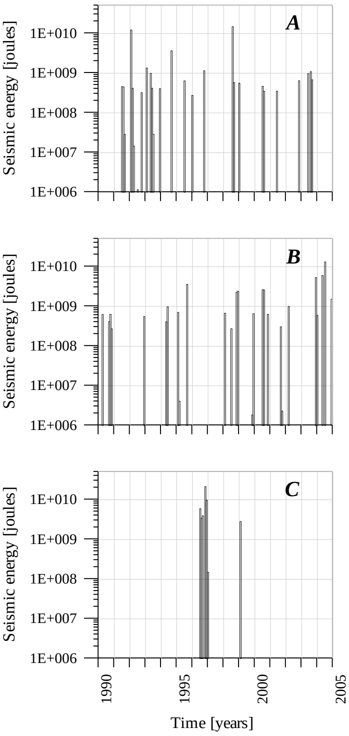

Fig. 4.6.1.4. Energy release during the period 1990-2004 in the subdivisions of Kroupnik-Pehcevo region: Western sector (*A*), Central-Eastern sector (*B*) and Northeastern sector (*C*)

Most (98%) of the seismic events with a magnitude down to 1.8 in the period 1990-2004 were micro-earthquakes (M<3.0). Almost all of them were realized at no more than 20 km under the Earth’s surface. The established sharp decreasing in the earthquakes number with depth increasing confirms the concept of an easily stress release in the superficial layers. The magnitude-depth distribution shows maximum density of seismic events at depths between 10 and 15 km; most of the strongest earthquakes are realized within the same depth range. Downwards the earthquake magnitude decreases.

The time distribution of earthquakes in the period 1990-2004 does not allow finding out any periodicity. What can be marked is some tendency of increasing in the earthquake frequency of occurrence. The biggest earthquake number can be noted in 1997 (the time of sixth-months’ swarm activity in neighboring area of South Rila) and in 2000. The smallest events’ number took place in the beginning of the interval.

Considering this recent seismicity in the Kroupnik-Pehcevo region, the following peculiarities can be specified. The biggest density of seismic events exists around and to the north from the Kroupnik fault where a strip in approximately west-east direction is

formed. To the east, the seismic activity spreads to the town of Razlog, and to the west it is connected with faults along the southwestern board of the Delchevo graben (Macedonia). The seismic activity in the central part of the "old" Kroupnik source, where a complicated tectonic knot takes place under the Simitli graben, expresses a high seismic potential. The influence of the Kroupnik fault is clearly expressed to the north from its morphotectonic manifestation; this is connected with its northwards dipping. To summarize, the recent seismicity in the Kroupnik-Pehcevo region is caused by movements in the area of the Kroupnik-Brezhani combined fault structure whose general direction, WSW-ENE, is clearly manifested by the seismic data. This seismogenic structure, namely, seems to continue as far as 20 more km to the west-southwest into the territory of Macedonia.

In the northeastern sector of the considered region we observe a swarm activity. This seismic activity, quite limited in time, does not allow connecting it genetically with the permanently active Kroupnik-Brezhani fault structure. It takes place at the southern periphery of the Rila Mountain although it has been localized at the imaginable prolongation to the NE of the Kroupnik-Brezhani fault lineament. On this reason we consider it connected with the well expressed Semkovo fault. The strongest earthquake in the whole study period, the one with M = 4.1, occurred just here. Some sluggish seismic activity to the South-East of Predela zone and within the Razlog earthquake source is to be noted.

Some characteristic seismogenic features related to the nowadays low energy seismicity in the Kroupnik-Pehcevo region come up. The space-time distribution of the earthquakes shows a certain separation of the region into three subdivisions - the Western sector, Central-Eastern sector and Northeastern sector (in the South Rila Mountain) - they become active consecutively in time (Fig. 4.6.1.4.). The main characteristic feature of the nowadays seismicity in the region is the obvious clusterization of the events in time and space. In reference to the energy release the following can be underlined. The appearance of relatively stronger events (with M>3.0) has most often sporadic character; in many cases these occur isolated in time or as doublets or triplets with almost equal magnitudes. As to the strongest events (M>3.5), formations of classical or swarm-type sequences are observed. Classical aftershock series (with or without foreshocks) are characteristic of the Western sector (late January and February of 1992, beginning of August 1994) and Central-Eastern sector (August 1995, July-August 1998, October 1998, February 2002 and November 2003), while the swarm-type sequences take place mainly in the Northeastern sector (July-August 1997, November-December 1997, January 1999 and June 2000). There are also cases when an earthquake sequence, no matter where in the region, terminates with its strongest event.

4.6.1.5. Seismicity of the Valandovo region related with 1931 earthquakes

The Valandovo earthquake of 1931 (M=6.7) being investigated showed characteristic foreshock phenomenon in the preparatory period which started in 1916. In the period 1916-1931 the seismic activity was manifested on a wider region around Valandovo (Gevgelija-Valandovo-Strumica-Stip-Veles) in the Vardar seismogenic zone.

The parameters of occurred earthquakes were determined by analyzing of isoseismal maps (Hadzievski, 1976 a, b, c) because of the lack of instrumental seismological data for the earthquakes before 1957. The *macroseismic* epicentres were determined for all earthquakes with M≥3.1 and the epicenters of the earthquakes in Valandovo epicentral area are presented on the epicentral map (Fig. 4.6.1.5.).

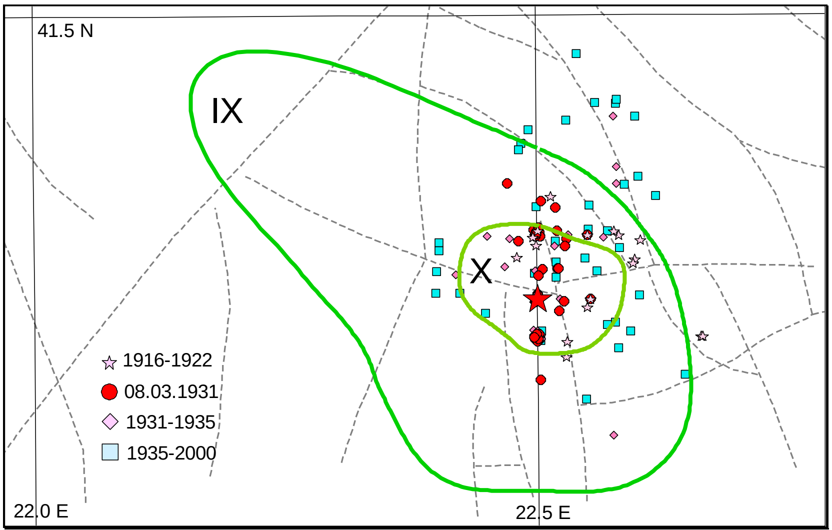

Fig. 4.6.1.5. Epicenters, isoseismals (of Valandovo earthquake☆) and faults in the Valandovo epicentral area

The observed time-space distribution of the epicentres (1916-2000) has pointed out some interesting characteristic of the seismic activity in the region under investigation (Hadzievski, 1982, 1983). In this period, three seismically active intervals have been recorded. Their duration decreases as the occurrence time of the main shock approaches:

- **from April 10, 1916 to March 7, 1931, 21 earthquakes occurred with magnitudes in 3.1-5.1 interval;**
- **from March 7, 1931 (00h 16m UTC), to March 8, 1931 (01h 40m UTC), 7 earthquakes with magnitudes 3.7-5.9 occurred in the Valandovo epicentral area, as foreshocks. The locations of the preceding earthquakes were arranged in a spiral whose end approached the location of the main shock;**
- **Valandovo earthquake main shock occurred on March 8, 1931 (01h 50m UTC) with M=6.7 and intensity 10 MCS;**
- **from March 8, 1931 to December 20, 1934, an aftershock sequence of 127 earthquakes with M 3.1-4.6 occurred. The arrangment of the aftershocks' locations was of star-like shape, while the epicenters being concentrated close to the epicenter of the main shock and some of them at a very close distance;**
- **after completion of the aftershocks sequence, from 1935 till the present time (period of the normal seismic activity), the strongest earthquake occurred in 1990, M=4.6, Strumica (Hadzievski, D., Pekevski, L., 1985, Jordanovski, Lj., Pekevski, L., et al., 1998).**

The elastic seismic energy released in Valandovo seismogenic area during the XXth century calculated by the empirical correlation of Hadzievski (1975): logE [J] = 4.5+1.5 M, is presented in Fig. 4.6.1.6. It clearly shows that the main energy amount was connected with the 1931 large earthquake and its fore- and aftershocks. It is worth underlining the relative quiescence in the interval 1935-1967 which might have been caused by two factors: the significant excitation in the Valandovo source was over and/or the stress redistribution in the part of the Vardar zone (through the territory of R. Macedonia) where the Skopje catastrophe was forthcoming.

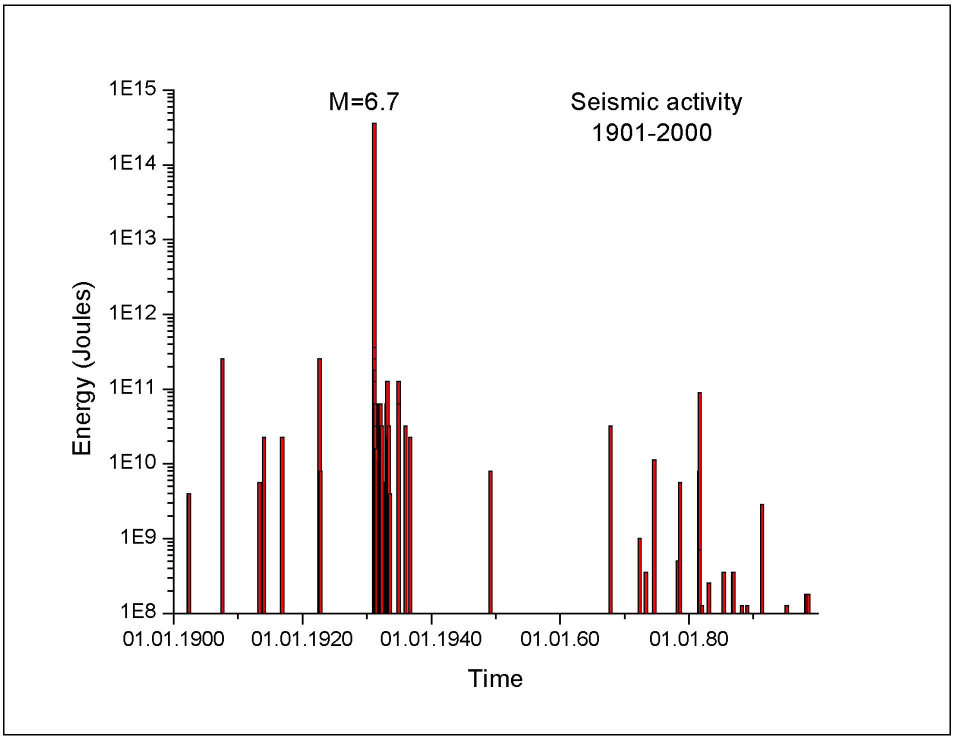

Fig. 4.6.1.6. Seismic energy released in Valandovo epicentral area during 1901-2000

Other interesting results concern the volume V of increased seismic stresses and the slip rate σ of the Valandovo earthquake.

Based on spatial distribution of the earthquake sources during the time interval 1916-1931 the value $V=2.15x10^5$ km^3 has been obtained for the volume in which stresses had accumulated prior to the occurrence of the main 1931 Valandovo earthquake. According to theoretical considerations and applying the equation (Hadzievski, 1982)

$$4\mu\ a\ E=S^2\,V \qquad (3)$$

where $\mu=10^{11}$N/m^2, $S=10^6$ N/m^2, $E=10^{15}$ J almost the same value is determined: $V=2.0x10^5$ km^3. That means that in the case of Valandovo earthquake the seismic energy was generated from significantly larger area than the hypocentral area/volume of the main shock.

The slip σ along the fault in the origin of the Valandovo earthquake was recently investigated by one of the present authors (Hadzievski, 1983). The length (L) and the dislocation surface of the seismic fault (P) were determined from the epicentral aftershock map as well as from the pleistoseist of Valandovo earthquake isoseismal map. The σ values obtained are 0.46 m and 0.69 m, respectively.

4.6.1.6. Conclusions

In this paper the long-term seismicity in the Macedonia-Bulgaria border region has been critically considered. The revised picture suggests that the earthquake catastrophes in the region occur at intervals of 200 – 400 years on the average. Concerning the earthquake series in 1904 and 1931, a comprehensive study of the initial datasets is anew undertaken applying appropriately formulated criteria. Two peculiarities can be marked as common to these series: (i) tightening of the preceding

seismic activity towards the location of forthcoming main shock and (ii) lack of strong aftershocks after coupling of the catastrophic events.

New results are gained for each one of the considered zones.

Concerning the Kroupnik-Pehcevo area: a seismic precursory phenomenon of the M7.8 earthquake has been established – decrease in the average energy released per single event almost 20 times. The nowadays seismic activity in the Kroupnik-Pehcevo region is at the highest level amongst the seismogenic zones in Bulgaria. It may have been specified by the following peculiarities: (1) the biggest density of seismic events preserves the seismogenic orientation of the 1904 source zone (ENE-WSW) and passes through both countries, R. Bulgaria and R. Macedonia; (2) swarm activity and clusterization of events in time and space characterize the low energy seismicity.

Referring to the Valandovo zone: The duration of the outlined seismically active intervals decreases as the occurrence time of the main shock approaches. The volume in which stresses had accumulated prior to the occurrence of the main 1931 Valandovo earthquake is estimated in order of $V=2.0x10^5$ km^3 and the slip σ along the fault – in the interval 0.46-0.69 m. After precluding of the unusual activity 1931-1935, a relative quiescence has set in for several decades.

Summarizing, the undertaken analysis of the historical and nowadays seismicity in Macedonia-Bulgaria border region suggests a new outlook on the seismogenesis in each of the considered zones.

4.6.1.7. Acknowledgment

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4.6.1.8. References

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