Crustal Structure in the Western Part of Romania from Local Seismic Tomography

Bogdan Zaharia¹, Bogdan Grecu¹, Mihaela Popa¹, Eugen Oros¹, Mircea Radulian¹

¹National Institute for Earth Physics, Măgurele, Romania
bzaharia@infp.ro

Abstract. The inner part of the Carpathians in Romania belongs to the Carpathians-Pannonian system bordered by the Eastern Carpathians to the north and east, Southern Carpathians to the south and Pannonian Basin to the west. It is a complex tectonic region with differential folding mechanisms, post-collisional kinematics, rheology and thermal properties, including within its area the Apuseni Mountains and the Transylvanian Basin. The purpose of this study is to map the 3-D structure of the crust over this region on the basis of local earthquake data. Input data were recorded during the South Carpathian Project (2009–2011), a successful collaboration between the Institute of Geophysics and Tectonics of the University of Leeds and the National Institute for Earth Physics (NIEP), Romania. A temporary array of 32 broadband seismic stations (10 CMG-40T, 8 CMG-3T and 14 CMG-6TD) was installed across the western part of Romania (spaced at 40 to 50 km intervals) during the project. In addition, 25 stations deployed in the eastern Hungary and Serbia was considered. P- and S-wave arrivals are identified for all the selected events (minimum 7 phases per event with reasonable signal/noise ratio). All the events are first relocated using Joint Hypocentre Determination (JHD) technique. Then the well-located events were inverted to determine the crustal structure using LOTOS algorithm. The lateral variations of the crustal properties as resulted from the tomography image are interpreted in correlation with the station corrections estimated by JHD algorithm and with the post-collisional evolution of the Carpathians-Pannonian system.

1. Introduction

The Earth's structure is the main factor that controls the shape and the amplitude of the soil motion as recorded on the Earth's surface as a result of the action of seismic waves. The modelling of seismic wave propagation through complex three-dimensional structures is one of the most significant challenges for seismologists [1]. The analysis of the travel times for different phases of seismic waves provides basic information on the seismic wave ray path and the propagation velocity from source to observer.

Seismic tomography is an inversion technique that uses body and surface waves to determine the three-dimensional velocity structure under a particular region. Expanding, the study area depends on the size of the region covered by observation points and the wavelength of the propagated waves. Tomographic inversion allows the detection of areas with higher or lower velocities as compared to a one-dimensional reference model for the studied region. Presently, this technique has become a powerful tool for investigating the deep Earth interior. Seismic wave velocities depend on the elastic parameters of the structures that they are crossing. Tomography technique involves an input velocity model and calculates travel times for seismic waves propagating through the model. The differences between the observed and the calculated travel times for seismic waves come from seismic phase errors, hypocentre...
location errors, assumed velocity model errors, or, most likely, a combination of the three sources of errors. The precision of earthquake location is closely related to the knowledge of the Earth’s three-dimensional velocity structure.

2. Geotectonic setting of the area
The studied area is characterized by shallow seismic activity of moderate magnitude (ML < 6) with frequent clusters of events. Tectonically, the region is divided into blocks and basins bordered by intra-crustal faults. The major structural features (figure 1) developed in the region are: the Pannonian Basin with a thin subsiding lithosphere (about 60 km) and four Dacitic units (Inner Dacides (ID), Transilvanides (T), Middle Dacides (MD), Marginal Dacides (MaD) and Outer Dacides (OD)) with a thicker lithosphere (100 - 140 km), uplifted by recent orogeny. These structures outcrop in the mountain chains and extend westward under the sedimentary cover of the Pannonian Depression. The newest (Neotectonic) tectogeneses were extensional (syn-rift phase) and compressional (basin inversion) resulting in brittle structures: grabens and horsts, separated by NW-SE oriented faults, affecting both the basement and the sedimentary cover. Two Neogene NW-SE oriented major grabens developed at the basement level of the Pannonian Basin: Sannicolau Mare in the West and Caransebes in the East. These structures, extended in the mountains as small depressions, controlled by Neogene normal faults, with the basement lowered down to over 7 km (at Hungary - Romania border).

![Figure 1. Geotectonic map modified after [2].](image)

3. Data
A large part of input data comes from the recordings obtained during the South Carpathian Project (2009–2011) [3], a successful collaboration between the Institute of Geophysics and Tectonics and of the University of Leeds, the National Institute for Earth Physics (Romania) [4]. An array of 32 broadband seismic stations (10 CMG-40T, 8 CMG-3T and 14 CMG-6TD) was installed across the western part of Romania (spaced at 40 to 50 km intervals). In addition, 25 stations across eastern Hungary and Serbia were considered. P- and S-wave arrivals are identified for all the selected events.
(minimum 7 phases per event with reasonable signal/noise ratio). Thus, during 2009 - 2011, 380 local events were located (figure 2). The final set of data used in the tomographic inversion consists of 8125 station arrivals, from the 380 events with 4650 P-wave arrivals and 3475 S-wave arrivals.

![Figure 2](image.png)

**Figure 2.** Data used in the study were provided by seismic stations from Romanian National Seismic Network, South Carpathian Project and from the neighbouring seismic stations from ISC bulletins (black dots for seismic events and red triangles for seismic stations).

### 3.1. Inversion method

3D tomographic inversion is performed with the LOTOS-09 code [1] which performs the simultaneous inversion of the P and S velocity structures and source coordinates (figure 3). The algorithm can be applied to different sets of local earthquake data without complicated parameterization.

![Figure 3](image.png)

**Figure 3.** General structure of the LOTOS code. Orange blocks indicate the main program steps. Green block is the main input data; blue block contains free parameters defined by user; yellow block is the output data

The calculations start with two data files (green block): coordinates of the stations and arrival times of P and S seismic rays from local earthquakes to these stations. Additional information such as starting
velocity model, parameters of grid and inversion and others are defined in a separate file (blue block). The algorithm contains the following general steps:

1. Simultaneous optimization for the best 1D velocity model and preliminary location of sources;
2. Location of sources in the 3D velocity model;
3. Simultaneous inversion for the source parameters and velocity model using several parameterization grids.

Steps 2 and 3 are repeated in turn one after another in several iterations.

Ray paths show a good coverage on the western and south-western of the area and are constructed for a horizontal section and 3 vertical sections (figure 4).

Figure 4. Ray paths in the map view (left) and cross sections (right) shown by grey dots. Blue triangles are the seismic stations. Black points are the relocated events.

3.2. 1D model optimization

Data processing begins with preliminary source location and optimization of the 1D velocity model (figure 5 (A)). To evaluate the robustness of this procedure, we performed a series of tests (figure 5 (B)) with the observed data.

| Model description | RMS of P residuals, 1 iteration (s) | RMS of S residuals, 1 iteration (s) | RMS of P residuals, 5 iteration (s) | RMS of S residuals, 5 iteration (s) |
|-------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Model1            | 0.6974125                         | 1.083473                          | 0.6356978                         | 0.8631554                         |
| Model2            | 0.7534613                         | 2.010110                          | 0.7621431                         | 1.588148                          |
| Model3            | 1.154611                          | 1.246248                          | 0.9104431                         | 0.9805374                         |
| Model4            | 0.7914473                         | 1.261914                          | 0.7176021                         | 1.004341                          |
| Model5            | 0.7053562                         | 1.067389                          | 0.6353154                         | 0.8597891                         |
The 1D model that explains best the observed data was determined by testing different starting velocity models. Each of the five models tested was based on literature information (iaspei91 model, [5-7]). RMS residuals values after 1D optimization for all the velocity models tested are shown in Table 1. The Vp / Vs ratio = 1.74 for the investigated region was determined from the Wadati diagram using data from Romanian Seismic Network.

Analysing P and S residuals, we can conclude that the most probable 1D distribution for the western and south-western Romania region corresponds to the Model 5 presented in Table 2.

Table 2. P and S Velocities in the Reference 1D model after optimization

| Depth (km) | Vp (km/s) | Vs (km/s) |
|------------|-----------|-----------|
| 0          | 5.33      | 3.05      |
| 5          | 5.69      | 3.25      |
| 10         | 6.05      | 3.53      |
| 15         | 6.31      | 3.73      |
| 20         | 6.56      | 3.86      |
| 25         | 6.87      | 3.96      |
| 30         | 7.22      | 4.08      |
| 35         | 7.53      | 4.24      |
| 40         | 7.84      | 4.42      |
| 45         | 8.13      | 4.62      |
| 50         | 8.29      | 4.63      |
| 55         | 8.02      | 4.60      |
| 60         | 8.01      | 4.60      |

Model 5.

4. Results
In all cases, the inversion was performed in five iterations, a compromise between the calculation time and the quality of the solution (reduction of the non-linear effect). Figures 6-7 show the results for the P and S anomalies in four horizontal and three vertical sections corresponding to the Vp-Vs inversion scheme. In the first section are marked the vertical sections (black lines), the important faults in the region (dotted lines) and thermal water areas (green circles). The figures also show the locations of the
sources for each section. These anomalies and their possible interpretation are discussed in detail in the conclusions section.

**Figure 6.** Horizontal sections of P and S wave velocity anomalies, in percent with respect to the optimized 1D velocity model. Dots depict the relocated sources around the corresponding depth levels. The vertical profiles and thermal water areas are marked in the first section.
4.1. Testing the results

4.1.1. Test based on observed data

Residuals examination after inversion shows that the data set used in this study is quite noisy. The contribution of the noise in the final result can be estimated using the "odd /even test". The inversion procedure is the same as that used to obtain the main results (figures 6-7) and includes the optimization step of the 1D model. The 1D model distributions for odd and even subsets are shown in figure 5 (B). It can be noticed that there are no differences between the velocity models obtained after the test. The results of P and S wave’s anomalies for the two subsets are shown in horizontal sections in figure 8.

Figure 7. Vertical sections of P and S wave velocities anomalies. The locations of the profiles are shown in figure 7. Dot depicts show the relocated sources at distances less than 40 km from the profile.

Figure 8. Odd / even test. P and S wave anomalies for two half-subsets of the data. Dot depicts are the relocated sources.
4.1.2. Synthetic test

To assess the spatial resolution of the model, synthetic tests were performed using the standard "checkerboard" input model with alternating positive and negative velocity variation patterns. When performing synthetic modelling, it is important that the simulations are done in a manner as close to observed data processing. Synthetic modelling follows:

(1) assessing the spatial resolution of the model;
(2) determination of the optimum values for free inversion parameters (damping coefficients, confidence level for source parameters and station corrections, number of iterations, etc.);
(3) estimating the real amplitudes of the anomalies;
(4) building a model that shows the best fit with real observations.

To obtain the best values of the inversion parameters, several tests with synthetic and observed data were performed.

The lateral dimension of the checkerboard input model is 40 km along the latitude and longitude. The anomaly amplitudes were ±7% for the P and S models respectively. The reconstructed images for the P and S anomalies in the checkerboard test are shown in figure 10 in horizontal sections.

Figure 9. Checkerboard test performed according “Vp-Vs” scheme in horizontal sections
It is noted that periodic anomalies are generally reconstructed in the central part of the investigated area, where earthquakes occur.

5. Conclusions
Ray paths coverage (figure 4) shows that the best tomographic resolution for the western and south-western region of Romania is obtained up to 10 km depths. In the horizontal sections (figure 6, horizontal sections 5-10 km deep) there are several of alternations between the high velocity (blue) and the slow areas (orange). They develop in groups forming small zones NE-SW elongated. In figure 10 are presented the important fault systems from the investigated area. One of them is located in the southern part of the region and can be correlated with two active fault systems, Cerna – Jiu (FCJ) and Oravita-Moldova Noua (FOMN), respectively. The other one is located in the north, between Banloc and Buzias (FBB), and develop along the tectonic contact between Transilvanides and Median Dacides (figure 10).

**Figure 10.** Correlation of the velocity anomalies with geotectonic units and fault systems in the investigated area.

At the Romania-Hungary border there is another positive anomaly, elongated also towards NE-SW (Inner Dacides structures) and with some apparent maxims located within the local neostructures. These high velocity areas seem to be well correlated with active tectonic and associated seismicity and Cretaceous cold and compact magmatic plutons (“banatite”). The contrasts between the anomalies areas correlated with magmatic bodies can signify the existence of vertical trans-crustal faults visible in the vertical sections (figure 7). The negative anomalies develop in a large area elongated NW-SE, between the Apuseni Mountains in North and the Moesian Basin in the South and could be associated with the Neogene volcanites from the South of the Apuseni Mountains, fractured volumes with massive infiltrations of fluids on the faults systems which controlled the magmatic processes and which may still be favourable to fluids flow (the presence of many regions with thermal waters, figures 6, 10). On the other hand, the region of negative anomalies oriented from NW to SE direction can be related to the positive movements from the Southern Carpathians and the Apuseni Mountains, as compared to the subsidence from western part of the region. In this context it is observed that a delimitation on the NW-SE direction that appears somehow discontinuous, but seems to reflect the existence of a structural element between the two types of positive and negative anomalies, a delimitation which in the north of the region correlates with a fault that starts from the Siria area (Zărând-Lugoj line, FLZ) and enters the Timiş-Cerna corridor, in the Herculane area being able to intersect with Cerna-Jiu fault (FCJ). Historical
seismicity (Mw>=5.0) looks like it is associated the positive anomalies (e.g., Banloc, Moldova Noua, Baile Herculane, Northern Banat). Interesting, the seismicity shows a change of seismic regime: an active area to SE (at the Cerna - Jiu fault) and an active part to the NW (at the Buzias - Banloc fault), seismicity between them being less.

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