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RESEARCH ARTICLE

A new insight view to the strong (M7.2 and M7.8) earthquakes of 1904 in Bulgaria

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Abstract

The Kresna-Kroupnik seismic source (SS K-K) is under deep investigation. This source is famous with the occurrence of two very strong earthquakes (M7.2 and M7.8) on 4th April 1904 in a time domain of 20 minutes, thus considered to be a “doublet”. A short review of the European seismicity shows that during the last 200 years there is not so strong seismic event on the territory of continental Europe. Besides its power this “doublet” demonstrated a numerous peculiarities which do not fit the recent knowledge about the surface expression of such powerful seismic event. The very short length of the surface dislocation (less than 40 km), the relatively small area of high intensities (up to X-XI EMS), the large area of felt effects, the large area of liquefaction, etc., do not coincide with the recent observations of similar earthquakes (for example Kahramansharah-Gasientep on 6th February 2023). All these strange peculiarities triggered a wide interest to seismologists to study in depth the behavior of the SS K-K. We started with deep insight view to the low velocity layer established by us earlier at depths of 50 to 150 km. Then proceed up by seismic tomography for the depth interval 0-50 km, considered as a thickness of Moho and finally reach the recent GNSS measurements in the area to reveal how and why the SS K-K produced such effects by the earthquakes of 1904. Following the concept of the protrusion of the low velocity body just under the source, than the logic of existence of vertical blocks at shallow depths with different geophysical characteristics (lower and higher P and S waves velocities), thermal and Bouguer gravity anomalies and finally expanding our knowledge by the GNSS displacements of the surface layers which show the behavior of the recent stress field. Thus we were able to create an algorithm explaining the geodynamic environment of the SS K-K observed peculiarities without visible logical contradictions.

Keywords: strongest earthquakes in continental Europe; seismicity; tomography; Microseismic Sounding Method

1. Introduction

The most powerful seismic source in continental part of Europe for the last two centuries is the active zone of the Kresna-Kroupnik earthquake (on 4th April 1904 – two shocks with respective magnitudes of 7.2 and 7.8 in 20 minutes’ time domain – one strong foreshock and very strong main shock) have been observed

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with epicentral intensities reached X-XI EMS – (Ranguelov B et al., 2001). The 7 years aftershock sequence was detected (Rizhikova S et al., 2000). On the other side in surroundings of this large earthquake source, there are also several lower active sources (for example Velingrad, Mesta river, Belassica, etc.) seismic active units. There is also so called diffusive seismicity located mainly in the Rila and Pirin mountains, as well as some indications of induced seismicity related to the biggest in Bulgaria dam (called "Iskar"). This Iskar source is activated during seasonal fulfillment and empting time intervals. To the west of the investigated area are located the Valandovo (1931, M6.7, X EMS) seismic event and the Skopje (1963, M6.1, X EMS) earthquake with large number of fatalities and damages. (Ranguelov B et al., 2008). What trigger the interest of the investigators to study the Kresna-Kroupnik seismic source (SS Kresna-Kroupnik) are several unusual facts. First of all the relationship between the estimated magnitudes and the relatively short (less than 40 km) surface seismic dislocations generated by the events of 1904 is surprising (Ranguelov B et al., 2000). The second one is the large area of the observed sand volcanism (Ambraseys N, 2001). The third one is the E-W direction of the surface dislocations and the regional faults network with dominant N-S propagation. These discrepancies triggered high scientific interest and lead to a lot of seismological investigations (Dineva S et al., 2002) and interpretations. The main aim of this study is to disclose the geodynamic peculiarities studying the deep structure of the seismic source and earth's interior under it and to reveal the possible reasons for the specific seismogenic properties of the structures controlling the deep geodynamic processes. To reach this aim several methodologies have been performed – seismic tomography (to study the earth's crust in the area), local seismicity study and seismotectonic (to get the relationships between the strong 1904 seismic events and their peculiarities and the recent seismic activity of the source zone), deep asthenosphere investigations by seismic noise inversion, natural geophysical fields in the area, recent GNSS measurements and observations, etc. The complex study of the unique SS Kresna- Kroupnik is the first attempt to integrate knowledge about the local and regional geodynamics for better understanding the seismogenic properties of this valuable area.

2. Tectonic setting and position of the SS Kresna-Kroupnik

The area of SS Kresna-Kroupnik is located on a triple point of several morphologic units – Rhodopean, Struma and Belasitca. The Rhodopen masiv is an old craton buildup of ancient metamorphic rocks with Precambrian age. The Struma unit is composed by metamorphic and sedimentary rocks located in the Struma graben with Tertiary and Quaternary sediments. The Belasitca Unit is an elongated mountain structure built up by archaic rocks separated by younger grabens with Triassic age. The area is fragmented by younger active neotectonics faults with predominant N-S direction.

Figure 1. Tectonic sketch (according (Zagorchev I., 2001)) and main tectonic units in Bulgaria. Red polygon indicated the area of 4th April, 1904 earthquakes.

The Kresna-Kroupnic seismic source is the most active area in Bulgaria. About 80-90% of the recent seismic energy release is related to this source. More than 5 000 seismic events have been documented since the occurrence of 1904 strong earthquakes magnitudes of 7.2 and 7.8 in 20 minutes' time domain of 4th April 1904 with processed magnitude estimates (Ranguelov B et al., 2001), (Popova M, 2018). Numerous segments of active faults cross the area (**Figure 2**).

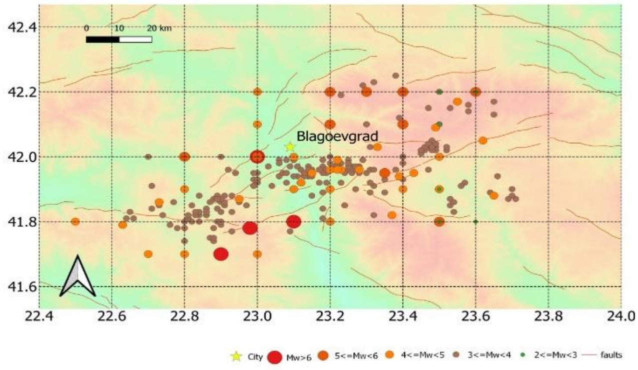

Figure 2. Seismicity of SS Kresna-Kroupnic source and surroundings (Christoskov L et al., 1979; Grigorova E et al., 1979; Solakov D et al., 2020) .

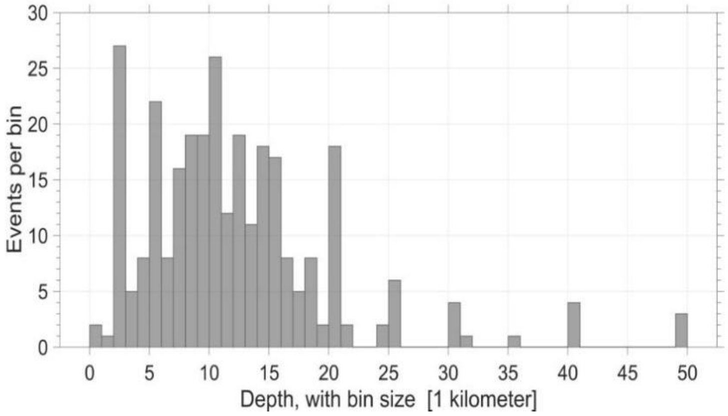

Figure 3. The depth distribution of investigated events.

As is visible on **figure 3** (the depth distribution) the main energy release occurs up to 20 km at depths where the crust destruction process is most active. Several events are registered deeper which is indicative for the deeper penetration of some faults. The earth's crust in the area reached no more than 50 km.

3. Seismic tomography

Seismological data from 1700 local and regional earthquakes registered by 64 seismic stations located on the Balkan Peninsula and surroundings (19^0-31^0E/35^0-46^0N) and processed by the national operative telemetric seismological system (NOTSSI) of Bulgaria for the time interval 01.01.2016 to 31.12.2021 (**Figure 4**) have been used. The total number of arrivals from all earthquakes to the seismic stations is 47487 of which 32927 are of P-phase and 14560 of S-phase seismic waves. The minimum number of arrivals for each event is 10, thus ensuring high accuracy. At the source pre-localization stage, some of the arriving waves with deviations larger than 1.5 seconds for P and 2 seconds for S waves have been rejected thus providing higher reliability. The methodology of data processing includes several steps of the tomography inversion algorithm, using 1D velocity model optimization, 3D visualization and finally results presentation and interpretations (Oynakov E et al., (in press)). The cross sections A1-B1, A2-B2, A3-B3, A4-B4 are discussed in details in (Oynakov E et al., (in press)). In this paper we focused on A5-B5 and A6-B6 as both are crossing the investigated SS Kresna-Kropunik.

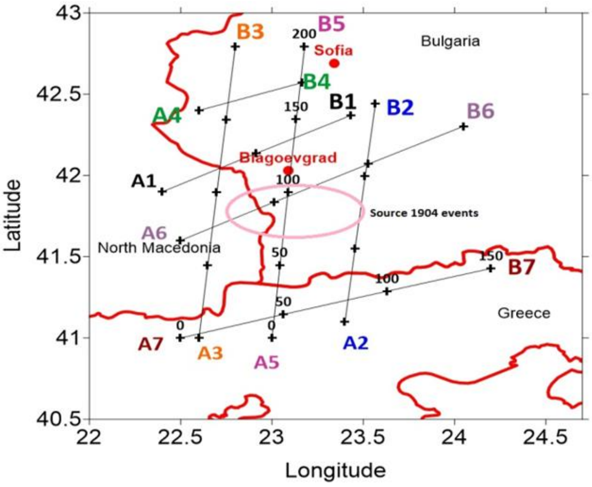

Figure 4. Seismic tomography cross-sections and the source of the 1904 strong earthquakes (magenta ellipse).

To study better the earth's crust deep interior the seismic tomography was performed and results presented at the dense network of straight lines cross-sections (**Figure 4**). The velocity from the standard optimized model derived in (Oynakov E et al., (in press)) of the P-waves and S-waves (**Figure 6**) as well as the ratio Vp/Vs (**Figure 5**) are presented at different depths following the numbering of the selected cross-sections.

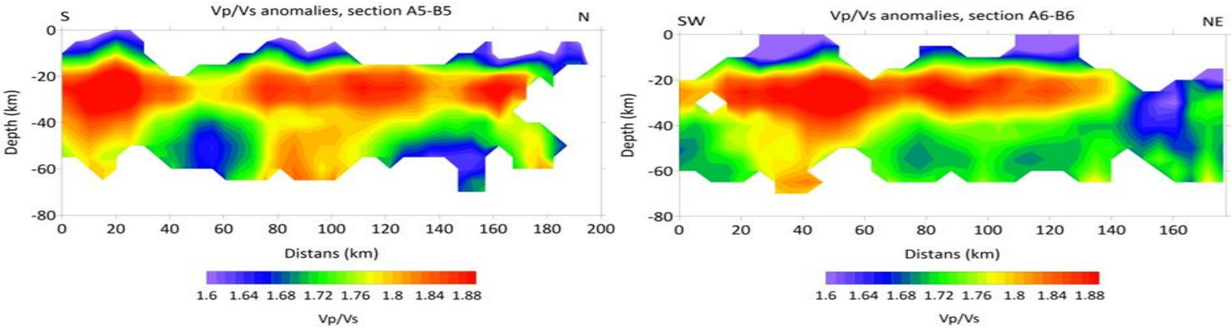

Figure 5. Vs/Vp anomalies on cross sections A5-B5 and A6-B6.

4. Microseismic sounding method (MSM)

To study the deeper interior of the area of the earthquakes M7.8, 1904 the method of the deep sounding by the wide spectrum natural seismic noise is performed by the following steps:

1. Measurements of the seismic noise values at all grid or profile points until the stationary time series are approached.
2. Perform a spectral analysis of each measurement and plot amplitude spectra for each of the measured time series of the seismic noise signal at each of the grid points.
3. In order to exclude the problems associated with the different time interval and stationary time series of the seismic noise in different frequency ranges, the sounding is performed in parallel at all points and at the reference point (earlier fixed by standard repeatable time series). The measurement results are corrected with those from the reference point by this procedure.

4. Amplitude's distribution maps are constructed for each frequency of the Rayleigh wave in the spectrum.
5. Attachment of the obtained values to the corresponding depth is made using the relation:

H(f)=k.λ(f),

where H is the respective depth, λ – the Rayleigh wave's length and k – empirical coefficient (in our case 0.5 (Oynakov E et al., 2016))

5. Depth slices of velocity inhomogeneity are plotted against the Rayleigh waves' frequencies and the results are visualized for easier interpretation.

5. Discussion and conclusions

As a result of the MSM low velocity body under the seismic source was recognized. To use the respective sensitivity of the method larger area was under investigation and several block structures with lower velocities have been outlined. In the area of the main shocks of 1904 the upper surface of the low velocity layer (LVL) is detected at depths of 50-55 km with average depth – 110-120km and thickness of about 20-40 km. This body of low velocities is laterally very variable (**Figure 7**) and was indicated by earlier experiments by deep seismic sounding performed in early 1970-ties by Russian expedition and confirmed by Yosifov et al in 2018 (Yosifov D, 2018).

The careful interpretation of the extended research by seismic tomography (Oynakov E et al., (in press)) adds new insight view to the crust interior of the 1904 strong shocks. As it is visible on the cross sections on fig.6, the lateral inhomogeneity exists just in the crust volume of the strong events – especially reflected by Vs pictures. The anomalous short surface ruptures indicated by witnesses and confirmed later by shallow geophysics is abnormal for such powerful seismic events and was a subject of many investigations, but none of them explained this phenomenon. In our view the short faults generated by M7.2 and M7.8 earthquakes are due to the side barriers, located to east and west locations with strengthen rocky substrate. This is confirmed by the low P and S velocities probably due to the destructive effects to the crust generated by the forces of the shocks. The block structures surrounding the seismic source are also visible to other geophysical fields (for example gravity Bouguer anomaly (**Figure 9**).

All these results support the imagination that the asthenosphere block in which the 1904 earthquakes occurred is relatively homogeneous and the destruction of the earth's crust happened down to the 40-45 km.

All observed peculiarities need a model to explain the observed facts and phenomena. We generated a possible algorithm to explain them.

The possible geodynamic's algorithm of the observed phenomena and the new investigations results for the region might be as follows (from depth to the surface):

1. Deep low velocity body (established by MMS) protrudes from East to the West at depths of 150 to 50 km, thus creating high stress to the layers above
2. The lateral inhomogeneity of the above blocks – depth 50-0 km (investigated by seismic tomography) confirmed bodies over the Moho boundary with alternating low and high velocity which redistributes the created stress of the lower pushing body.

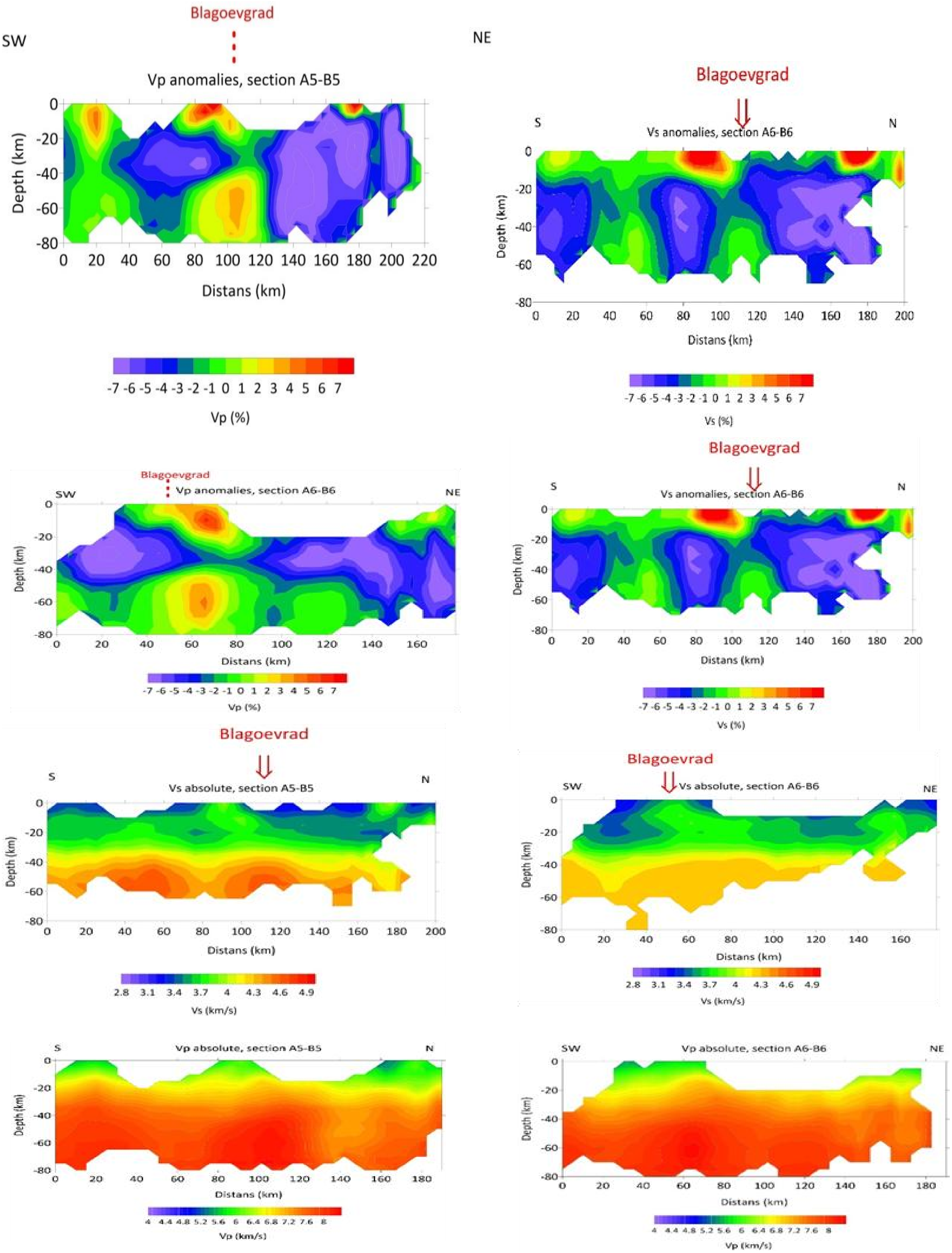

Figure 6. Seismic tomography results: tomography Vp,Vs anomalies (A5-B5 and A6-B6 cross sections - up) and absolute values of determined Vp and Vs on the same profiles).

1. The harder masses laying to the west of the seismic source area serve as barriers from the west, thus limiting the co-seismic fault propagation to the west.

2. The dragging effect of the branches of NAF is registered on the surface by the GNSS stations and show south direction of displacements in the whole area. The reconstructed stress field coincides with the concept.
3. The strong earthquakes occurred in Kresna-Kroupnik source are the recent expression of the stress release accumulated and redistributed on the vertical boundaries of the established blocks. The strong earthquakes produced normal fault surface vertical co-seismic displacements at the epicentral area of about maximum 12 meters and relatively short length of surface dislocation of E-W direction (about 40) km perpendicular to the N-S long term and relatively constant GPS surface velocities.
4. The high intensities observed in the area (IX-X,X-XI MMS) triggered large area of observed liquefaction points located mainly at the river beds and recent sediments in the region.

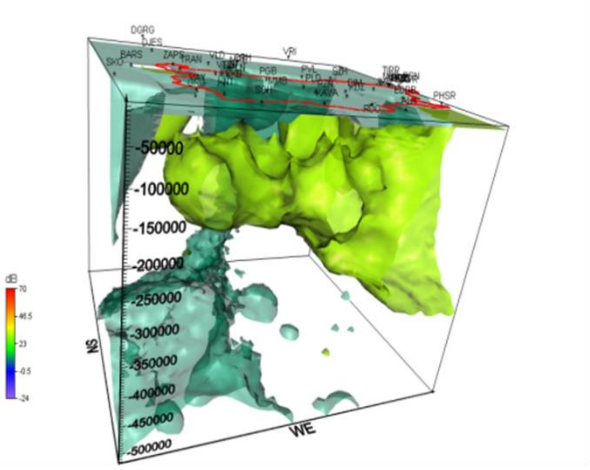

Figure 7. 3D stereogram of the low velocity layers (light green) and high velocity layers (dark green). The intermediate velocity layers are not colored (according (Yosifov D et al., 2018)).

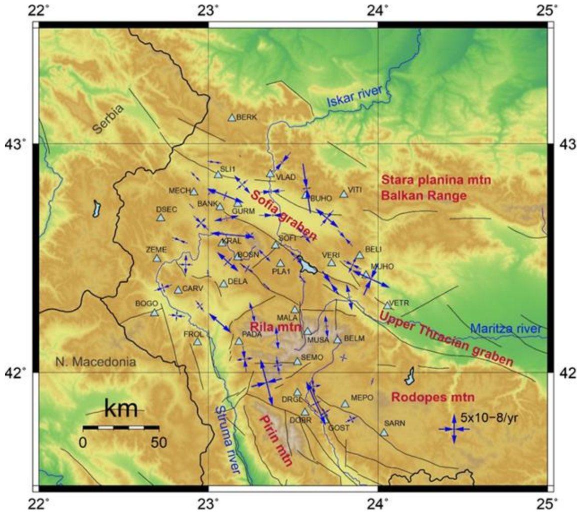

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Figure 8. The stress axes extracted by GPS velocities and displacements.

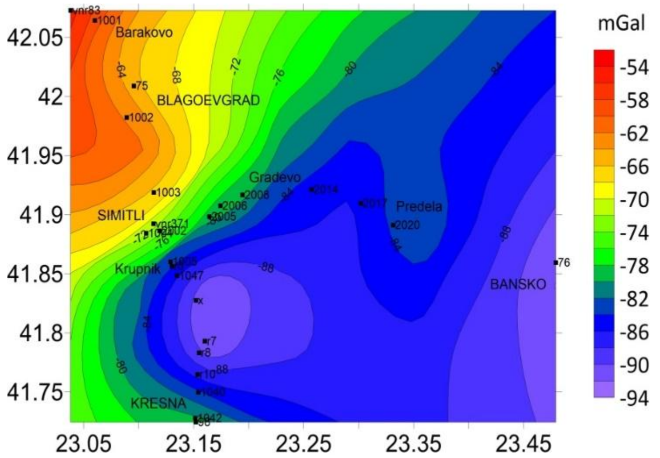

Figure 9. Bouguer gravity anomaly in the region.

6. Conclusion

The strong earthquakes of 1904 in the Kresna-Kroupnic seismic zone (which has the highest seismicity rate in comparison with all seismic sources on the territory of Bulgaria (Christoskov L et al., 1979; Grigorova E et al., 1979; Solakov D et al., 2020)) have a lot of specifics presented earlier. To explain them new investigations have been performed combining the knowledge from higher depths substrate behavior to the upper parts of the Erath's crust and blocks established by this study just to the surface. The explanation of the observed surface phenomena documented by witnesses of that time and the new observations we use to create a new model of a geodynamic algorithm and establish a concept in the context of the recent geodynamic observations. The no contradictory results of our interpretations give us the feeling that we succeed in this presentation of our new insight view to the source of the strongest seismic events in Europe during the last 2-3 centuries and located in the continental land (Popova M, 2018).

References

1. Ambraseys N (2001). The Kresna earthquake of 1904 in Bulgaria. Analli di Geofisika, v.44, No1.
2. Christoskov L, Sokerova D and Rijikova S (1979). New catalogue of the earthquakes in Bulgaria for the period V century BC to XIX century (1899), Geoph. Inst., BAS, Sofia.
3. Dimitrov N and Nakov R. (2022). GPS Results from long time monitoring of geodynamic processes in South-Western Bulgaria. Applied Sciences 12.5 2682.
4. Dineva S, Batllo J, Mihaylov D, van Eck. T (2002). Source parameters of four strong earthquakes in Bulgaria and Portugal at the beginning of the 20th century., Journal of Seismology 6: 99–123.

5. Grigorova E, Sokerova D, Christoskov L and Rijikova S (1979). Catalogue of the earthquakes in Bulgaria for the period 1900-1977, Geoph. Inst., BAS, Sofia.
6. Mihailov E, Dimitrov D (2006). Results from Gravimetric measurements in the region around the Krupnik fault, SW Bulgaria. Geodesy, *Bulgarian Academy of Sciences,* ISSN 0324-1114, Sofia, vol 17, 108-115.
7. Oynakov E, Aleksandrova I, Popova M, Ranguelov B. Seismic tomography model of earth crust of SW Bulgaria and surroundings (in press).
8. Oynakov E, Ranguelov B (2016). Sensitivity of the Microseismic Sounding Method related to the Depth Structure Research in Two Different Seismic Zones – Vrancea and Calabria., Journal of Physics and Technology, Volume 1 (2017), Number 1, pp. 33–38, ISSN 2535-0536. http://jpt.uni-plovdiv.bg/index.php/current-issue/.
9. Popova M, (2018). Relations between Mp and ML magnitude scales. *Bulgarian Geophysical Journal*, *41* , 21.
10. Ranguelov B., Rizhikova S, Toteva T (2001). The earthquake (M7.8) source zone (South-West Bulgaria)., Acad.Publ.House “M.Drinov”, 279 pp.
11. Ranguelov B, Mardirosian G,. Velkosky St, (2008). Seismicity and Geodynamics of Macedonia and Surroundings., Conf. BALWOIS - Ohrid, Republic of Macedonia – 27 - 31 May 2008, pp.1-8 (on CD).
12. Ranguelov B, van Eck T, Papadopoulos G, Pavlides S, Shanov S, Shenk V (2000). Initial data for the magnitude reevaluation of the strong earthquakes during 1904 in Kresna-Kroupnik zone (SW Bulgaria). In. Reports on Geodesy, No4 (49), Warsaw, pp. 50-55.
13. Ranguelov B, Rizhikova S, Shanov S, Gospodinov D, Toteva T (2000). The seismic potential for the Kresna-Kroupnik zone - SW Bulgaria., No4 (49), Warsaw, pp. 237-241.
14. Ranguelov B (2005). A model of the Aegean geodynamic zone. In “The South Aegean active volcanic arc.” (Eds. M. Fytikas and G. Vougioukalakis)., ELSEVIER. pp. 11-17.
15. Rizhikova S, Toteva T, Ranguelov B (2000). Seismicity of the Kresna source zone for eighty-year post active period (1909-1989). In. Reports on Geodesy, No4 (49), Warsaw, pp.56-60.
16. Solakov D, Simeonova S, Raykova Pl, Aleksandrova I (2020). Catalogue of the earthquakes in Bulgaria and surroundings since 1981, National Institute of Geophysics, Geodesy and Geography-BAS, DOI: https://doi.org/10.34975/ctlg-2020.v.1.
17. Toteva T, Rizhikova S, Ranguelov B (2000) Recent seismicity in Kresna region and surroundings. In. Reports on Geodesy, No4 (49), Warsaw, pp. 90-98.
18. Yosifov D, Ranguelov B, Oynakov E (2018). Deep low velocity layers inferred by the MSS – indicators of the asthenosphere structure in Bulgaria. Proc. IX National Geophysical Conference, 30th November 2018, pp. 43-50. ISSN 1314-2518.
19. Zagorchev I (2001). Introduction to the geology of SW Bulgaria, GEOL. BALCANICA, 31. 1-2.