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# Crustal and upper mantle structure in the southen part of the Moesian platform obtained by data from seismic stations MPE, PVL and SZH

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Receiver function technique is used to study the crustal and upper mantle structure beneath Bulgaria. It is applied to the data from National Digital Seismological Network. The results for three seismic stations, situated in the southern part of Moesian platform, are reported. These stations, Malopestene (MPE), Pavlikeni (PVL) and Strazhitsa (SZH), are equipped with broad-band seismometers and RefTech 130 digitizers. The crustal structure beneath the seismic stations is very complex and the Moho discontinuity can't be tracked in all azimuths around the stations. The shallow Earth's crust discontinuities are obtained close to the three seismic stations. The most complex crustal structure is observed beneath the seismic station MPE.

The main discontinuities in the upper mantle are well observed beneath the territory of Bulgaria. These are asthenosphere-mantle discontinuity, which has a depth between 190–220 km, and discontinuities at 410 and 660 km. In North of Bulgaria these two discontinuities have different depths than in iasp91 velocity model.

**Key words:** seismology, Earth's structure, Earth's crust, receiver function

## INTRODUCTION

Moesian platform is characterized by a very thick sediment layer. Its thickness is estimated to 8-10 km from different geophysical investigations and increases towards Fore Balkan zone to 18-20 km [1, 2]. The Moho depth varies in range 30-33 km and increases in the edge zones of the platform [2].

Mantle structure beneath Bulgaria is not well observed. Several studies of the crustal structure [3, 4] show results up to 250 km, which includes the upper mantle. Yegorova [5] use gravimetry techniques to estimate the density beneath Balkans. They found lifting of 410 discontinuity in the central part of the Balkans and Sredna gora mountain.

## DATA AND METHOD

Receiver function technique, which has developed in recent decades, offers good opportunities for the study of the crustal and upper mantle structure. It does not require an array of seismic stations and may be applied also in areas where the number of stations is limited. The frequency of the seismic waves used in the technique allows to obtain information on the structure to a relatively great depth.

The receiver function is called the radial component of the seismogram, deconvolved with the vertical component. Few percent of the energy of the incident P wave in some teleseismic events are converted into the S wave (Ps), if we have a relatively sharp discontinuity in the crust or upper mantle. This converted seismic phase arrives at the station in the coda of the P wave. The Ps onset, amplitude and polarity depended on the distribution of the S waves velocities beneath the seismic station. Therefore, if Ps onset is estimated and an initial velocity model is used, one can determine the depth of the discontinuity that generated the converted phase.

Rotation of the seismogram is needed before the deconvolution to separate the energy of P and Ps phases. The new coordinate system is so called LQT coordinate system, where L axis is in the direction of incoming P wave. Q and T axes are perpendicular to L. In this case L, Q and T components contain mainly the energy of P, SV and SH waves respectively. In case of isotropic media and horizontal layers (with slope up to 10° [6] ) no energy should be observed on T component. Below the perpendicular components, Q and T, will be analyzed.

It is difficult to determine the converted Ps phase on a single receiver function. So the receiver functions are stacked together and easy to determine the coherent phase, converted from the Mohorovicic discontinuity.

The depth of the Mohorovicic discontinuity is estimated in two ways - by the method of [7] and from the velocity model, computed by seismic inversion. The stacked receiver functions were divided in azimuthal intervals so that in each interval they have a similar shape.

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Zhu and Kanamori [7] use a stacking method in depth-velocity ratio space. For each receiver function they compute the depth of Moho and $V_P/V_S$ ratio. Where most of the phases are grouped coherent is the area where with 95 % probability the real Moho depth and $V_P/V_S$ ratio can be estimated.

The piercing points, where the seismic rays cross a discontinuity, for mantle discontinuities at 410 and 660 km are mapped and three groups of profiles through the area are traced. Migration is done along each profile, analogously to migration in seismic investigations, to obtain the depth section.

Earthquakes with epicentral distances 30°–95° are used in the study to satisfy the mentioned above condition for the energy distribution of the P wave. It is required that earthquakes have a magnitude is in the range of 5–7 and records have high signal/noise ratio. Results for stations, located in Northern Bulgaria – Malopeshtene (MPE), Pavlikeni (PVL) and Strazhitsa (SZH), are presented in this study. Earthquakes used in the study are recorded between December 2005 and July 2010, they have magnitudes in range from 5,7 to 7,5, and epicentral distance as in the condition. The selected seismic events are about 200 for each station and provide good azimuthal coverage.

RESULTS

*The structure of the Earth's crust*

Seismic station MPE is located in the southwest corner of the Moesian platform. About 180 events are used to calculate receiver functions for this station. PVL station is located in the middle of the Moesian platform while SZH station is located in the eastern part of the Moesian platform. Receiver functions for 217 seismic events are calculated for both stations. Good azimuthal coverage with data is achieved for all seismic stations (Fig. 1).

Stacked receiver functions (Q components) for station MPE are presented in (Fig. 2A), and the

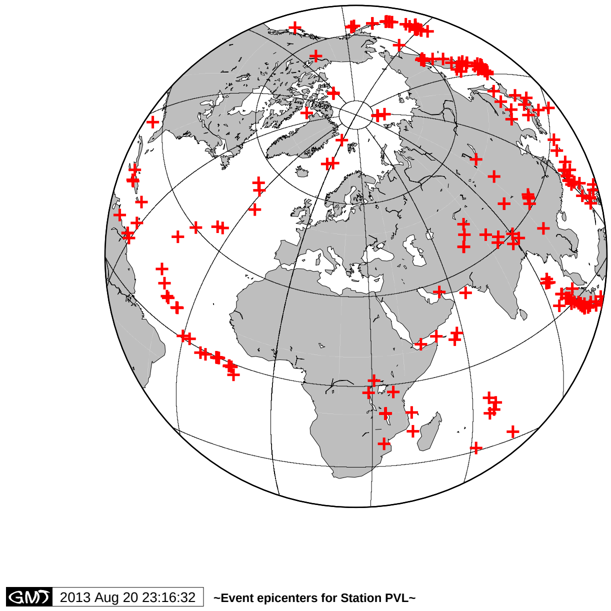


Fig. 3. Map of the earthquakes epicenters recorded at PVL station and used in the study.

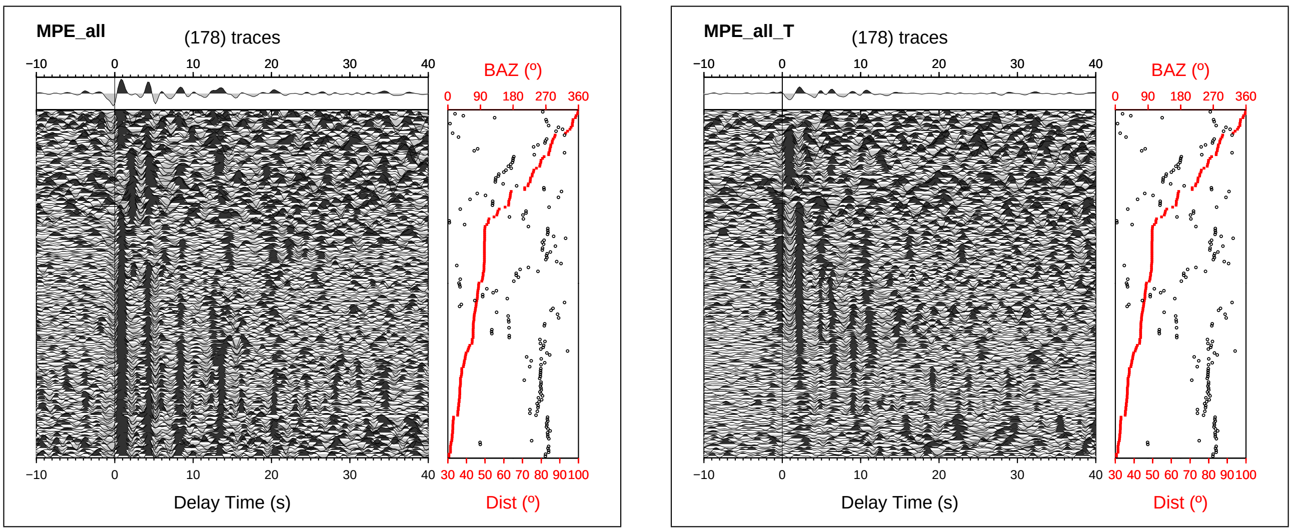


Fig. 2. Staked and sorted from 0° to 360° azimuth receiver functions (A) and stacked and sorted from 0° to 360° azimuth T components (B) for seismic station MPE. First trace above the plot represents the sum of receiver functions. Red squares represents the back azimuth for each trace (earthquake) and black dots represents the epicentral distance.

stacked T components –- in (Fig. 2B). Mohorovicic discontinuity, which is presented by the Ps phase with 4.2 s onset, is tracked clear across the whole azimuth range around the station. Some converted phases, coming from discontinuities in the crust, occurred in several azimuth intervals. For example, in the range 180°–270° a phase is observed at onset time 2.5 s on T component. Any phases should not be observed on the T component under ideal conditions – horizontal borders with a slope no more than 10° [6] and homogeneous medium. In case of station MPE, for same azimuth intervals, when Ps phase is not observed on the radial component, distinct positive and negative amplitudes are presented on the T component. Such a plot of stacked receiver functions can be observed when an anisotropic layer is presented in the crust. The results for the receiver functions and the T components of station MPE show that the existence of anisotropic layer or tilted discontinuity with a slope of more than 10° can be expected beneath this station. This means that more techniques should be applied to investigate the crustal structure beneath this seismic station.

Stacked receiver functions for station PVL are presented in (Fig. 3). As phase, converted by the Mohorovicic discontinuity, is identified positive peak with 4,5 s onset. This phase is not clearly visible in all azimuth ranges. Analogically to the results obtained by Eckhard and Rabbel [8] and similarly to the results from MPE, it can be assumed that beneath the station PVL an anisotropic layer in the Earth's crust is presented.

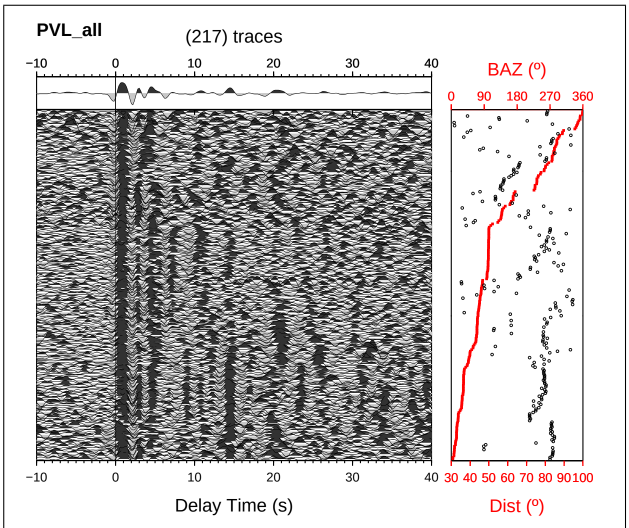


Fig. 3. Stacked and sorted from 0° to 360° azimuth receiver functions for station PVL.

Two converted phases are presented in the summed receiver function for seismic station SZH (Fig. 4) The phase with 4.8 s onset time is identified as converted from Mohorovicic discontinuity. This phase has earlier onset and smaller amplitude in some azimuth ranges, like 210°–350°. Such a phase is not observed in the range 120°–180°. The reason for this would be the existence of a fault structure close to the station in the same azimuth range.

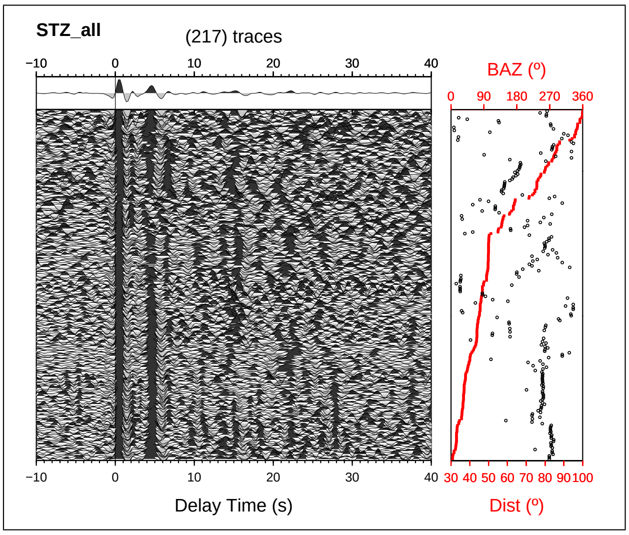


Fig. 4. Stacked and sorted from 0° to 360° azimuth receiver functions for station SZH.

On the stacked receiver functions for all three stations a phase with about 1 s onset is observed. It is presented in the whole azimuthal interval around the stations PVL and SZH while for the station MPE there is azimuthal interval where this phase is not observed. Instead a later phase is presented with onset time about 2 s.

Using the method of Zhu and Kanamori [7] for MPE station is obtained the depth of Moho in the range 29–31 km and the range for the $V_P/V_S$ ratio is from 1.81 to 1.92 with 95% probability (Fig. 5A).

The computed velocity models show that the seismic inversion is very unstable (Fig. 6A). The inversion is done only in two azimuthal intervals 0°–90° and 100°–110°. The Mohorovicic discontinuity can not be defined clear in the obtained velocity model. The only layer, that is shaping close to the Earth's surface, is the sediment layer and has a depth of about 7 km with S wave velocity 2.5 km/s.

The data show the presence of anisotropic structures in depth. The results by the method of [7] show

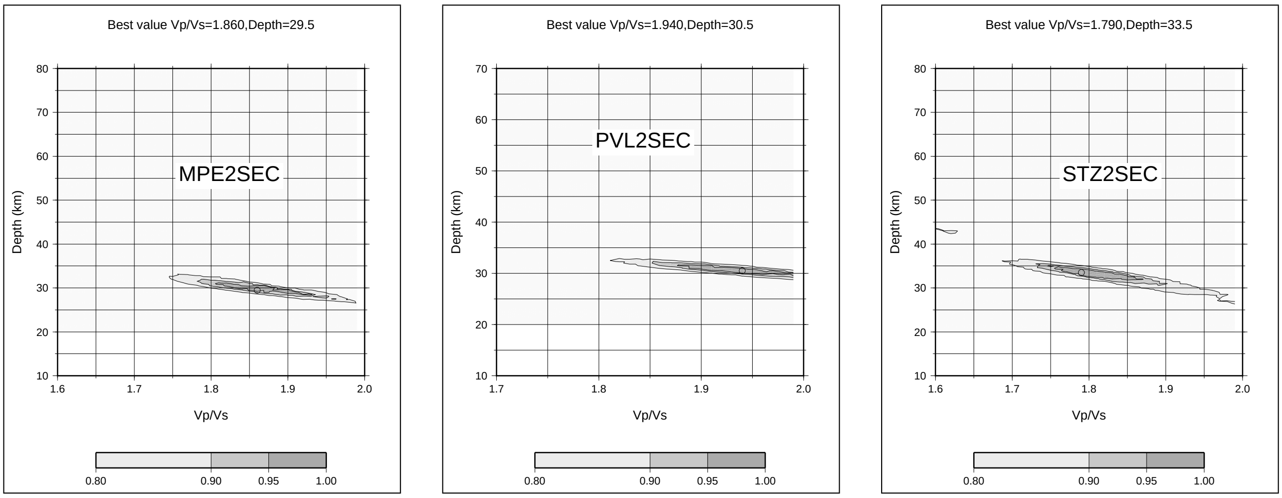


Fig. 5. Areas of solution for depth of Mohorovicic discontinuity and $V_P/V_S$ ratio for seismic stations (A) MPE, (B) PVL and (C) SZH.

very high values of the velocities ratio and the seismic inversion is unstable. Thus the results for station MPE should be regarded as preliminary. It is necessary to carry out further research and to apply other geophysical methods.

Depth of Mohorovicic discontinuity beneath the station PVL was obtained with 95% probability in the interval 31–33 km (Fig. 5B) by method of Zhu and Kanamori. Seismic velocities ratio varies greatly in different azimuth intervals. It ranges from 1.74 to 1.81 for the range 260°–300°, where no anisotropic layers is assumed. Elsewhere around the station values of $V_P/V_S$ is very high, between 1.84 and 1.93, yielding a two areas of solution. Such values are usually not observed in the Earth's crust, and therefore the method of Zhu and Kanamori doesn't give reliable results in these azimuth intervals.

Inversion for station PVL was made in four azimuth ranges: 300°–40°; 40°–68°; 70°–230°; and 260°–300°. Initial parameters for the inversion are: slowness in the range 6.0–6.4 $s/°$, angle of incidence 20°–24°, and initial velocity structure is obtained by averaging the model computed by [3] for the cell 25° E/43° N.

Inversion of receiver function is extremely unstable in the azimuthal range 300°–40° and small changes in the initial parameters lead to large differences in the final velocity models. Synthetic seismograms, computed for velocity models obtained by inversion, have a relatively small overlap with real seismograms. Although, three layers can be identified, with small changes of their depth and significant jump in S waves velocity. Near the Earth's surface a layer is obtained with thickness of about 1 km and a very low seismic waves velocities ($V_S = 1.5$ km/s). The thickness of the sedimentary layer, where the $V_S$ is around 3.2 km/s, is about 9 km. Depth of the Mohorovicic discontinuity is obtained about 32 km for the most of the initial parameters.

The overlap between synthetic and recorded waveforms is not good also in the azimuthal range 40°–68° and there is a visible gap in amplitudes. Inversion is relatively stable in this range. The very low velocity layer ($V_S = 1.5$ km/s) close to the surface has a thickness of about 2 km, while the sedimentary layer reaches a depth of 5 km ($V_S = 3.0$ km/s). The Mohorovicic discontinuity in this azimuth interval is obtained 34 km, where the S waves velocity has jump from 3.7 km/s to 4.3 km/s.

Inversion in the azimuth range 70°–230° shows also existence of sediment layer with $V_S = 3.1$ km/s. It extends to a depth of 5 km, and the depth of Mohorovicic discontinuity is computed 32 km. A low velocity layer ($V_S = 3.5$ km/s) is shaped at a depth of 17–23 km.

Ameliorated inversion results are obtained in the azimuth range 260°–300°. The depth of Mohorovicic discontinuity is obtained about 32 km where the S waves velocity changes from 3.8 km/s to 4.1 km/s. Several layers are individuated into the earth's crust. A sedimentary layer with thickness of 2 km and $V_S$ about 2.5 km/s exists near the earth's surface. Sediment layer continues to a depth of 7 km ($V_S =$ 3.3 km/s). In this azimuthal range also a low velocity

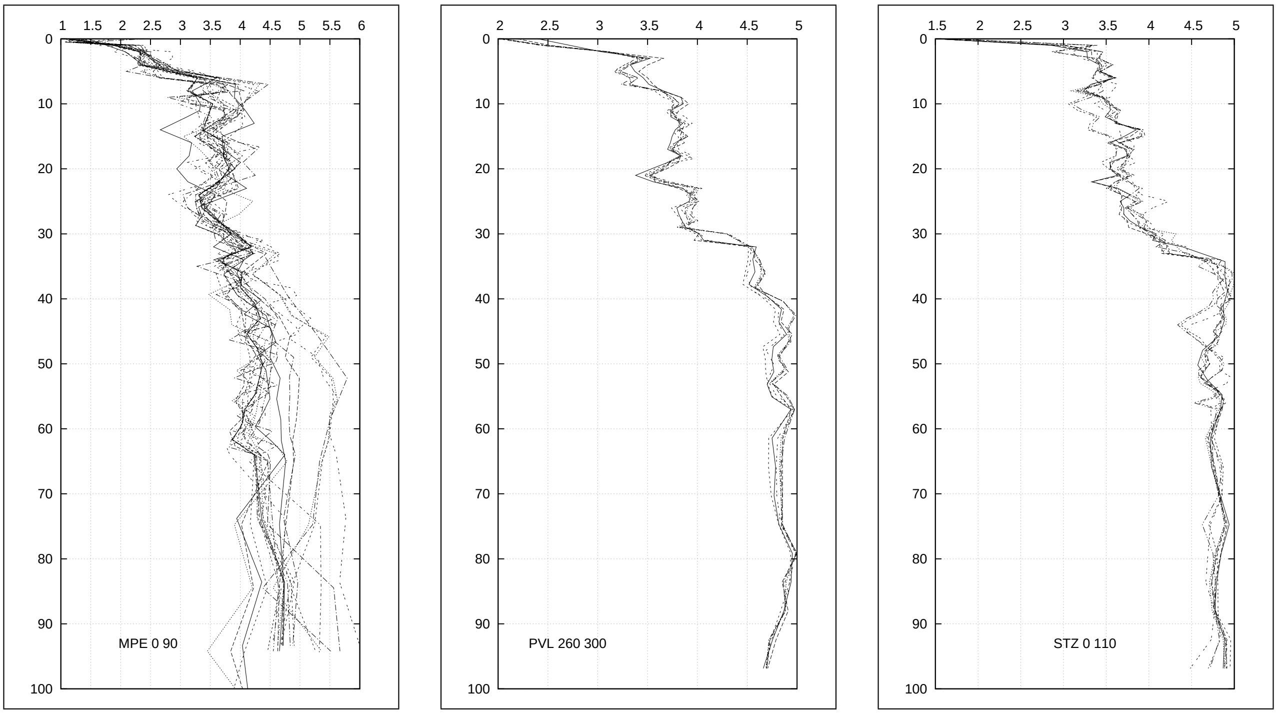


Fig. 6. Velocity models, computed from seismic inversion for some of azimuth intervals for seismic stations (A) MPE, (B) PVL and (C) SZH.

($V_S = 3.5$ km/s) layer at a depth of 19–22 km (Fig. 6B) is observed.

Thickness of the crust beneath the station PVL is 32–33 km. Different ways of estimation give similar results. The most reliable are the results for the thickness and structure of the crust in the azimuth range 260°–300°. For other areas more detailed studies should be made.

Thickness of the crust beneath the station SZH, estimated by the method of Zhu and Kanamori [7] with probability 95% is in range 32–34 km, and the ratio of the seismic waves velocities is in the range from 1.79 to 1.87 (Fig. 5C).

The data for inversion are divided in three azimuth intervals: 0°–110°, 120°–180° and 210°–350°. Crustal thickness for the three intervals is estimated 34 km (Fig. 6C). A sedimentary layer with a thickness of about 1 km and very low seismic waves velocity ($V_S = 2$ km/s) is identified. In the azimuth interval 0°–110° S waves velocity increases to 3.3 km/s down to a depth of 7 km, where jumps to 3.5 km/s and again continues to increases smoothly up to a depth of 34 km where jump to the value of $V_S$=4,9 km/s. A layer with thickness of 14 km and S wave velocity of 4 km/s is detected in the azimuthal range 120°–180°. In the last azimuth interval 210°–350° S wave velocity changes with a jump from 1.5 km/s to 3.4 km/s at depth of 2 km. The velocity amends with a jump from 5.8 km/s to 6.3 km/s at a depth of 8 km. Another abrupt change of the seismic waves velocity (from $V_S = 3.8$ km/s to $V_S = 4.4$ km/s) occurs at a depth of 29 km.

Results for the three stations located in northern Bulgaria can be summarized as follows. Typical of their receiver functions is the existence of a distinct phase with 1 s onset time. This phase indicates the presence of well distinguishable sedimentary layer beneath the three seismic stations. Beneath the MPE station there is a break for this phase on the plot of stacked receiver functions. Such a break is observed also for the phase, converted from Moho. Such kind of gaps are observed beneath other two stations SZH and PVL. Beneath station PVL the converted by Moho phase has a smaller amplitude of the phase in the crust. Break beneath the station SZH could be explained by the fault passing near the seismic station. Overall, beneath the three stations, the complex plots of stacked receiver functions, show a strong azimuthal dependence, an indication of the presence of the anisotropic layers. This is confirmed by the phases observed on the plot with stacked T components.

Results for the depth of Mohorovicic discontinuity obtained by the method of Zhu and Kanamori with 95% probability are in the range 29–31 km for station MPE, 31–33 km beneath the station PVL and 32-34 km beneath the station SZH. Intervals for the ratio of seismic waves velocities are: 1.81 to 1.92 at station MPE, at station PVL is 1.74–1.81 and 1.79 to 1.87 at station SZH.

Inversion of receiver function waveforms is performed in different azimuth intervals around the seismic stations. Inversion for station MPE is extremely unstable and further studies should be performed, including different techniques and other geophysical methods, to obtain a velocity model for that station. Inversion for station PVL is stable only in the range 260°–300°, where the obtained thickness of the crust is about 32 km. Inversion for station SZH is performed in three azimuth intervals and the obtained crustal thickness in all intervals is 34 km.

*Structure of the mantle transition zone*

Stacked receiver functions is not a good option for representing the results from the research in the mantle. Instead a map with piercing points of the seismic rays should be made and profiles should be traced across the area of interest. In (Fig. 7) the map with piercing points for 410 discontinuity and traced profiles are presented. The results for profiles C2 and C3 are analyzed in this study.

Profiles of the C series are chosen parallel to the geographical parallels with direction from west to east. Their western end is located on the territory of Serbia (C2 and C3) and eastern end is located in the Black Sea. Profiles have a length of about 600 km and are 1° apart each other.

Main discontinuities in the upper mantle are identified relatively well in this series of profiles. Deviations from the initial velocity model are observed along profiles of C2 and C3. From the middle of the profile C2 to east the 410 discontinuity is estimated of 420 km. The depth of 660 discontinuity is shallower and it is estimated as 650 km in some parts of the profile (Figure 8). In the greater part of the profile C3 410 discontinuity has also a depth of 420 km.

Lithosphere – mantle discontinuity is estimated at 190 km along the profiles from C series. In certain parts of the profiles the depth is greater and reaches up to 220 km. Phases from depths of about 300 and 500 km are also observed. Along profile C2 are observed phases at a depth of 300 and 340 km, and along profile C3 – at depth of 300 km. Identifications for the presence of discontinuity at a depth 500–510 km are obtained along profiles C2 and C3. A phase of depth 600 km can be observed on profile C3, which

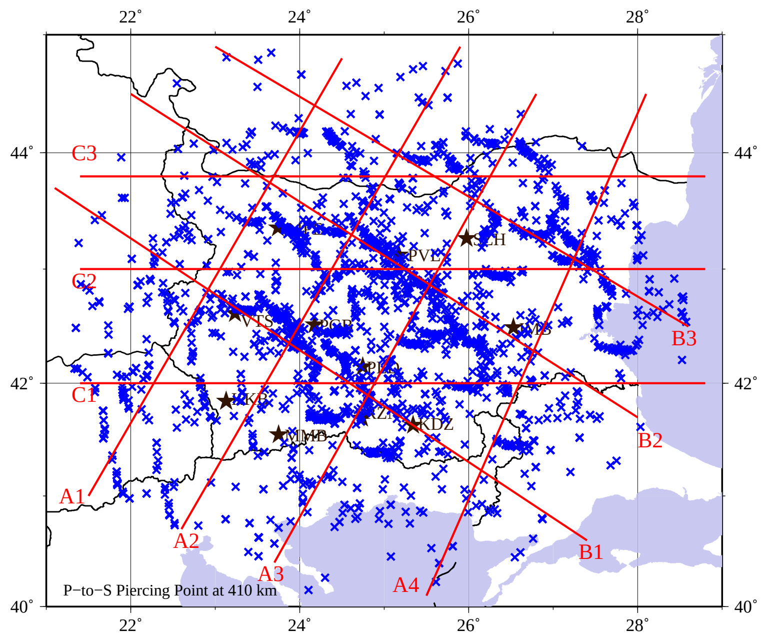


Fig. 7. Map of piercing points for 410 discontinuity and traced profiles. Only profiles C2 and C3, located in the southern part of Moesian platform, are considered in this study.

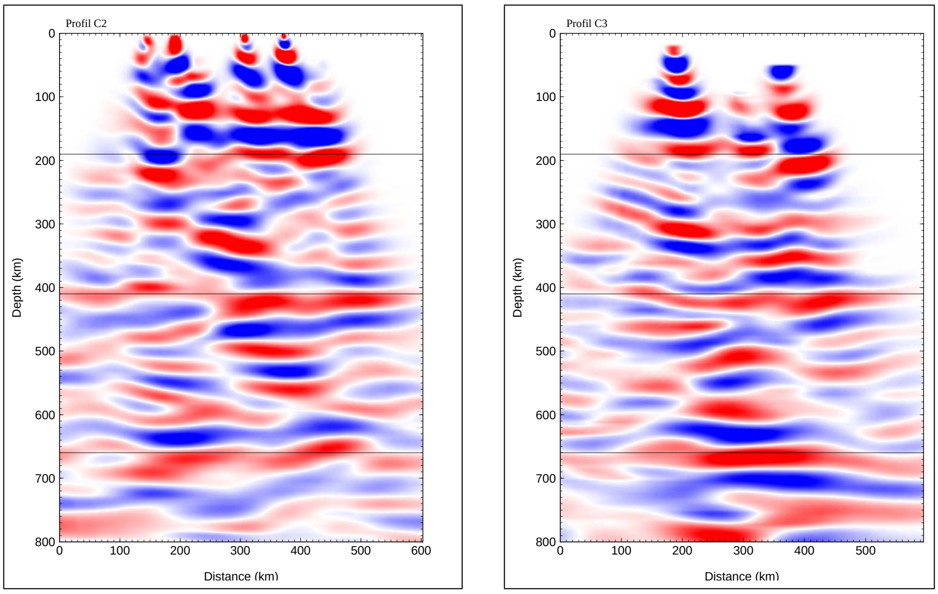


Fig. 8. Depth sections along profiles C2 and C3, obtained after migration. Horizontal lines show discontinuities 410 and 660, and also Lithosphere-mantle discontinuity.

origin is not identified yet. The appearance of these phases may be due to deep structure in the Vrancea region [9, 10].

The results along the profiles from C series can be summarized as follows. Depth of 410 km discontinuity is greater in northern Bulgaria. This is an indication of the presence of a hot mantle in this region [11]. The depth of 660 is shallower, which is as expected in the regions with hot mantle [11].

## CONCLUSIONS

The results obtained by the receiver function method for the area of seismic stations in North Bulgaria MPE, PVL and SZH, show complex structure of the crust. The Mohorovicic discontinuity is not shaped throughout the azimuth range around the seismic stations. The reason for this could be the presence of a fault structure, as beneath the station SZH. On the plots with the stacked receiver functions although converted by Moho phase, another distinct phase in the Earth's crust is observed. One explanation for its existence is that it is generated at the bottom of the sediments. Performed seismic inversion, however, showed unstable results in some of the azimuth intervals (station MPE). This means that probably the structure of the earth's crust beneath the seismic station is more complex: most probably existence of anisotropic structures. The main discontinuities in the mantle transition zone, namely the 410 and 660 are obtained after migration of the data, but the obtained depth is different than in iasp91 velocity model.

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# СТРУКТУРА НА ЗЕМНАТА КОРА И ГОРНАТА МАНТИЯ В ЮЖНАТА ЧАСТ НА МИЗИЙСКАТА ПЛАТФОРМА ПО ДАННИ ОТ СС MPE, PVL И SZH

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(Резюме)

В изследването е използван метода на функциите на приемане. Той е приложен към данни от станциите на Националната Цифрова Сеизмична Мрежа (НЦСМ). Обработени са данните от 11 сеизмични станции, екипирани с широколентови сеизмометри. В този доклад ще бъдат представени получените резултати за три станции разположени в южната част на Мизийската платформа – Малопещене (MPE), Павликени (PVL) и Стражица (SZH).

Мизийската платформа се характеризира с наличието на много дебел седиментен слой. От различни геофизични измервания неговата дебелина е определена на до 8-10 km. Резултатите, получени по метода на функциите на приемане показват наличието на слой с ниски скорости на сеизмичните вълни и голяма дебелина под повърхността на Земята. Дебелината на границата на Мохоровичич варира между 29 km и 34 km, като нейната дебелина се увеличава от станция MPE към станция SZH. Като цяло времевите разрези, получени за отделните станции за строежа на земната кора, имат изключително сложен характер. Границата на Мохоровичич не се проследява в целия азимутен диапазон и при трите станции.

При изследването на строежа на мантията са избрани три групи от профили, които пресичат територията на България в различни посоки. Идентифицирани са фази, които идват от основните граници, ограждащи зоната на преход в мантията. Северна България е установено слабо отклонение в дълбочината на тези граници спрямо isap91 модела. Установено е наличието на фази, които идват от граници в зоната на преход мантията.