427
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CRUSTAL STRUCTURE BENEATH REPUBLIC OF NORTH MACEDONIA BASED ON RECEIVER FUNCTION ANALYSIS

Jasmina Najdovska, Katerina Drogreška

Seismological Observatory of the Faculty of Natural Sciences and Mathematics,
Ss. Cyril and Methodius University, Arhimedova 3, Skopje, Republic of North Macedonia
najdovskaj@yahoo.com

Abstract: Teleseismic waveforms recorded by Wideband Ranger WR-1 seismometers at three permanent stations of the Seismological Network of the Republic of North Macedonia – Skopje (SKO), Valandovo (VAY) and Ohrid (OHR), were analyzed using the *P* receiver function method, which enables identification of major seismic discontinuities within the crust and upper mantle below the seismological stations. Analysis of the data revealed variations in the timing of the *Ps* phases, indicating heterogeneity in Moho depth across the region. Specifically, *Ps* phases were observed between 4.0 and 4.5 seconds after the incident *P* arrival at the seismological station Skopje (SKO), between 3.5 and 4.5 seconds at the seismological station Valandovo (VAY), and between 5.0 and 5.5 seconds at the seismological station Ohrid (OHR). To determine the crustal structure, an inversion of the obtained receiver functions was performed using a linearized iterative technique to derive 1-D seismic velocity models of the crust. The inversion results reveal significant variations in crustal thickness, with Moho depths ranging from approximately 34–36 km beneath the VAY station in the east to over 42–44 km beneath the OHR station in the west. At the seismological station SKO, the Moho depth is around 36 km. These results provide new constraints on the lithospheric structure of our country and offer valuable insights into the complex tectonic framework of the region.

Key words: receiver function; crustal structure; Moho depth

INTRODUCTION

Understanding the structure of Earth's crust and upper mantle is essential for interpreting tectonic processes, seismicity, and lithospheric evolution. Variations in crustal thickness, seismic velocities, and major discontinuities such as the Mohorovičić discontinuity (Moho) provide key insights into regional tectonics and lithospheric dynamics.

Receiver function analysis has become a reliable and widely used method for mapping crustal and upper mantle structures underneath isolated seismic stations. This method is used to isolate the Earth's structural response near the receiver from other influences, such as the earthquake source characteristics and the ray path effects through the mantle and local structures underneath the recording site.

In 2005, Seismological Observatory at the Faculty of Natural Sciences and Mathematics in Skopje undertook significant efforts to upgrade and maintain modern digital seismological network. This advancement enabled continuous, high-resolution instrumental monitoring of seismic activity across the territory of the Republic of North Macedonia and its surrounding regions.

As a result, the network has generated a substantial volume of high-quality seismic waveforms, providing a valuable resource for geophysical investigations within the country.

The dataset used in this study comprises teleseismic recordings from three permanent seismological stations: Skopje (SKO), located in the northern part of the Vardar seismic zone; Valandovo (VAY), situated in the southeastern part of the Vardar seismic zone; and Ohrid (OHR), positioned in the southwestern part of the West-Macedonian seismic zone (Arsovski, 1997) (Figure 1).

Using receiver function analysis, we investigate crustal discontinuities, construct 1-D shear velocity models, and estimate the depth of the Moho beneath each station.

The results provide new constraints on lateral variations in crustal thickness and allow us to interpret these variations within the context of North Macedonia's complex tectonic framework.

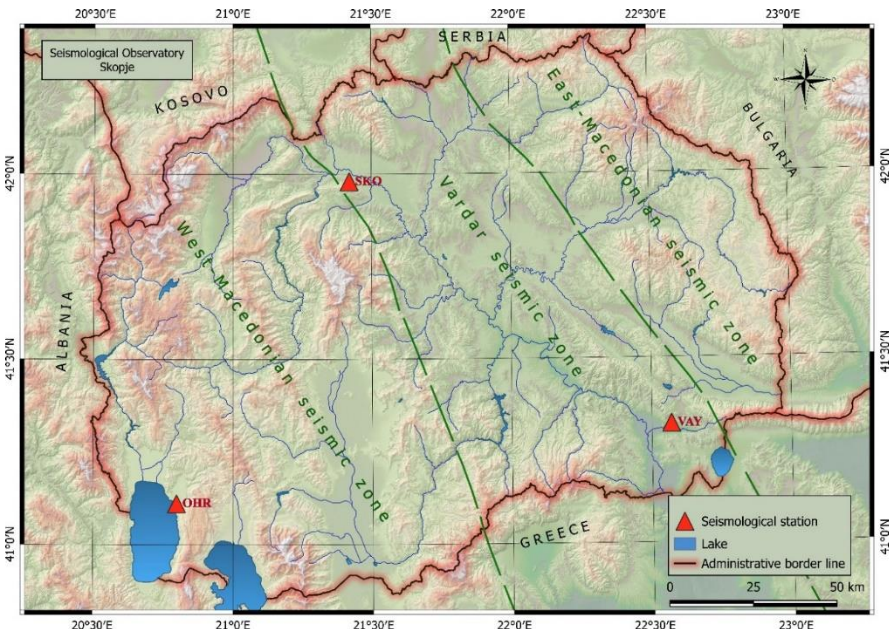

Fig. 1. Permanent seismological station locations across the Republic of North Macedonia.

DATA AND METHOD

The events used to estimate receiver functions in this study were recorded during the observation period from 2006 to 2013. The selected teleseismic earthquakes consist of three-component seismograms with epicentral distances ranging from 30° to 95° and magnitudes greater than 5.5 (Figire 2). The number and quality of recorded waveforms at each seismic station depend on the duration of station operation, local site conditions, instrumental performance, and ambient noise levels.

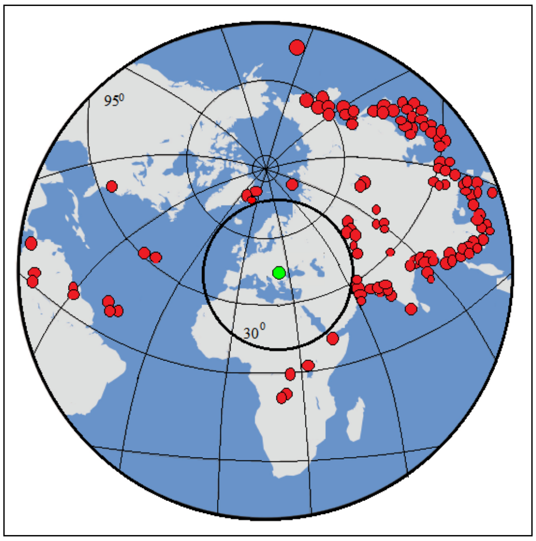

Fig. 2. Distribution of teleseismic events (red circles) recorded by three seismological stations (SKO, VAY, OHR). Selected events are with epicentral distance between 30° and 95°. Green circle marks position of the Republic of North Macedonia.

Most of the selected events are located to the north and east of the stations, with back-azimuths between 0° and 95°, while only a few events originate from the south and west.

The *P* receiver function method is based on analyzing *P*-to-*S* converted phases contained in the *P*-wave code, which provide information about the velocity structure beneath seismological stations (Figure 3a). The theoretical background of the technique was described using the approach of Langston (1979), Owens et al. (1984), Kind and Vinnik (1988), Kosarev et al. (1993). The simplicity of the method allows for routine application in the analysis of data from permanent network stations, and its widespread use has led to several detailed descrip-tions of the technique (Ammon et al., 1990; Ammon, 1991).

These converted phases, generated at significant velocity discontinuities beneath a station, are especially useful for studying the crust and upper mantle. Due to the strong velocity contrast at the crust-mantle boundary, the converted *Ps* phase is often the most prominent signal following the direct *P* wave and typically exhibits a much stronger amplitude on the horizontal component than on the vertical.

The delay time of the converted phase relative to the direct *P*-wave arrival depends on the depth of the discontinuity, the ray parameter of the incident *P* wave, and the seismic velocity structure of the layers (Langston, 1977). By rotating *ZNE* component waveforms into the local *P*-*SV*-*SH* ray-based coordinate system, the *Ps* converted phases are isolated on the *SV* component, which is perpendicular to the *P* component that carries the direct *P*-wave motion.

The influences of the instruments, local structural effects, source parameters, and mantle path effects are removed, and the *P* component is deconvolved from the *SV* component (Vinnik, 1977; Phinney, 1964). The resulting waveform, known as the receiver function, contains not only the primary converted phases but also multiple phases generated by reflections between the Earth's surface and velocity discontinuities (Figure 3b). Receiver functions are calculated according to the approach of Herman (2002) and Herrmann and Ammon (2002, 2004).

In this study, receiver functions obtained from different teleseismic events at each seismic station are sorted by back azimuth and stacked to enhance signal coherence, then analyzed through forward modeling to investigate velocity discontinuities within the crust and estimate the depth of the Mohorovičić discontinuity, ultimately enabling the reconstruction of the shear-velocity structure beneath each station.

The inversion was performed using Computer Programs in Seismology, developed by Herman (2002), Herrmann and Ammon (2002), with the AK135 Earth model as a starting point (Kennett et al. 1995), assuming a shear-wave velocity of $v_s = 4.55$ km/s, Projet PNUD-UNESCO (1972). To enhance the clarity of the receiver function signals, low-pass Gaussian filters with parameters of 1 and 2.5 were applied during the inversion.

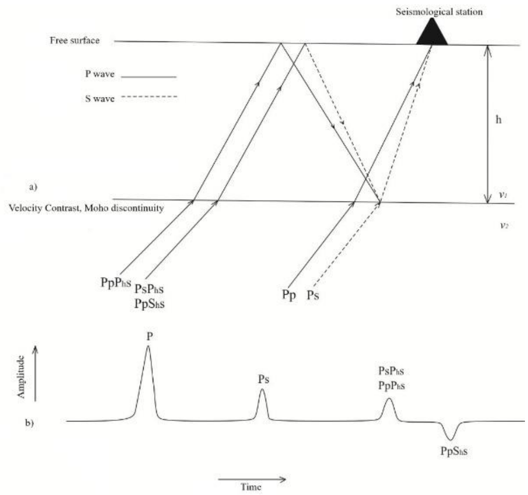

Fig. 3. a) Ray diagram showing *P*-to-*S* conversions and multiples generated at the velocity contrast,
b) Receiver function for a simple crust showing direct *P* arrival, Moho *Ps* conversion, and multiples.

RESULTS AND DISCUSSION

P receiver function

Radial receiver function was computed for the three stations, and summed as a function of back azimuth from 0° to 360°, in a time window of –10 s to 40 s (Figure 4). A total of 116 events were initially recorded at the SKO station, 185 at the VAY station, and 151 at the OHR station. After removing traces affected by high noise levels or instrumental issues, receiver functions were computed for 77 events at the SKO station, 132 events at the VAY station, and 50 events at the OHR station.

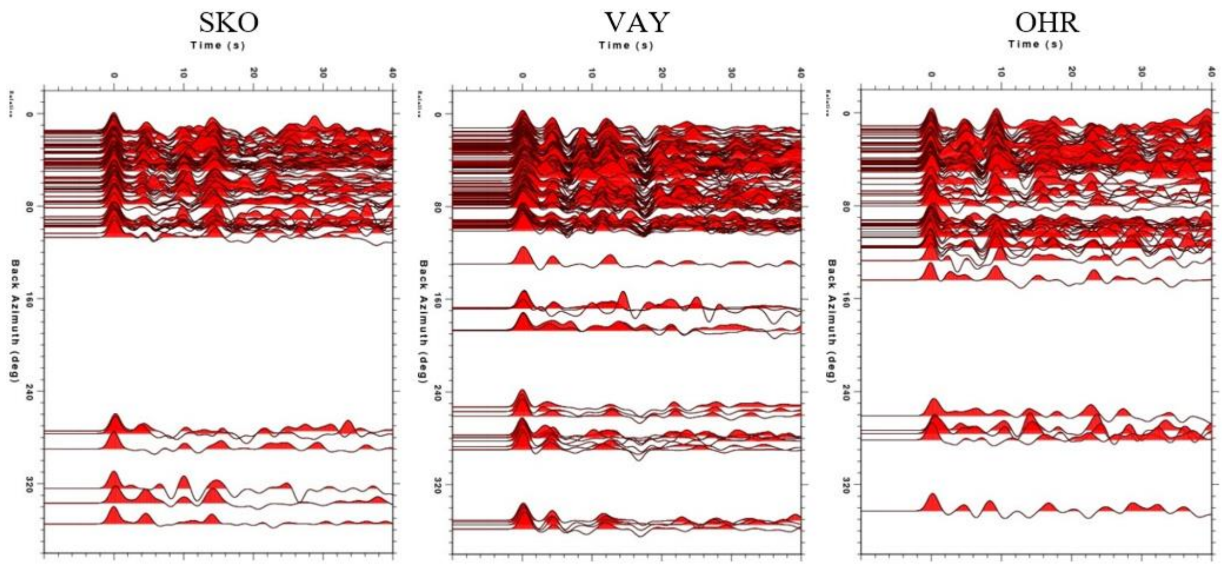

Fig. 4. Radial receiver function plotted as a function of back azimuth for each stations.

Positive amplitudes (red-colored) represent an increase in seismic velocity with depth, while negative (non-colored) amplitudes reflect a decrease in velocity with depth. The zero-time marker aligns with the arrival of the direct *P*-wave.

The receiver function for all stations showed the direct *P* arrival at 0 s. The converted *Ps* phases from the Moho discontinuity arrives around 4.0 s – 4.5 s after the incident *P* on the radial receiver function for the SKO station.

The *Ps* Moho arrival is showed at 3.5 s – 4.5 s for the VAY station and for the OHR station *Ps* phases arrive around 5.0 s to 5.5 s after the incident *P* wave.

The converted *Ps* phase from the Moho discontinuity arrives between 3.5 s and 5.5 s, depending on the seismological station. The time of the converted *Ps* shows the shallowest Moho depth beneath the VAY and SKO stations, and the deepest Moho discontinuity at OHR seismological station.

Inversion of receiver function

The inversion process and derivation of the crustal velocity models were performed using 34 receiver functions analysis for the SKO seismological station, 32 for the VAY station, and 12 for the OHR seismological station.

Figure 5 presents the velocity models derived from receiver function analysis for SKO station. Figure 6 shows the velocity models for the VAY seismological station. Figure 7 displays the velocity model for the OHR seismological station.

The blue curve represents the observed data, while the red curve corresponds to the model prediction.

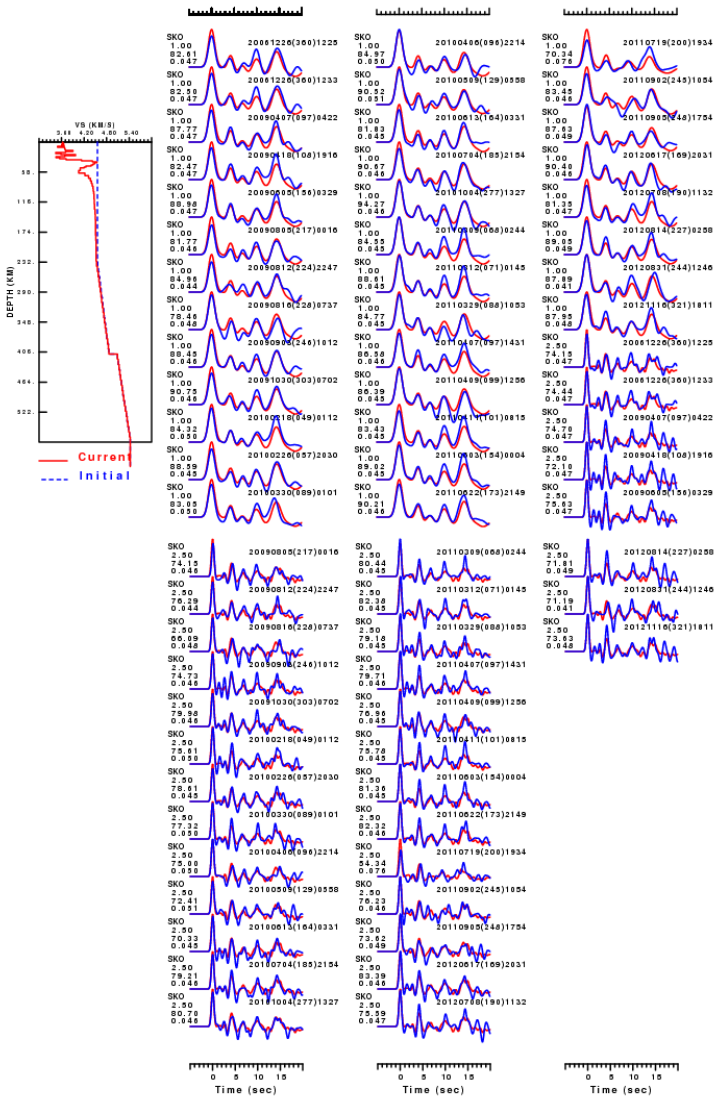

Fig. 5. Model fit to the receiver function at the SKO seismological station

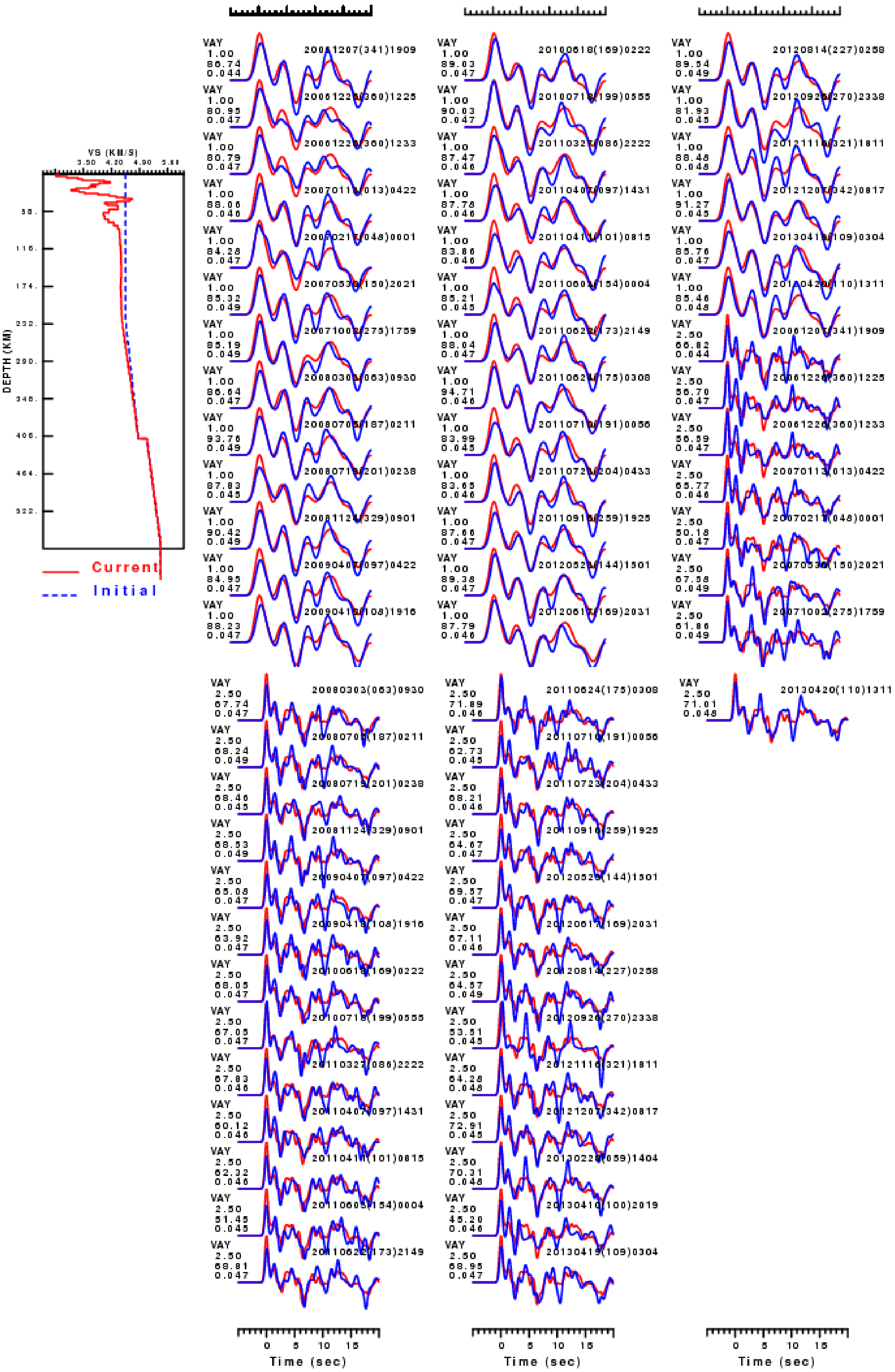

Fig. 6. Model fit to the receiver function at the VAY seismological station

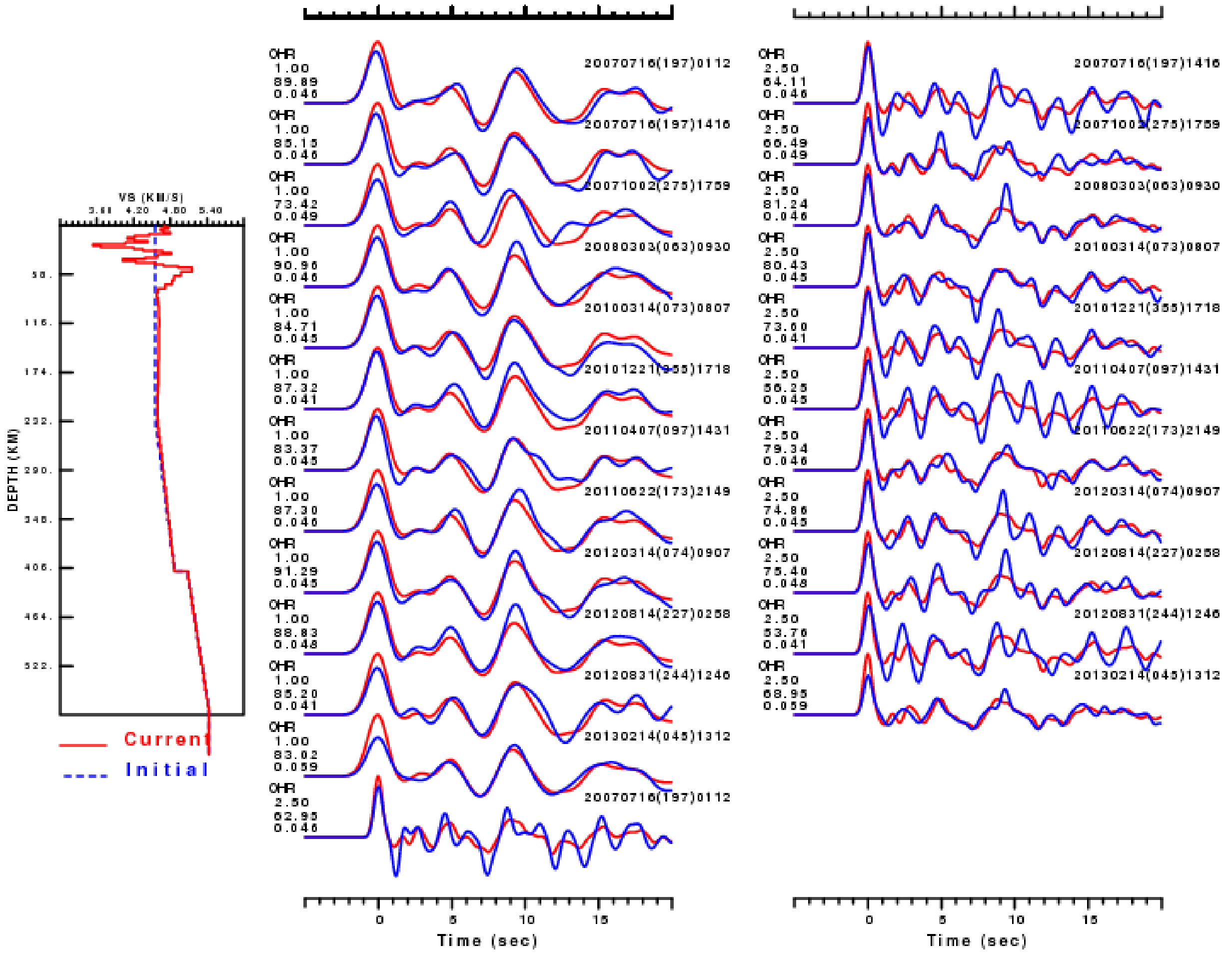

Fig. 7. Model fit to the receiver function at the OHR seismological station

In the upper left corner of each trace, the station name, Gaussian filter parameter, percentage of fit, and ray parameter are indicated. Each receiver function is labeled on the right side of the trace with the year, month, day, hour, and minute of the recorded event.

A coherently stacked receiver function, obtained from multiple events, was used as input for the shear-wave velocity inversion to calculate the crustal velocity models. Figure 8, for the following seismological stations: a) Skopje (SKO), b) Valandovo (VAY), and c) Ohrid (OHR), presents the receiver function stacks used for the inversion, along with the final crustal velocity models.

The red line represents the initial velocity model, while the blue line shows the final velocity model obtained from the receiver function inversion.

The Moho depth beneath the SKO seismological station is estimated to be approximately 36 km, which is consistent with values reported in previous geophysical studies (Dragašević and Andrić, 1982; Delipetrov et al., 2016; Boykova, 1999).

The Moho discontinuity beneath the VAY seismological station is estimated, based on inversion results, to be located at depths between 34 km and 36 km. These values show good agreement with prior studies conducted in the region (Dragašević and Andrić, 1982; Papazachos, 1998; Boykova, 1995).

At the OHR seismological station, complex patterns are observed in the stacked receiver function, with two distinct peaks identified as converted *Ps* phases (Figure 8c left).

A more detailed analysis of these data is necessary to determine whether the subsurface structure beneath the OHR seismological station is influenced by faults, lateral heterogeneities, or anisotropy.

The estimated Moho depth from receiver function analysis beneath the OHR seismological station ranges between 42 and 44 km, which is in good agreement with results obtained from other seismological and geophysical surveys (Dragašević and Andrić, 1982; Ormeni, 2009; Delipetrov, 2016).

Overall, the Moho is the shallowest in the southeastern part of the Republic of North Macedonia, at depths from 34 to 36 km, and the deepest in the southwestern part, where it reaches depths of 42 to 44 km.

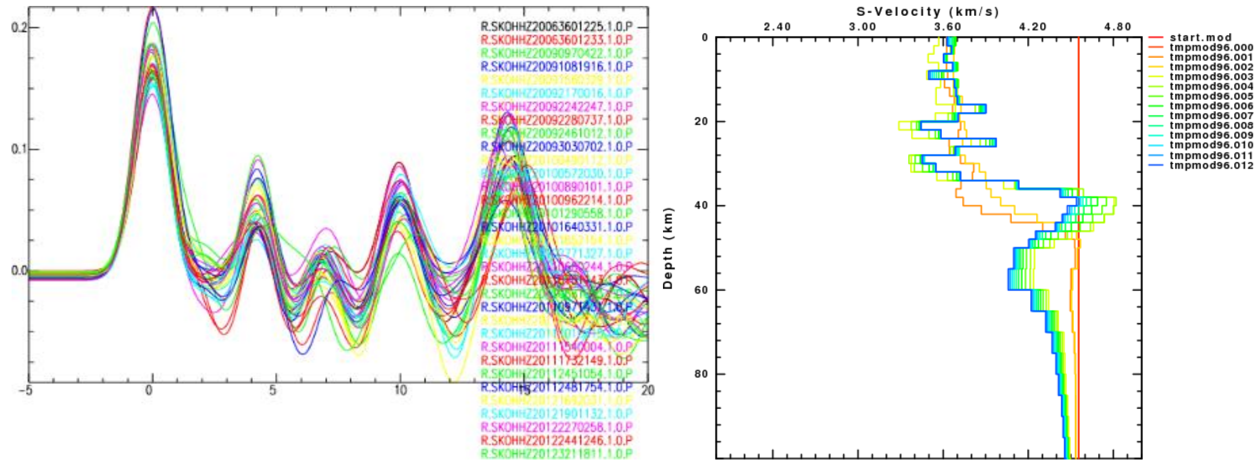

Fig. 8a. Receiver function stack used for inversion (left); crustal velocity model beneath the SKO seismological station (right). Only the upper 100 km of the models are displayed.

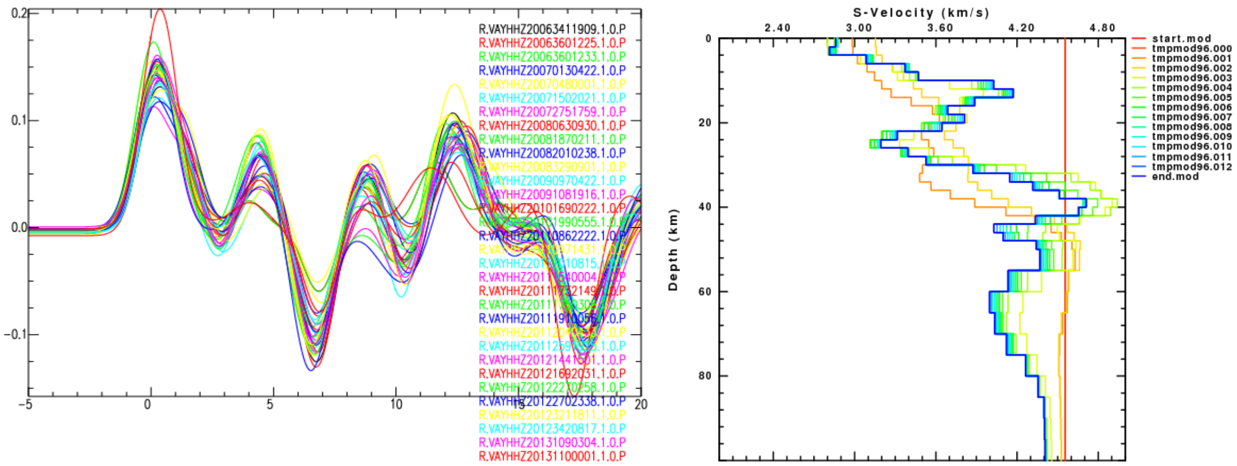

Fig. 8b. Receiver function stack used for inversion (left);, crustal velocity model beneath the VAY seismological station (right) Only the upper 100 km of the models are displayed.

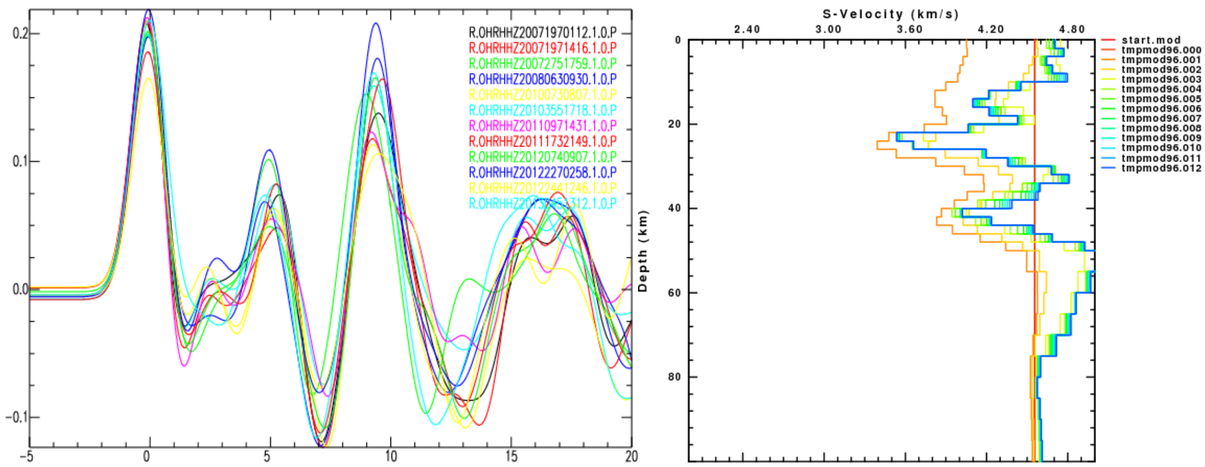

Fig. 8c. Receiver function stack used for inversion (left); crustal velocity model beneath the OHR seismological station (right). Only the upper 100 km of the models are displayed.

CONCLUSIONS

This study provides new insights into the crustal structure beneath the territory of the Republic of North Macedonia through analysis of teleseismic data recorded at three permanent seismological stations: Skopje (SKO), Valandovo (VAY), and Ohrid (OHR). Using the receiver function method and subsequent inversion techniques, we estimated the depth of the Mohorovičić discontinuity (Moho) and derived 1-D shear velocity models for each location.

The results reveal significant lateral variations in Moho depth across the region. The shallowest Moho depths are observed beneath the VAY seismological station (from 34 to 36 km) and SKO seismological station (around 36 km), while the deepest Moho is found beneath the OHR seismological station, ranging from 42 km to 44 km. These differences reflect the complex tectonic and geological framework of the region, influenced by crustal thinning in the east and crustal thickening in the west.

The stacked radial receiver functions show clear *Ps* conversions from the Moho, confirming the reliability of the depth estimates. In particular, the seismological station in Ohrid (OHR) exhibited more complex receiver function signatures, suggesting the presence of additional structural features such as faults, lateral heterogeneities, or anisotropy in the crust.

Overall, this work contributes valuable constraints on the seismic structure of the North Macedonian lithosphere and enhances our understanding of regional tectonics. Future studies with expanded seismic networks and additional methods (e.g., ambient noise tomography or joint inversion with surface waves) could further refine these results and provide a more detailed view of the crust and upper mantle in the region.

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Р е з и м е

СТРУКТУРА НА ЗЕМЈИНАТА КОРА ПОД ТЕРИТОРИЈАТА НА РЕПУБЛИКА СЕВЕРНА МАКЕДОНИЈА ВРЗ ОСНОВА НА АНАЛИЗА НА ФУНКЦИИТЕ НА ПРИЕМНИКОТ

Јасмина Најдовска, Катерина Дрогрешка

Сеизмолошка опсерваторија, Природно-математички факултет,Универзитет „Св. Кирил и Методиј“, Архимедова 3, Скопје, Република Северна Македонија
najdovskaj@yahoo.com

Клучни зборови: функции на приемник; брзински модел; дисконтинуитет на Мохоровичиќ

Телесеизмичките земјотреси, регистрирани со фреквентно широкопојасни сеизмометри Wideband Ranger WR-1 во трите постојни сеизмолошки станици од сеизмолошката мрежа на Република Северна Македонија – Скопје (SKO), Валандово (VAY) и Охрид (OHR), беа анализирани со методот на *P*-функции на приемник, кој овозможува идентификација на главните сеизмички дисконтинуитети во кората и горната мантија непосредно под секоја сеизмолошка станица.

Анализата на податоците покажа варијации во времето на појава на фазите *Ps*, што укажува на хетерогеност на длабочината на дисконтинуитетот на Мохоровичиќ низ регионот. Во овој случај функциите на приемникот покажуваат јасни настапи на конвертираните фази од 4,0 s до 4,5 s по настапот на директниот *P*-бран за сеизмолошката станица Скопје (SKO), од 3,5 s до 4,5 s за сеизмолошката станица Валандово (VAY) и од 5,0 s до 5,5 s за сеизмолошката станица Охрид (OHR).

За одредување на структурата на Земјината кора беше извршена инверзија на функциите добиени на приемникот со употреба на линеаризирана итеративна техника, со која беа добиени еднодимензионални (1D) модели на брзини во кората. Резултатите од инверзијата покажуваат значителни варијации во дебелината на Земјината кора, при што дисконтинуитетот на Мохоровичиќ се наоѓа на длабочина од околу 34–36 km под сеизмолошката станица Валандово (VAY) на исток и на 42–44 km под сеизмолошката станица Охрид (OHR) на запад. Под сеизмолошката станица Скопје (SKO) дисконтинуитетот на Мохоровичиќ е на длабочина од околу 36 km.

Овие резултати даваат нови ограничувања за структурата на литосферата во Северна Македонија и нудат значајни сознанија за комплексната тектонска градба на регионот.