Bulgarian Geophysical Journal, 2022, Vol. 45
National Institute of Geophysics, Geodesy and Geography, Bulgarian Academy of Sciences

SEISMIC TOMOGRAPHY MODEL OF EARTH CRUST OF SW BULGARIA AND SURROUNDINGS

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DOI: 10.34975/bgj-2022.45.7

Abstract. The paper deals with the tomography investigations of the earth's crust inhomogeneity of the SW Bulgarian area and its geodynamic features. The main aim is to reveal the relationships of the seismic tomography model and the crustal inhomogeneity's structures located at SW Bulgaria and surroundings. This aim is strongly related with the seismic activity of the region, where strong earthquakes in Kresna-Kroupnik (M7.2 and M7.8, 1904), Valandovo (M6.7, 1931) and Skopje (M6.1, 1963) with a lot of destructions and victims occurred. There are also other less active seismic sources as Velingrad, Mesta, Struma, etc. with lower seismic potential. The seismic tomography model, calculating the velocity residuals for P and S seismic waves from the optimal velocity model helped to establish the possible reasons for the geodynamic features of the region. Discovered velocity anomalies coincide pretty well with the previously investigated geophysical anomalies (velocities' depth changes, asthenosphere gradients, thermal conductivity, fluids saturation, etc.) and geodynamic features (fracturing, faults, grabens and horsts, crustal movements, etc. The local seismicity is also considered, showing higher concentrations of hypocenter near the established velocity gradient areas. The performed tests about the accuracy of the calculations and ongoing interpretation helped to increase the reliability of the results obtained.

Kay words: earthquake, seismicity, tomography

Introduction

The Southwest Bulgaria geology and geodynamics have a complex structure and complicated mixture of different in time development and size elements: grabens and horsts, lowlands and river beds, high mountain peaks and small and larger structures and blocks, separated by faults and morphology features. The most important geodynamic peculiarities of the area are high seismic activity of different type, vertical crustal movements and intensive erosion.

Seismic tomography uses seismic ray inversion and velocity models to reveal inhomogeneity in deep layers, reflecting local and regional features of the Earth's interior Studying the deviations in the velocity at different depths of the P and S seismic waves, are possible to outline anomalies in wave's propagation. This could be a powerful tool to reveal the specific geodynamic structures as blocks, faults and structure boundaries at different depths.

The focus of this tomography study is the SW Bulgaria and surroundings because this area has specific seismic regime – strong earthquakes in Kresna-Kroupnik (1904), Valandovo (1931) and Skopje (1963) with a lot of destructions and victims and other less seismic active sources as Velingrad, Mesta, Struma, etc. with lower seismic potential (Ranguelov et al., 2001). So, the geodynamic study of the area needs a specific approach combining information of seismic tomography with the geodynamic and seismic regime of the region.

Data

Data from 1700 local and regional earthquakes registered by 64 seismic stations located from 19°-31°E/35°-46°N and processed by the national operative telemetric seismological system (NOTSSI) of Bulgaria for the time interval 01.01.2016 to 31.12.2021 (fig. 1) were used in the study. The total number of travel times from the sources to the seismic stations is 47487 of which 32927 are of P-phase and 14560 of S-phase seismic

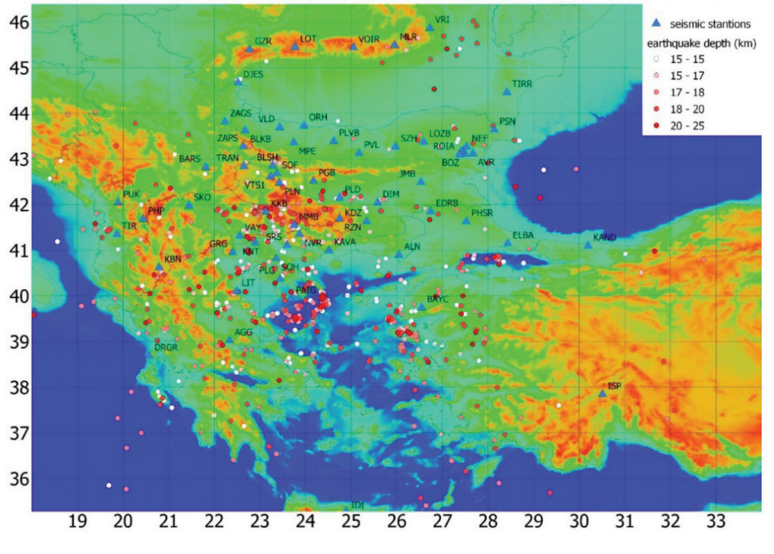

Fig. 1. Map of recorded local and regional earthquakes by NOTTSI for the time interval 01.01.2016 to 31.12.2021

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 residuals larger than 1.5 seconds for P and 2 seconds for S waves were rejected for higher reliability.

Method

The methodology includes several steps of the algorithm – Tomography inversion, 1D velocity model optimization, 3D visualization and results presentation.

- Tomographic inversion is performed based on the LOTOS 12 nonlinear passive seismic tomography algorithm. The general principles and technical details are described [Kulakov, 2009] and on the website www.ivan-art.com/science/LOTOS (Fig. 2). The LOTOS-12 computer code performs the simultaneous inversion of P- and S-wave velocities and source and stations' coordinates. The algorithm can be applied to various local earthquake data sets without complicated parameterization.
- In the initial stage of the computations, simultaneous optimization of the best one-dimensional velocity model and preliminary source localization is performed. The distribution providing the minimum value of the mean residuals was selected as the reference model for further tomographic modelling.
- The iteration procedure starts with the step of localization of the seismic sources in a three-dimensional model (at the first iteration, this algorithm is applied to a one-dimensional reference model). One of the features of this algorithm is the three-dimensional ray tracing, which is based on the bending method (Um, Thurber, 1987) using Fermat's principle for minimizing the time functional described in (Koulakov, 2009). This algorithm is used at each step of the iterative inversion, in the localization of the sources and is resulting in a three-dimensional model of the strata.

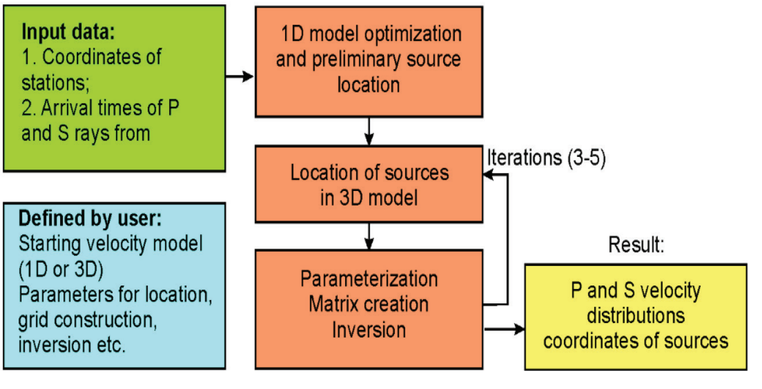

Fig. 2. Block diagram of the algorithm of tomography inversion (Koulakov, I. (2013). Code LOTOS-10 for 3D tomographic inversion is based on passive seismic data from local and regional events.)

- The matrix of first derivatives (M.R. Fréchet matrix), in addition to the P- and S-velocity distributions, includes elements needed to correct the coordinates and timing in the source (4 parameters for each source) and station corrections. The matrix inversion is performed using the LSQR method (Paige, Saunders, 1982; van der Sluis, van der Vorst, 1987).
- When performing inversion, the problem of weighting individual parameters with different dimensions (velocity distribution, source parameters and station corrections) as well as determining the smoothing parameters arises. In this study, this procedure is performed by applying synthetic tests with realistic noise in the data, providing similar inversion conditions as in the case of real data.

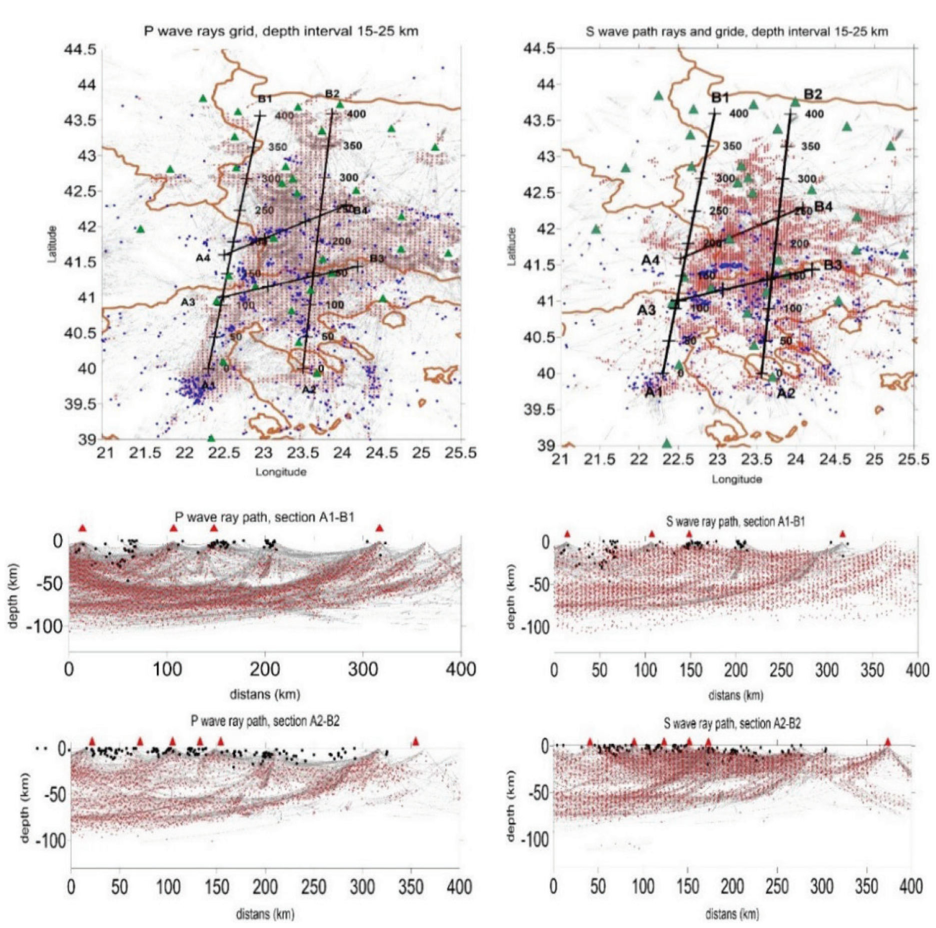

Fig. 3. Profiles A1-B1 and A2-B2 with distances [in km] for the P- and S-waves – left; and rays from the sources to the seismic stations (triangles) in depth – right.

1D model optimization

The data processing starts with the determination of a preliminary source location and the optimization of the one-dimensional velocity model (Figure 4 a). To assess

- The robustness of this procedure, we ran a series of tests (Figure 4 b) with the real observations data.
- The 1D model that best approximate the observed data was determined by testing different initial velocity models. Each of the five models tested was based on earlier literature information
- The RMS residuals after 1D optimization for all velocity models tested are shown in Table 1. Analysing the P and S residuals, it is concluded that the most probable 1D distribution for the western and south-western region corresponds to model 5 presented in Table 1.

Table 1. RMS values for P and S wave residuals after the first and fifth iteration for different starting Models

Values of RMS of P and S residuals in 1st and 5th iterations for different starting models				
Model	**RMS of P and S residuals, 1st iteration**		**RMS of P and S residuals, 5th iteration**	
	P wave	**S wave**	**P wave**	**S wave**
Model 1	0.678036	0.900532	0.504163	0.843715
Model 2	0.62186	1.08115	0.486333	0.751208
Model 3	0.503481	1.570825	0.479569	0.743028
Model 4	0.457719	1.668452	0.544237	0.741775
Model 5	0.497578	1.708503	0.472819	0.734828

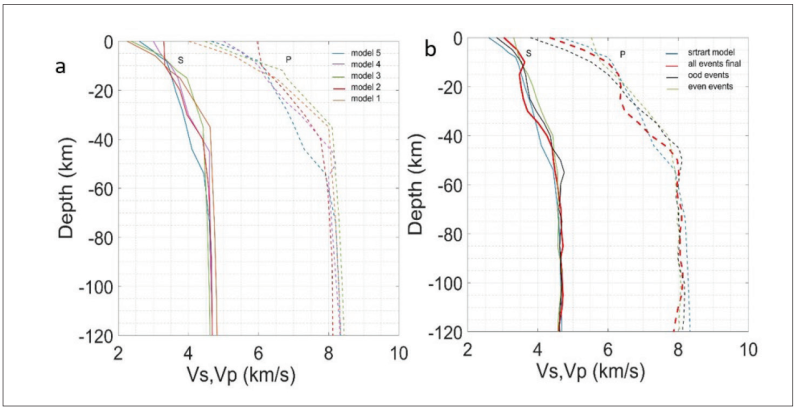

Fig. 4. Optimization of the 1D model for observed data. a) Optimization results with observed data and different starting 1D models. Different colours indicate different models. b) Optimization results for halved data subsets in the odd/even test

Table 2. Vp and Vs in the start and reference 1D model 5 after optimization in the table 2.

Depth (km)	Vp start model 5 (km/s)	Vp (km/s)	Vs start model 5 (km/s)	Vs (km/s)
1		4.63		3.09
5		5.29		3.41
10	5.96	5.84	3.30	3.56
15		6.16		3.65
20	6.09	6.54	3.33	3.83
25		6.85		3.92
30	6.74	7.14	3.76	4.1
35		7.27		4.21
40	7.31	7.58	3.96	4.33
45		8.04		4.52
50		8.07		4.57
55		7.86		4.54
60	7.77	7.92	4.41	4.59
65		7.97		4.69
70		7.97		4.67
75		7.99		4.69
80	7.97	8.02	4.58	4.68

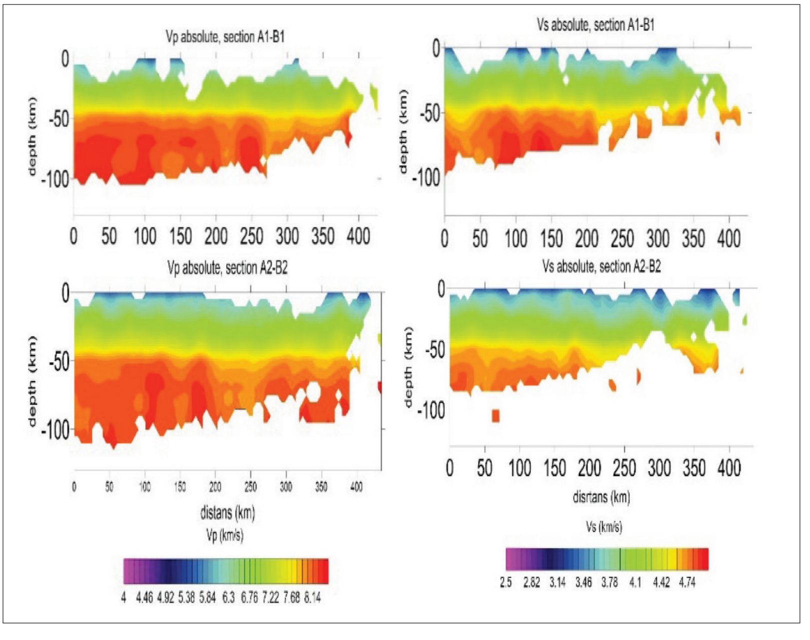

Fig. 5. Vp and Vs absolute values on the cross sections after the optimization.

Results

2D horizontal slices sections have been constructed for depths of 5, 10, 15, 20, 25, 30, 35, 40, 45 and 50 km where sufficient rays' coverage is provided. The inversion was performed in five iterations, which is a compromise between computation model and the solution quality (reduction of nonlinear effect). In all sections, calculated values of low and high Vp and Vs anomalies can be seen for various depths up to 50 km. The positive and negative anomalies between the initial and final velocity models vary with ±7%. Findings from different layers reveal that the velocity models show significant low velocity anomalies to the lower crust, larger than expected. Vp/Vs ratio range from 1.6 to 1.9. Horizontal slices are presented in Fig. 6, showing Vp and Vs disturbances in well resolved areas.

The important tectonic structures in the area are marked (red lines) on Fig. 7. The figures also show the location of the sources for each depth. In general, low velocities in the shallow layers can be attributed to severe fracturing, fluid-filled formation in the rock matrix, and weak materials (Serrano et al., 2002).

Low velocity anomalies are also an expression of thermal conductivity, the presence of high fluid flux, and weakened (attenuated) fragments consistent with uplifts from the asthenosphere material to shallow depths because of ongoing lithospheric extension (Dolmaz et al., 2005; Salk et al., 2005; Tarcan et al., 2009; Delph et al., 2015)

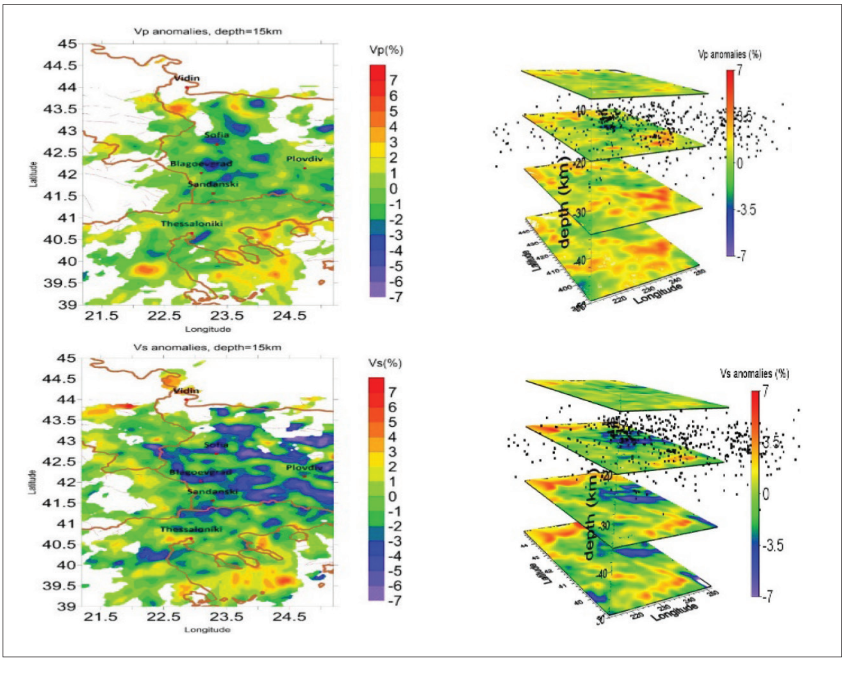

Fig. 6. The Vp and Vs anomalies of the 1D model at 15 km (left) and Horizontal slicing of 5, 20, 35 and 50 km (right).

Discussion

In search of correlation between the anomalies of Vp, Vs, Vp/Vs with other indicators for the geodynamic features of the region several comparative experiments have been done:

- Search of correlation between Vs at different levels and the outlined tectonic units defined by Dabovsky (Dabovsky et al., 2002). The visual correlation (fig. 7) is noticed on the maps presented on fig 7. The gradient areas of low Vs at 15 km depth, coincide with the tectonics unit boundaries outlined in west Bulgaria especially Srednogorie, Rila-Rhodops and Balkans. Such correlation might be explained by the consideration that this upper part of the Earth's crust delineates the depths of destruction of the earth crust due to earthquake stress emission, water and other fluids saturation and in general the weakening effects ofthe different 1991; such as temperature and pressure changes, etc. (Selverstone et al. Evans and Chester 1995; Sanders et al. 1995 г.; Faulkner et al. 2010) geodynamic processes
- The visual correlation between Vp/Vs ratio at the depth of 20km with the gravity Bouguer vertical gradient (P. Trifonova et all, 2013) is another indicator about the relationships between these two parameters. Possible geophysical interpretation could be in a search of the penetration of deep faults in the coinciding areas – fig. 8

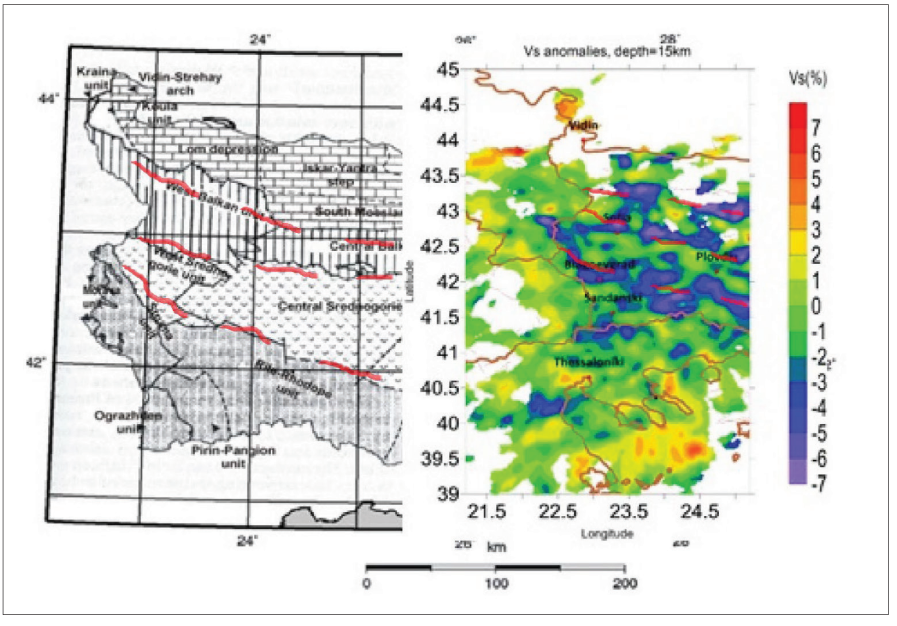

Fig. 7. Tectonic scheme of Bulgaria (modified from Dabovsky et al., 2002) and the Vs anomalies at depth 15 km (right).

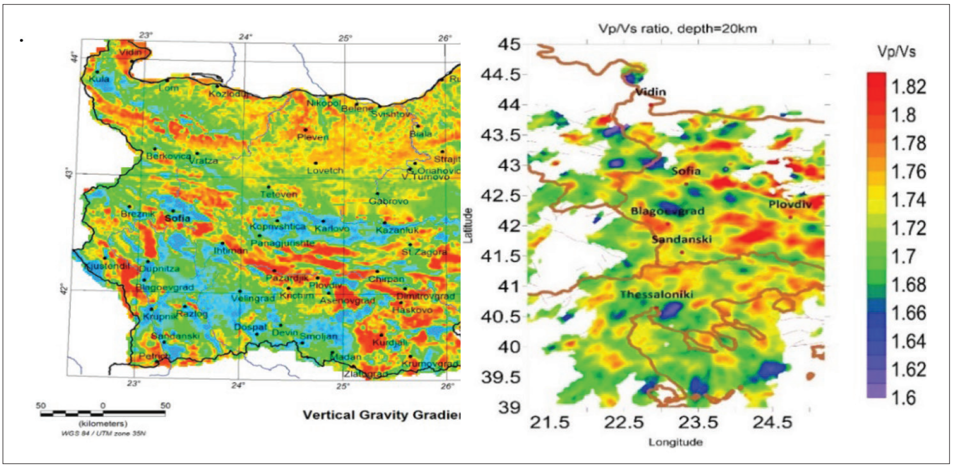

Fig. 8. Map of the vertical gravity gradient (VGG) of Bouguer gravity anomalous field in Bulgaria. The positive (red) and accompanying negative (blue) gradients represent single gradient anomaly

Accuracy tests

To control the accuracy of the calculations – an experimental test was performed. Two calculations have been done with the "odd" events and with the "even" events. The odd and the even events are according the numbering in the initial data set. The results are presented on fig. 9. for both cross-sections.The accuracy varied between 6% (A1-B1) and 11 % (A2-B2).

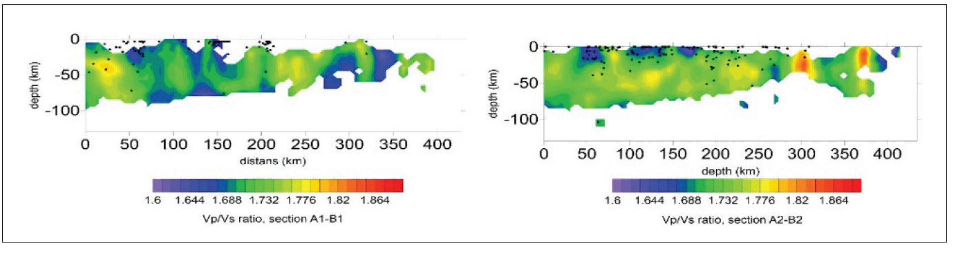

Fig. 9. Vp/Vs ratios on the cross section A1-B1 (left) and A2-B2 (right).

The test results with "even and odd" events in a horizontal plane at a depth of 5 km are shown in Fig. 10. It can be seen that all major anomalies are identified quite reliably in both models, thus presenting their reliability. The remaining smaller anomalies where differences are observed are most likely a result of a random factor and should not be taken into account in the interpretation. Another spatial synthetic checkerboard test was used to evaluate the spatial resolution of the model.

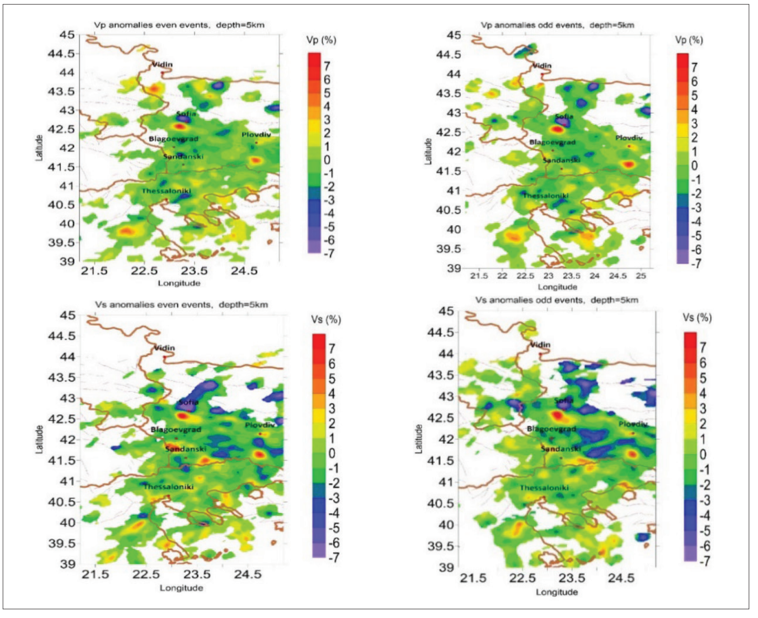

Fig. 10. Vp and Vs anomalies for the odd and the even events at depth 5 km

In this test, a synthetic model alternated rectangular positive and negative anomalies with a lateral size of 30 × 30 km. This model used the real data inversion. In order to obtain the best values of the inversion parameters, several tests were conducted with the synthetics. The result of the test is that the recovery of the cells of the "Chess board" is reliable and shows that the spatial resolution is rather good (fig. 11).

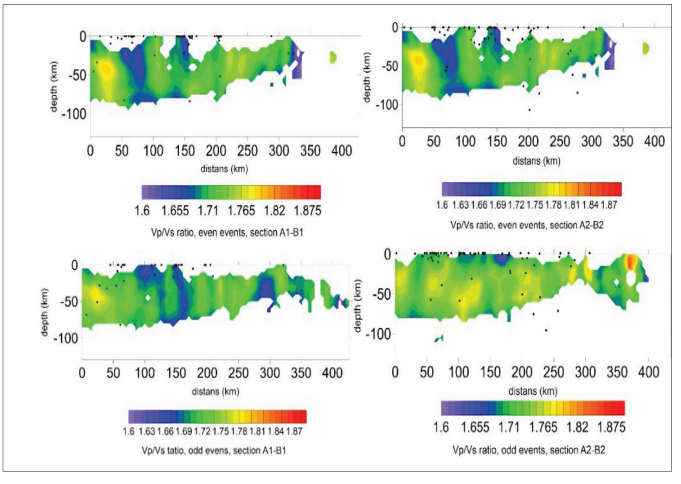

Fig. 11. Cross-sections and visual anomalies of Vp/Vs ratios for odd and even numbered seismic events

Conclusions

The methodology and results about a seismic tomography of the SW Bulgaria and surroundings are presented. The results show a very complex structure in both – lateral and depth directions with variations of about +/- 7 % deviations around the optimized velocity model obtained by a huge amount of initial data. From the recent geodynamics point of view this means that the complicated block structures are dominated by lateral and depth variations of the velocities and the ratio Vp/Vs.

Several parameters are compared by visual correlations of Vp, Vs, Vp/Vs at different depths with other elements of natural geophysical fields and tectonic implications. Future interpretations are intended to correlate the deep earth's structure with seismicity and other geophysical parameters.

The performed tests about the accuracy of the obtained results, the spatial distribution of calculation cells is investigated by two methods – odd and even seismic events as sources of the rays for inversion and the "chess table" cross-correlation for the spatial resolution optimization. The results about the accuracy confirmed deviations in the range of 6-11% in comparative mode.

Acknowledgment. Authors acknowledge the reviewer D. Solakov for the fruitful discussion and recommendations improving the quality of the presented paper.

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Модел за сеизмична томография на земната кора на югозападна България и околните райони

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Резюме: Статията се занимава с томографични изследвания на нееднородностите в кората на Земята в югозападния район на България и техните геодинамични особености. Основната цел е да се разкрият връзките между модела на сеизмичната томография и структурите на корните нееднородности, разположени в югозападната част на България и околните райони. Тази цел е тясно свързана със сеизмичната активност в региона, където се случват силни земетресения в Кресна-Крупник (M7.2 и M7.8, 1904), Валандово (M6.7, 1931) и Скопие (M6.1, 1963) с множество разрушения и жертви. Има и други по-малко активни сеизмични източници като Велинград, Места, Струма и други с по-нисък сеизмичен потенциал. Сеизмичният модел на томографията, който изчислява остатъците на скорост за P и S сеизмични вълни от оптималния модел на скорост, помогна да се установят възможните причини за геодинамичните особености на региона. Откритите скоростни аномалии кореспондират доста добре с предишно изследвани геофизични аномалии (промени в дълбочината на скоростите, градиенти на астеносферата, топлинна проводимост, наситеност с течности и др.) и геодинамични особености (фрактури, фолти, грабени и хорсти, корстни движения и др.). Локалната сеизмичност също е взета предвид, като показва по-голяма концентрация на епицентъра в близост до установените области с градиент на скоростта. Извършените тестове относно точността на изчисленията и текущата интерпретация помогнаха за повишаване на надеждността на получените резултати.