Abstract. The main goal of this study is to investigate the lithospheric structure beneath Vrancea seismic area using local earthquakes. Vrancea area, located at the South-Eastern Carpathians Arc bend, is characterized by strong earthquakes generated at intermediate depths (60–170 km) in a complex geotectonic system. The tomography image resulted from teleseismic data (Martin et al., 2005; 2006) reveals a high-velocity body extended significantly beyond the seismic active zone in depth (going down to 400 km depth or even more), as well as laterally. An updated and revised catalog of 927 well-located events occurred between 1982 and 2006 in Vrancea and around was considered in the present study. The application of the tomography inversion for local events (Koulakov et al., 2007) allowed a notable increase of the resolution of the previous tomography image. The high-velocity body is strongly reduced in extension and practically mimics the distribution of hypocenters.

Key words: local tomography, Vrancea earthquakes, litospheric structure.

1. INTRODUCTION

The main objective of this study is to investigate the lithospheric structure beneath the Carpathian Arc bend, more precisely in Vrancea (Romania) area, using a tomographic inversion of P- and S-wave arrival time data. Vrancea region is characterized by intermediate-depth earthquakes (\( h > 60 \) km) with high energies that can produce important damage on large areas (there are 2 – 3 earthquakes per century that are felt from Russia and Scandinavia to Greece).

The first studies regarding the three-dimensional velocity structure in Vrancea area were made by Fuchs et al. (1979), Oncescu (1982, 1984), Oncescu et al. (1984), Koch (1985) and Fan et al., 1982. These studies use the P wave arrivals from teleseismic earthquakes, recorded by the Romanian Seismic Network. More recent studies (Wortel and Spakman, 1992; Lorenz et al., 1997) invert for the velocity structure using P- and S-phase arrivals from local events.

The tomography inversion for local, regional and teleseismic earthquake data put in evidence the existence of a low-velocity structure situated between 40 and 80 km depth, which separates the crust from a lithospheric body characterized by
high velocities, which sinks into the asthenosphere almost vertically. The high-velocity slab is located between 80 and 160 km depth, in the region where the Vrancea subcrustal seismic activity occurs.

Moreover, the analysis of seismicity patterns (Trifu and Radulian, 1991; 1994; Radulian and Popa, 1996) indicate the possibility of another region with low velocity inside of the subducted lithospheric slab, somewhere around 100 km depth. This hypothesis is also supported by results from studies of the thermal regime under the Vrancea area (Andreescu, 1993; Demetrescu and Andreescu, 1994).

The CALIXTO’99 experiment (Wenzel et al., 1998), which took place between Mai and October 1999 in the framework of CRC461 project, provided a unique opportunity to study the detailed velocity structure in the Vrancea region. The experiment aimed for a better understanding of the 3-D geodynamic evolution of the Carpathian Arc in the SE part of Romania, in particular for an improved characterization of the upper mantle lithospheric fragment in the Vrancea region. Using teleseismic data recorded during CALIXTO’99 project, Martin et al. (2005, 2006) determined the 3-D velocity structure in the Vrancea area. For the tomography inversion they used the ACH method (Aki et al., 1977; Evans and Achauer, 1993). Inversion results showed the existence of a high velocity lithospheric body below the Carpathian Arc bend, which includes the region where the subcrustal Vrancea earthquakes occur. These studies put also in evidence a change in the orientation of the lithospheric body, from a NE-SV direction in the upper part to a N-S direction in the lower part. P-wave velocity anomalies of the high-velocity body are of up to 3.50% of the 1D reference velocity used (Martin et al., 2006).

In this study we use the local earthquake data recorded during the CALIXTO’99 experiment, as well as local earthquake data recorded by the permanent seismic network in Romania, to invert for the 3D velocity structure in the Vrancea region. The number and quality of data would hopefully complement the results of the teleseismic earthquake tomography (Martin et al., 2005, 2006) and allow for a more refined image of the underground structure in the Vrancea region.

2. DATA

The data set used consists of P- and S-wave arrival times of 994 local events (Fig. 1) recorded from 1982 to 2006. The earthquakes were selected by requiring a minimum of six P-wave arrivals with a clear onset per event. There are 687 intermediate-depth events and 307 crustal events that fulfilled this criterion.

The distribution of temporary and permanent seismic stations that recorded the earthquakes is shown in Fig. 2. The temporary network was in use during the CALIXTO’99 experiment and consisted in 30 broad-band and 90 short-period stations, installed in a region of about 350 km in diameter, centered in Vrancea area. There were 160 local events ($M_t \geq 2.0$) that were recorded in a period of six months, during CALIXTO’99. The initial event locations were done with the HYPOPLUS program, used by NIEP for routine earthquake locations.
Fig. 1 – Epicentral distribution for the earthquakes used in this study. Red and black dots show intermediate-depth and crustal events, respectively.

Fig. 2 – Distribution of seismic stations.
The quality of the initial earthquake locations is relatively good, with a mean value of RMS travel time residuals below 0.5. The distribution of RMS residuals for the initial data set is shown in Fig. 3.

![RMS distribution for initial dataset](image)

Fig. 3 – Distribution of RMS travel time residuals for the initial data set.

The starting 1D velocity model is the one used by NIEP in routine earthquake locations and includes information from refraction and reflection seismic studies (Enescu et al., 1972; Rădulescu, 1988; Răileanu et al., 1994, Răileanu et al., 2001, Fielitz et al., 2001).

<table>
<thead>
<tr>
<th>Depth (km)</th>
<th>$V_p$ (km/s)</th>
<th>$V_s$ (km/s)</th>
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</thead>
<tbody>
<tr>
<td>-1.000</td>
<td>4.450</td>
<td>2.542</td>
</tr>
<tr>
<td>20.000</td>
<td>5.501</td>
<td>3.143</td>
</tr>
<tr>
<td>40.000</td>
<td>6.768</td>
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<tr>
<td>100.000</td>
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<td>130.000</td>
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<td>170.000</td>
<td>8.301</td>
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</tr>
<tr>
<td>240.000</td>
<td>8.387</td>
<td>4.793</td>
</tr>
</tbody>
</table>
3. METHOD

The study is based on tomographical inversion code for local data LOTOS-07 (LOcal TOmography Software) accomplished by Ivan Koulakov. The codes do simultaneous inversion for P and S waves. A detailed description of LOTOS-07 code is made in Koulakov et al., 2007, where are presented tomographical results for Indonesia and Central Java seismic areas.

4. RESULTS

![Graph a](image1)

**Fig. 4 – a)** RMS travel time residuals for the P and S-wave after each of the five iterations that were performed for 1D model optimization.

![Graph b](image2)

**Fig. 4 – b)** RMS P and S-wave travel time residuals for each earthquake after the last iteration.

RMS travel time residuals for the P and S-wave after each of the five iterations that were performed for 1D model optimization.

- **P-wave**
- **S-wave**

RMS P-wave and S-wave travel time residuals for each earthquake after the last iteration.
The RMS travel time residuals after iterations 1 to 5 are shown in Fig. 4a, for the P-wave and S-wave, respectively. It can be noticed that the RMS residuals for both P- and S-wave travel times are gradually decreasing and reach stable values. Figure 4b show the distributions of P and S-wave travel time residuals after the fifth iteration.

4.1. 3D INVERSION RESULTS

For the simultaneous inversion for earthquake location and 3D velocity structure, we adopt a parametrization with nodes distributed in the study volume using the algorithm described in Koulakov et al. (2007). The nodes are installed in vertical planes which are spaced at 5 km from each other. In each vertical plane, nodes are distributed according to ray density. In areas with small amount of rays the distance between nodes is larger. To avoid an excessive concentration of nodes in areas with high-ray density, we fix the minimum spacing between nodes at 5 km, which is significantly smaller than a characteristic size of the expected anomalies. The model center was considered in Vrancea area (geographical coordinates: 26.5° E and 45.5° N). Figure 5 shows P and S-wave velocity anomalies in horizontal planes situated at 5, 15, 25, 35, 55, 75, 80, 90, 110, 120, 130, 140 and 160 km depth. Figures 6a and b present the P and S wave velocity anomalies in vertical cross-sections oriented from SW to NE and from NW to SE, respectively.

Figs. 5 and 6 show the presence of a high velocity material between about 60 and 200 km depth. The crust shows in general negative velocity anomalies. In the interval between 45 and 60 km depth, where are very few seismic events (Fig. 6a, b), no important velocity anomalies are detected. At intermediate depth, relatively high velocities appear only under Vrancea area. Most earthquake hypocenters at intermediate depth are located in regions of relatively high velocity. At global scale, all images from active subduction zones are characterized by high velocity for P waves. This is in agreement with the existence of a subducted oceanic lithosphere fragment under Vrancea area. The high velocity volume is oriented in the SV-NE direction. Our results suggest a restriction of the high velocity region to the active seismic zone, unlike the tomography results obtained from the inversion of teleseismic data (Martin et al., 2006). The presence of lower velocity asthenospheric material strictly delimitate (“strangle”) the subducted lithosphere under Vrancea on both two ends (in the crustal coupling area and at 180 km depth where the seismic activity sharply ends) and laterally over all intermediate depth domain (60–180 km).
The vertical sections (Fig. 6a and b) suggest that the relatively high velocity region at intermediate depth correlates with the vertical distribution of hypocenters, which appears like a column in the profile OZ in Fig. 6b. Most crustal hypocenters are located between 10 and 50 km depth.
Fig. 6 – a) P and S wave velocity anomalies with respect to the 1D velocity model in a cross-section from A to N (South – West to North – East); b) same as a), but for a cross-section from O to Z (North-West to South – East).
4.2. TESTING METHOD – CHECKERBOARD

To establish the resolution and reliability of our velocity model we apply a checkerboard test. The initial model is represented by unlimited vertical columns of alternated positive and negative anomalies. The initial anomaly (± 7% amplitude) together with the P and S-wave velocity anomalies at 15 km depth obtained after inversion using the synthetic velocity model are shown in Fig. 7.

![Fig. 7 – Result of the checkerboard test for P and S models using the real data observation system.](image)

The initial model is represented by unlimited vertical columns of alternated positive and negative anomalies. The initial anomaly (± 7% amplitude) is shown in the first map. The reconstruction procedure is identical to the one used in the real data inversion, including absolute location of sources.
5. CONCLUSIONS

The obtained results are in accord with previously observations regarding the lithospherical structure on Vrancea area. It is accentuated the presence of the high velocity material until 200 km depth (Fig. 6a, b). In the crustal part it is observed lower velocity material. In the interval between 45 and 60 km depth, where are not seismic events (Fig. 6a, b), there are no important velocity anomalies. At intermediate depth, high velocities appear only under Vrancea area. In main, the high velocity volume is oriented on SV-NE direction.

REFERENCES


