CRUSTAL MODELS ASSESSMENT IN WESTERN PART OF ROMANIA EMPLOYING ACTIVE SEISMIC AND SEISMOLOGIC METHODS

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Abstract. In the years 1999 - 2001 two regional seismic refraction lines were performed within a close cooperation with German partners from University of Karlsruhe. The western part of the line Vrancea 2001, with 420 km total length, crosses part of the Transylvanian Basin. The structure of the crust along the seismic line revealed a very complicated crustal structure beginning with Eastern Carpathians and continuing in the Transylvanian Basin until Medias. As a result of the development of the National Seismic Network in the last ten years, more than 100 permanent broadband stations are now continuously operating in Romania. Complementary to this national dataset, maintained and developed in the National Institute for Earth Physics, new data emerged from the temporary seismologic networks established during the joint projects with European partners in the last decades. The data gathered so far is valuable both for seismology purposes and crustal structure studies, especially for the western part of the country, where this kind of data were sparse until now. Between 2009 and 2011, a new reference model for the Earth's crust and mantle of the European Plate was defined through the NERIES project – *EPCrust* - from existing data and models.

Although the present dataset has its origins in several periods over the last 50 years, the results are made homogeneous and they improve and strengthen our image about the depth of the principal boundaries in the crust. In the last chapter two maps regarding these boundaries are constructed, one for mid-crustal boundary and one for Moho. They were build considering all the punctual information available from different sources in active seismic and seismology which are introduced in the general maps from *EPCrust* project for Romania. The depths maps in the study region are presented with all their regional peculiarities as they appear, projected on the local tectonic structure for the area under examination. The database gathered from different kind of measurements in Transylvanian Basin and eastern Pannonian Basin were included in *EPCrust* and an improved and upgraded model of the Earth crust emerged for Romania.

Keywords: crustal models; active seismic methods; Green functions; receiver functions; map with Moho depth.

1. INTRODUCTION

Tectonic of Romania includes both pre-alpine platforms and Alpine orogenic structures. The pre-alpine platforms are: Eastern European Platform, with its western margin in Romania - Moldavian platform; Scythian platform; Moesian platform. The Alpine Orogeny includes Carpathian Orogen and North Dobrogean

Orogen, plus foredeep area in front of the Carpathians, as well as the Transylvanian Basin and Pannonian Basin [1]. In this study we will focus on the western part of Romania. Following is a description of the main tectonic units in this area.

Transylvanian Basin is a back-arc basin with a Paleogene - Neogene cover with different degrees of deformation. The basement of the basin is of Carpathian type and comprises a series of uneven blocks separated by faults, some with crustal character. The general orientation of these faults is NNW- SSE. The area is more subsided in Târnave Depression where sediment thickness reaches 10 km. Compared to other tectonic units Romanian, Transylvanian Depression has weaker seismogene potential, with some events in the west and south-west.

Apuseni Mountains are part of the Carpathian Orogen and they consist of a canvas of basement thrusts and nappes, formed during the compressional stages, which started in Cretaceous and was completed in Pleistocene. Contact between some of the thrusts units proved to be seismogenic. In addition to the localized subcrustal seismicity in the Vrancea Seismic Zone, Carpathian Orogen hosts crustal seismicity in Baia Mare, the crustal Vrancea zone, Fagara□ - Sinaia and the Danubian zone - the bend of the Southern Carpathians.

Eastern Pannonian Basin is a depression in Romania's western margin. Neogene filling of the basin covers an uneven block system consisting of Carpathian origin basement in the east and Pannonian origin in the west. Neotectonic activity manifested on the eastern edge of the basin is materialized by crustal seismicity in Banat and Cri□ana zones.

2. CRUSTAL STRUCTURE ASSESSMENTS IN WESTERN PART OF ROMANIA

2.1 Deep seismic sounding on a fan shooting in north-western part of Romania

The first attempts towards the crustal structure assessments were made in 1966 by the Applied Geophysics Institute in a cross-border cooperation with scientists from Hungary and were reported in [2].

Seismic waves were generated in Hungary, near the north-western part of Romania, on an alignment parallel to the border, by explosions in boreholes with loads up to 1500 kg. Four recording devices geophones of 10 Hz were employed, providing a total length of 1180 m recording device, for seismic surveys in the area Jibou - Baia Mare. The result was a large fan shooting in which the Moho depth was located at half the distance between the explosion point (in Hungary) and the recording array in north-western Romania [2].

To calculate the Moho depth on the base of reflected waves, the classic formula used in the equation hodograph for these waves was employed, where horizontal reflecting limit covered by a homogeneous medium was used, characterized by seismic speed V_m. In a second attempt, assuming that the recorded waves are actually refracted frontal waves, formed on the surface of the Moho, the depth was computed as resulting from the hodograph of a refracted wave on a horizontal surface, after [2].

2.2   Deep seismic sounding on a profile in northern part of Apuseni Mountains, Cluj Napoca – Oradea

In the years 1973 – 1974, seismic researches were carried out on a profile Cluj-Napoca - Huedin - Oradea (GT XI in Figure 1) by a group of the Applied Geophysics Institute. Seismic refraction method was applied along Cri□ Valley on a Cri□ - north Bor□ profile (65 km). For the rest of the region the information was obtained from a series of punctual seismic surveys, with circular recording devices, which has the advantage of determining the spatial elements of the reflecting limit. Filling out the profile in the western part of the seismic profile was done using an explosive charge at Nagyrábé (Hungary), located about 35 km from the Romanian/Hungarian border.

The structure of the crust obtained by continue seismic surveys and punctual seismic recording summarizes the results from the northern part of the Apuseni Mountains, in fact the north-west part of the regional crustal profile XI in Romania after [3].

It should be stressed that comparing the data with crustal thickness determined in other areas belonging to Carpathian Orogeny [4], the Apuseni Mountains shows unusually reduced crustal depths. This bring up the hypothesis according to which these mountains represent in the Carpathian geosyncline zone, an area with an independent tectonic crustal structure with low crustal depths, compared to other areas belonging to Carpathian Orogeny.

Both set of results are added to the database of the Moho depth in western part of Romania.

2.3 Moho depths from the regional seismic refraction profile VRANCEA 2001

In order to study the lithospheric structure in Romania, a 450 km long WNW – ESE trending seismic refraction profile was carried out in August/September 2001; it runs from the Transylvanian Basin, across the Eastern Carpathians and the Vrancea seismic region, to the foreland areas with the very deep Neogene Foc□ani Basin and the North Dobrogean Orogen, near the Black Sea. From Aiud town in Transylvania to Tulcea, in northern Dobrogea [5] (see Figure 1).

A total of ten shots with charge sizes of 300 - 1500 kg were recorded by over 700 geophones. The data quality of the experiment was variable, depending primarily on charge size but also on local geological conditions. The data interpretation indicates a multi-layered structure with variable thicknesses and velocities. The sedimentary stack comprises up to 7 layers with seismic velocities of 2.0 - 5.9 km/s. It reaches a maximum thickness of about 22 km within the Foc□ani Basin area. The sedimentary succession is composed of (1) the Carpathian nappe pile, (2) the post-collisional Neogene Transylvanian Basin, which covers the local Late Cretaceous to Paleogene Târnava Basin, (3) the Neogene Foc□ani Basin in the foredeep area, which covers autochthonous Mesozoic and Palaeozoic sedimentary rocks as well as a probably Permo-Triassic graben structure of the Moesian Platform, and (4) the Palaeozoic and Mesozoic rocks of the North Dobrogean Orogen.
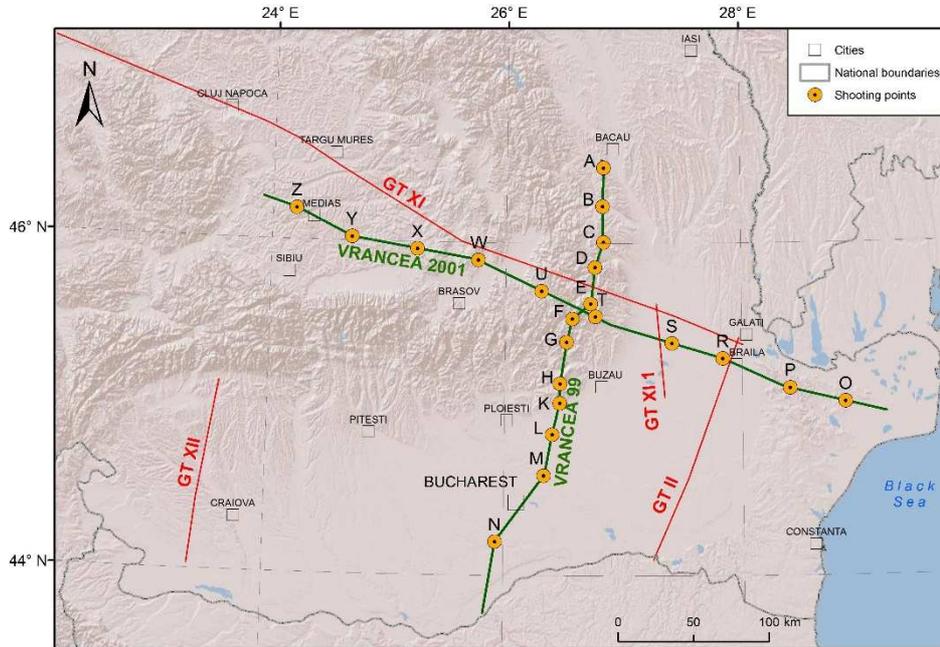
Figure 1. Topographic map showing the VRANCEA2001 seismic line in green (shotpoints O – Z), as well as older parallel or transecting refraction and reflection lines with thin red lines, e.g GT XI = geo-traverse XI.

The underlying crystalline crust shows considerable thickness variations in total as well as in its individual subdivisions, which correlate well with the Tisza-Dacia, Moesian and North Dobrogean crustal blocks. The lateral velocity structure of theses blocks along the seismic line remains constant with about 6.0 km/s along the basement top and 7.0 km/s above the Moho. The Tisza-Dacia block is about 33 to 37 km thick and shows low velocity zones in its uppermost 15 km, which are presumably due to basement thrusts imbricated with sedimentary successions related to the Carpathian Orogen. The crystalline crust of Moesia does not exceed 25 km and is covered by up to 22 km of sedimentary rocks. The North Dobrogea crust reaches a thickness of about 44 km and is probably composed of thick Eastern European crust overthrusted by a thin 1 - 2 km thick wedge of the North Dobrogean Orogen.

A crustal model based on P-wave arrivals is performed and then interpretated in structural terms in Figure 2, after [5].
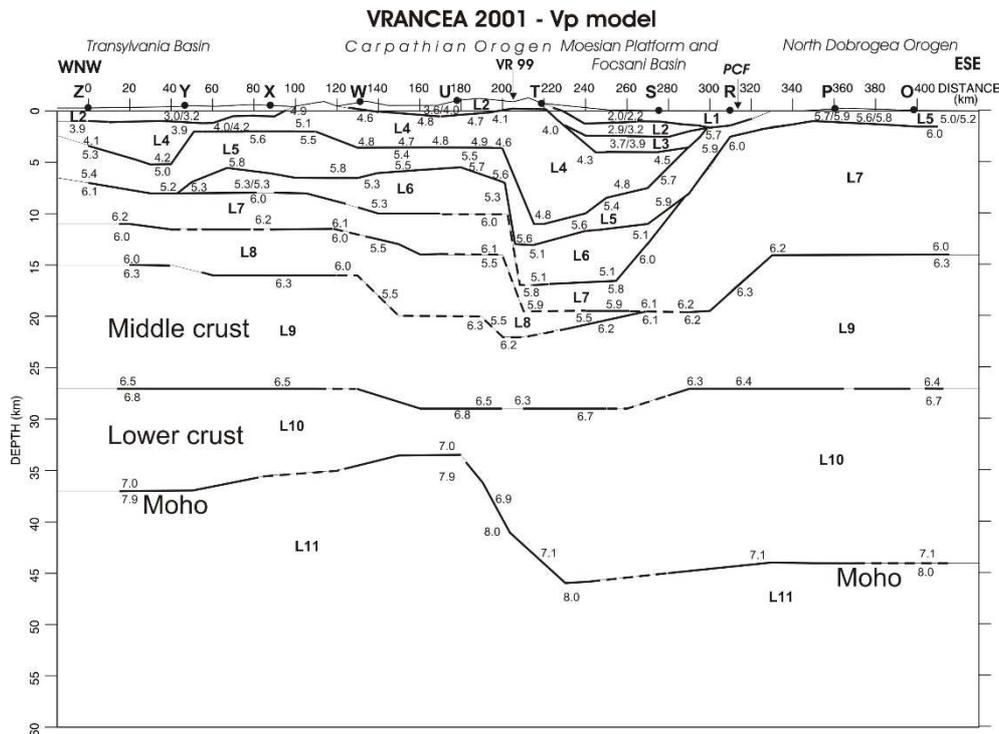
Figure 2. Simplified interpreted cross-section from the 2D seismic model along the main VRANCEA2001 seismic refraction line, between the Transylvanian Basin and the Black Sea. The upper crustal geological structures of the Tisza-Dacia and the Moesian crustal blocks are transverse to the section. The part of the cross section in Transylvanian Basin is from shotpoint Z – W.

2.4 Models of crustal structure at the principal seismic stations located in western part of Romania

At the basis of the seismic stations' crust models presented below were the available data: the Vrancea 2001 seismic refraction profiles, the data provided by the European model EuCRUST 07 [6], seismic reflection profiles in the vicinity of sites, geological sections and maps, maps at the crystalline basement, data on the distribution of seismic velocities derived from active seismic data, borehole seismic recordings, etc.

The models consist of successive layers having longitudinal wave (Vp) and transverse wave (Vs) seismic velocities on the interfaces separating them. The velocities can be constant within the layer, or rising in the depth. With the exception of sites located along or adjacent to seismic profiles, the seismic velocity data is retrieved by extrapolation from areas close to measurements, or established by assigning similar values for similar formats at comparable depths.

In Table 1, besides the Moho depths determined from the data and maps, the next column presents the depths at Moho* calculated by the receiver function method at the same station (location). From the comparison of the 2 columns, the values show differences in the range of 1 - 2 km, which is under the magnitude of the errors of

determination in both methods. In this way, the results from the two columns support each other and we can give a high degree of confidence to the depth values determined by the receiver function method. The exception is the Gura Zlata station with 41 km Moho depth determined by the interpretation of the classical methods and 36 km Moho* depth, determined by the receiver function method. It is possible that, due to local tectonics, the receptor function method provides lower values over Carpathian Orogeny. The same effect was observed over the mountains and discussed in [7].

Table 1. Broadband stations and accelerometer stations in Transylvania and western part of Romania. Moho* depth – computed from receptor functions method at the same location.

Seismic station	Lat. (^{0}N)	Long. (^{0}E)	h (m)	Midcrust boundary (km)	Moho depth (km)	Moho* depth (km)	Locality
BANR	45.382	21.135	80	21	28.5		Banloc
BMR	47.67	23.49	227	20	31	*30*	Baia Mare
BZS	45.616	21.616	260	22	31	*29*	Buzia☐
DEV	45.88	22.89	249	24	34	*33*	Deva
DOP	45.967	26.388	526	20	36		Dopca
DRG	46.791	22.711	923	23	31	*32.5*	Drăganul
GZR	45.393	22.776	850	27	41	*36*	Gura Zlata
MED	46.149	24.376	428	26	38		Media☐
OZUR	46.095	25.786	674	28	33.5		Ozunca Băi
SIBR	45.81	24.17	463	26	38		Sibiu
TIM	45.736	21.220	134	21	29		Timi☐oara
SIRR	46.265	21.655	495	21	29	*28*	Şiria

3. MODERN METHODS USED TO ASSESS THE MOHO DEPTH - JOINT INVERSION OF DISPERSION CURVES AND RECEIVER FUNCTIONS

A joint inversion method of receiver function and Rayleigh wave dispersion was employed in order to derive the 1D seismic velocity models for several seismic station locations in western part of Romania. The study uses new data emerged from permanent network of broadband stations in Romania, as well as data from temporary networks established during the joint projects with European partners in the last decades. Such a joint project between University of Leeds, UK and National Institute for Earth Physics (NIEP), Romania (South Carpathian Project-SCP), deployed 33 broadband seismic stations autonomously operated in an area covering the western part of the country and which continuously provided data for two years (2009 - 2011).

The first results of the crustal structure obtained employing this method were presented by [8] and [9], show a thin crust for stations located in the eastern part of Pannonian Basin (28-30 km). In the Apuseni Mountains, the Moho discontinuity can be found between 31 - 33 km depth. The stations within the Southern Carpathians are characterized by deeper crustal depths of about 32-36 km. 2D models of the variation of the seismic velocity in depth are presented by along 3 lines crossing the western part of Romania. The Moho boundary coincide generally with the isoline of seismic transverse velocity of about 3.80 – 3.85 km/s.

Some punctual values of the Moho depth were obtained and projected on the map from Figure 3 on the sites of the temporary seismic network (SCP) or on the seismic stations operated by NIEP.

The blue dots in Figure 3 are the locations with computed Moho depths and they represent the first attempts of deciphering the crustal structure in the NW Romania by geophysical methods. Although the methods are really classic, we consider that the results are validated by the two methods employed by [2] to derive the Moho depth. The yellow dots are described in chapter 2.2, and they represent the Moho depth from the seismic profile Cluj Napoca – Oradea, which runs from the middle of Transylvanian Basin to the west, near the border, crossing the northern part of Apuseni Mountains (Figure 3).
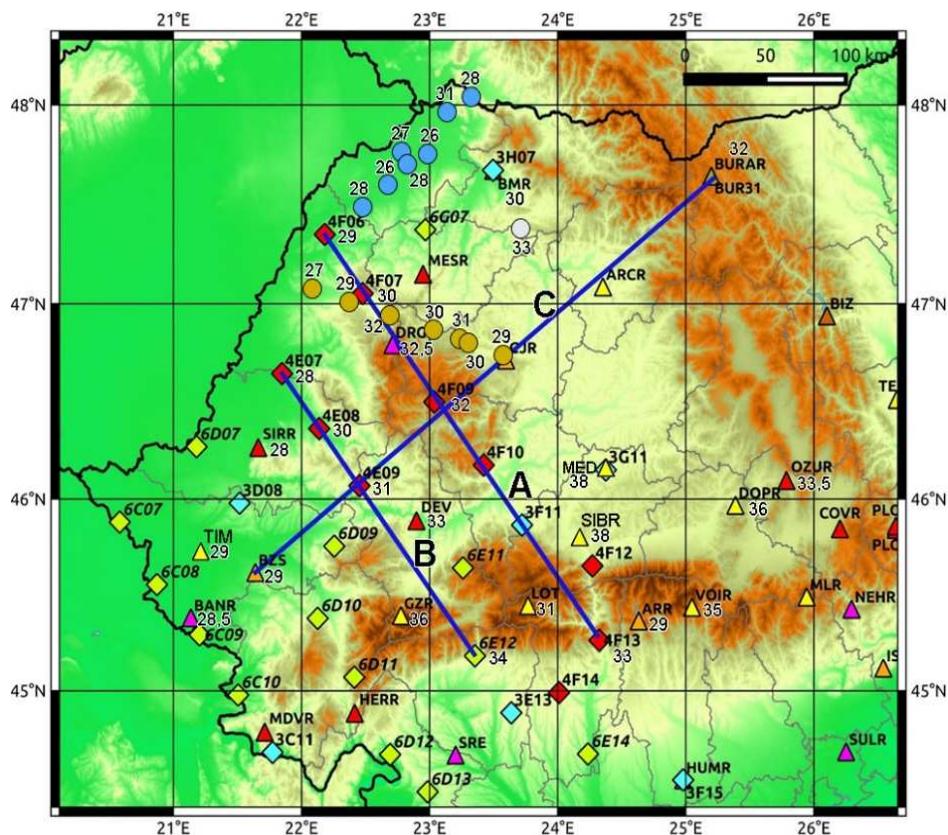

Figure 3. Punctual depth to Moho according to first deep seismic surveys in XX century: the blue dots are compiled from [2]; the yellow dots are represented on the profile Cluj Napoca-Oradea [3]. The triangles are seismic station (NIEP) and the rhombs are the temporary seismic network (SCP) at which the depth to Moho is computed with the new method of joint inversion of dispersion curves and receiver functions in [8] and [9]. The values near triangles or dots are the computed Moho depths.

In Figure 4A the profile *A* is represented through the temporary seismic stations 4F03 – 4F13, which is crossing an important section of Pannonian basin from

north-west to south-east, the contact with Apuseni Mountains and crossing even the Southern Carpathians, with the stations LOT and 4F13 (see Figure 3). The Moho depth is at about 29-30 km in the west, then a section with reduced velocities of 27-28 km. In the central part of Apuseni Mountains (DRGR). The Moho is at 31-32 km depth followed by a flat section and decreasing to 33 km depth near the station 4F13, in the Southern Carpathians.

The other two depth profiles to Moho represented in Figure 4B: **B.** 4E07 – 6E12 and Figure 4C: **C.** BZS – BURAR are computed first by [8].
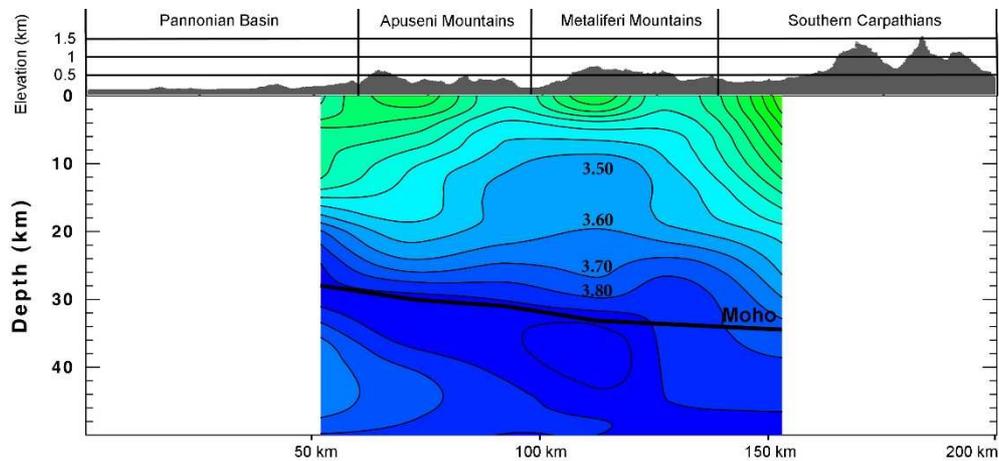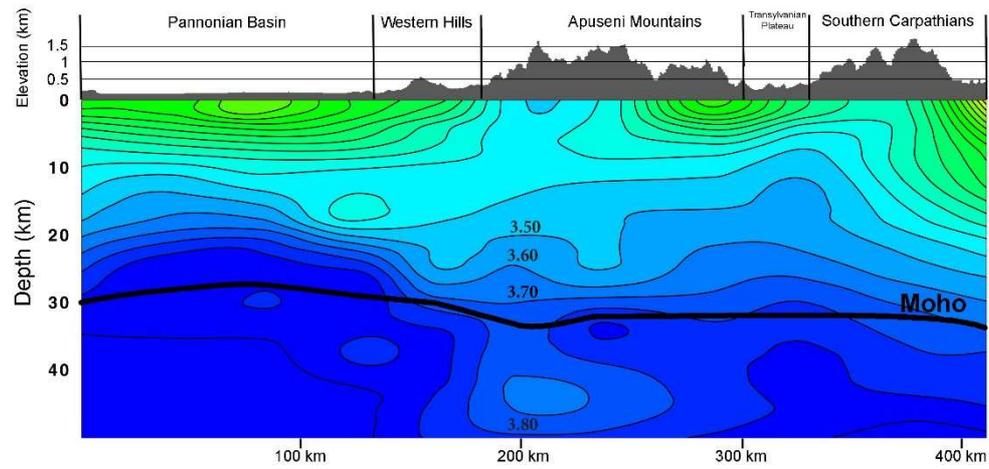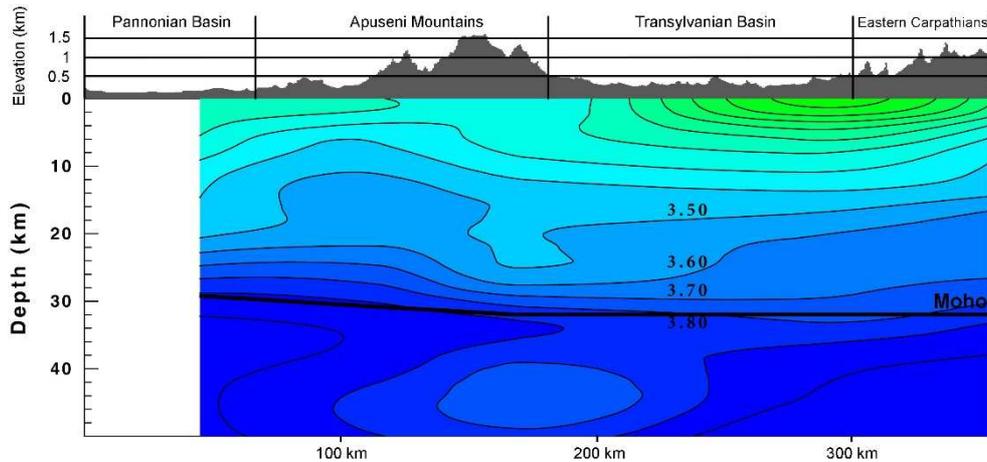
Figure 4. Composite profiles with continuous distribution of V_S velocity (transverse waves) in depth and position of Moho boundary: A. profile 4F03 – 4F13; B. profile 4E07 – 6E12; C. profile BZS – BURAR. The Moho boundary is represented from joint inversion of Green functions and receptor functions.

4. NEW REFERENCE MODEL FOR THE EARTH'S CRUST OF THE EUROPEAN PLATE

Within the Network of Research Infrastructures for European Seismology (NERIES), European Union Research Project 'JRA1' which aims at defining a unified reference Earth model for the European region, twenty of the most popular existing global models are being reviewed (http://www.neries-eu.org)

Even if the reason for the existence of such diversity of models is easy to be understood - having in mind the different data sets used, degree of details as well as various models and imaging techniques - it makes difficult choosing a model as input for other studies or just as a comparison.

EPCrust is a new reference model for the earth's crust and mantle of the European Plate that was defined through the NERIES project from existing data [10] and [11].

The model covers the whole European Plate from North Africa to the North Pole (20°N–90°N) and from the Mid-Atlantic Ridge to the Urals (40°W–70°E). The chosen parameters represent the crust in three layers (sediments, upper crust and lower crust), and describes the 3-D geometry of the interfaces and seismic relevant parameters—isotropic P- and S-wave velocity, plus density—with a resolution of $0.5° \times 0.5°$ on a geographical latitude–longitude grid [11].

P-wave velocity is obtained from merging the different existing V_P models and S-wave speed and density are derived from scaling relations with respect to V_P derived from a Nafe-Drake curve regression [12]. In the upper and lower crust, most of the original information about V_P derives from CRUST2.0 [13] and EuCRUST-07 [6]. To include point determinations, such as Moho depth from receiver functions, a surface with a grid resolution of $0.1° \times 0.1°$ was created covering all the data available, and interpolates values between data points. The

distribution format is based on the TomoJSON data exchange format described by [14].

4.1 Improved models of crustal structure in the north-western part of Romania

The approach of the present paper was to combine *a priori* information, collecting and amalgamating reliable, although scattered, information about the crust attempting to retain the best from each constituent and render it with a uniform representation. In this scope all the original maps were georeferentiated and 1D and 2D crustal models were added to a database.

The crustal model (EPcrust) derives from a compilation of existing information: large-scale overlapping with high-resolution local models, receiver functions point determination, active seismic profiles.

The database gathered from different kind of seismic and seismological measurements in Transylvanian Basin and eastern Pannonian Basin, presented in the paper, were included in this EPCrust model and an improved and upgraded model of the Earth crust emerged for western part of Romania. Figures 5 and 6 present maps obtained based on our completed dataset for both interfaces – mid-crustal and Moho boundary.
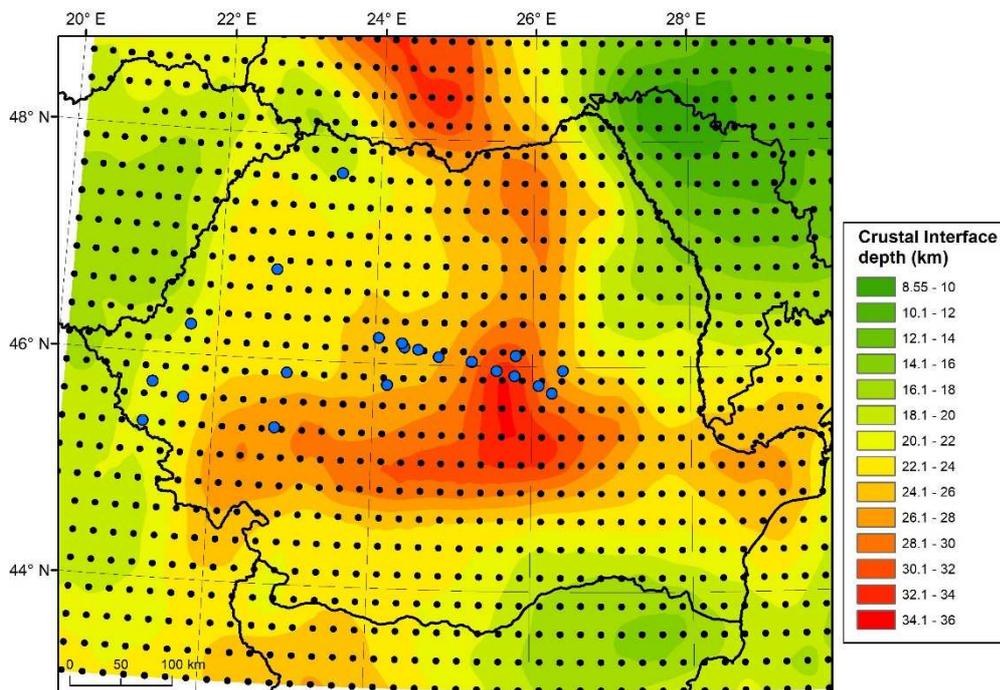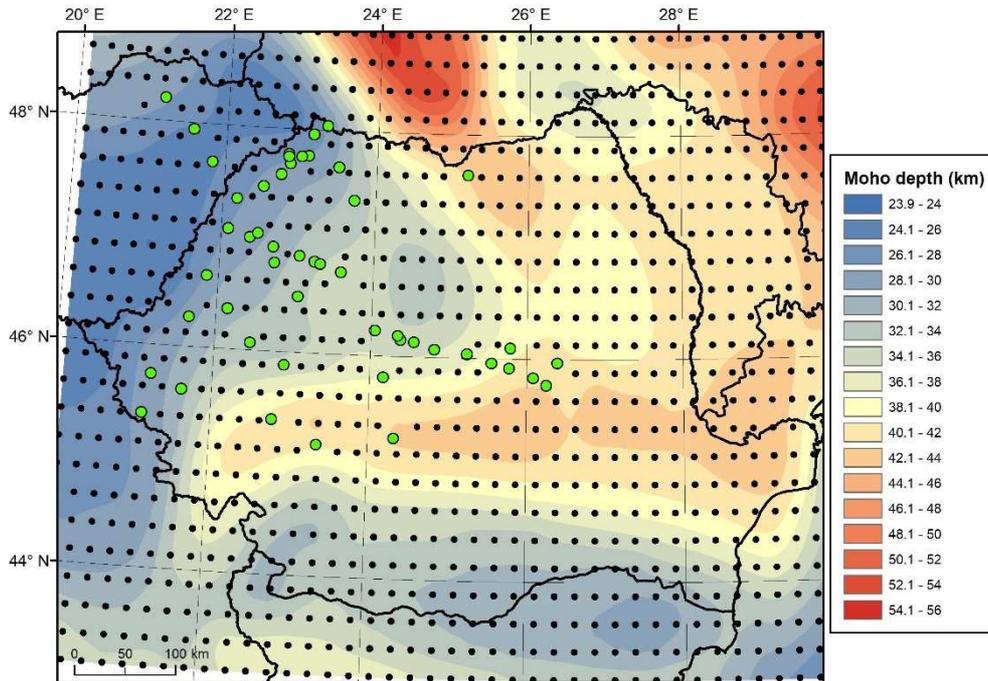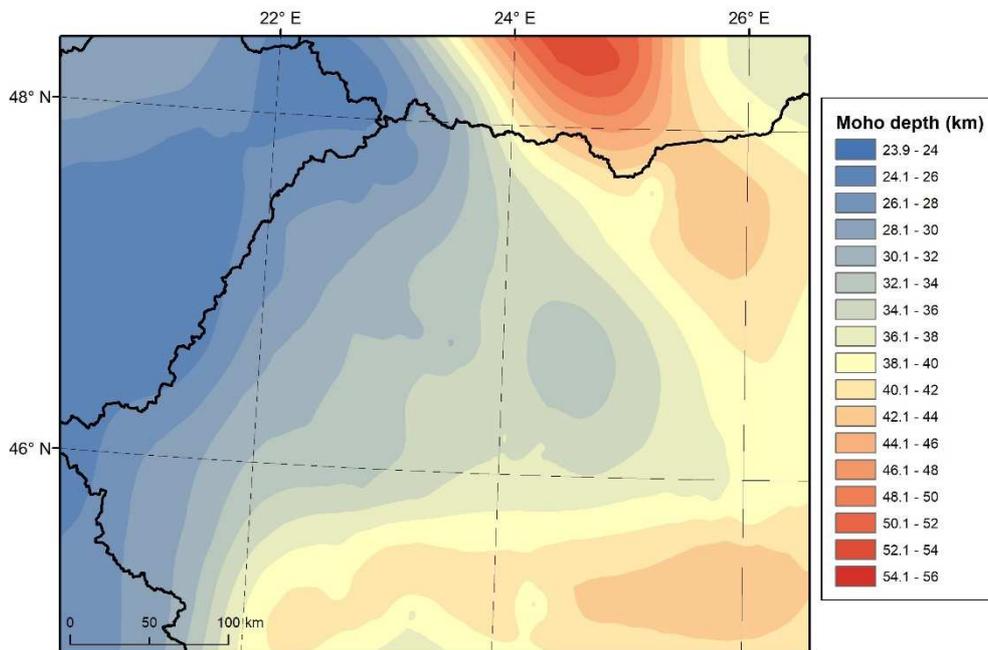

A.
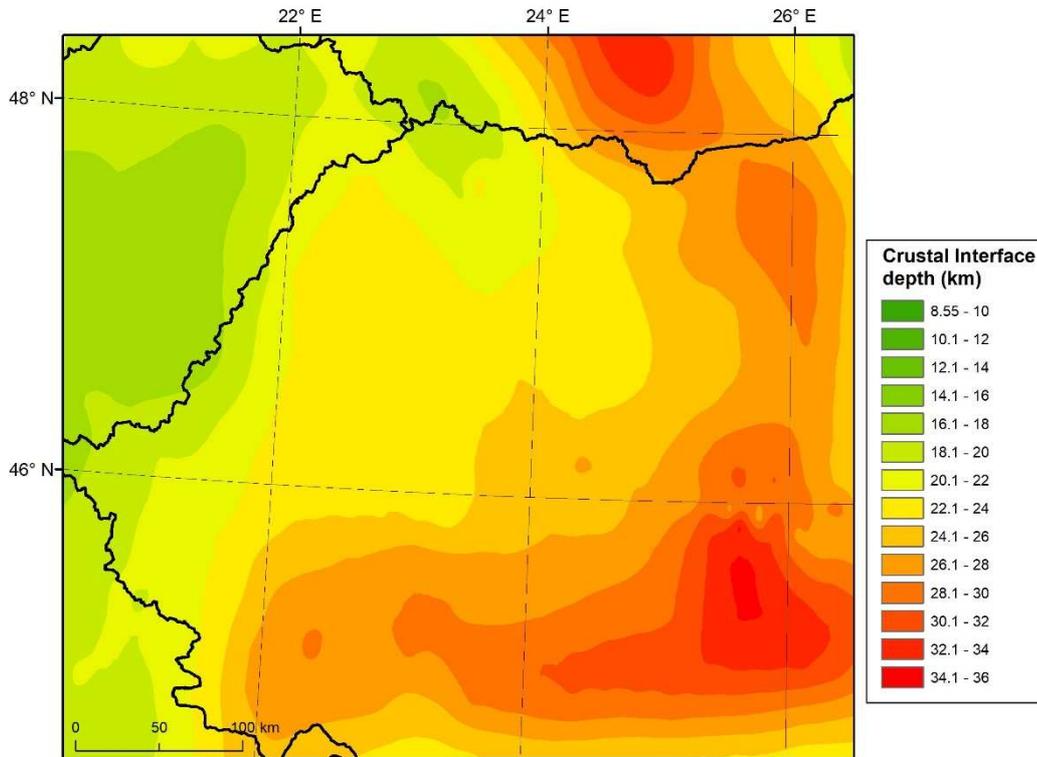
B.

Figure 5. A. Mid-crustal interface depth in western part of Romania, base grid after *EPCrust*. Blue points are added from the database from different seismic and seismological sources. B. Improved model of the mid-crustal interface after introducing the new points in the base grid.

Maps were generated through kriging interpolation (ordinary method, spherical semi-variogram model and 12 points search radius - default settings within ArcGIS, providing stable results). The points that were used for interpolation belong to the two different datasets: the first was the grid provided for EPCrust reference model [11]; the second dataset was obtained in our research and it was superimposed on the first one, from which we removed points within a 10 km radius of the second dataset. The method was chosen in order to be as close as possible to the original procedure given by [11].

Although the new obtained dataset has its origins in several periods over the last 50 years, the results are homogeneous and they improve and strengthen our image about the depth of the principal boundaries in the crust.

A.

B.

Figure 6. A. Moho depth in western part of Romania, base grid after *EPCrust*. Green points
 are added from the database recorded from different seismic and seismological sources.
B. Improved model of the Moho boundary after introducing the new points in the base grid.
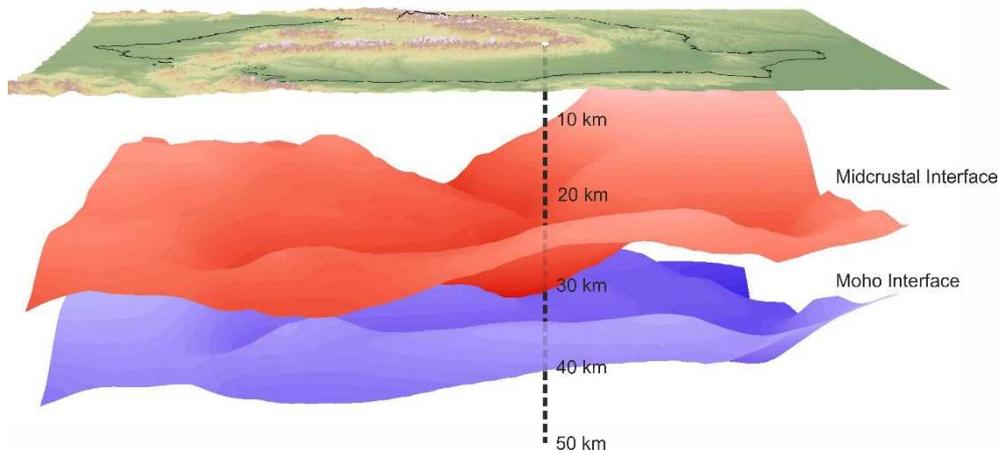
Figure 7. 3D crustal model in Romania including midcrustal interface and Moho boundary,
after the maps in Figures 5 and 6.

The mid-crustal interface is not changed much from the model EPCrust due to the
fact that only few new points were added from sources that we have mentioned
(Figure 5A) to the model computed in Figure 5B, mainly in the central part of
Transylvanian Basin. Improvements can be seen on the Moho depth model,
especially under Apuseni Mts., as well as in the western Pannonian basin (Figure 6
A and B).

In the Figure 7, both maps from Figures 5 and 6 are represented in a 3D model, in
which we can see that the principal crustal boundaries are having zones in which
their evolution in depth is similar, but there are other zones in which their evolution
is different, as it is in the north-eastern part of Romania, in Moldavian Platform.
We must consider also the exaggeration of the vertical scale.

5. CONCLUSIONS

Deep seismic surveys using classic methods were performed in the last part of XX
century in the north-western part of Romania, as well as a seismic refraction
regional line (GT XI) which crosses the entire Transylvanian Basin from Eastern
Carpathians to the Romanian/Hungarian border (Figure 1).

All the data from these surveys were geo-referenced and added to a database with
Moho depth in Romania. Models of crustal structure compiled based on
geophysical methods at the principal seismic stations located in western part of
Romania were also added to this database.

The models of the crustal structure obtained by joint inversion of dispersion curves
and receiver functions are presented and described in [8]. They are represented by
1D models dispersed on the map of seismic stations from one seismic network
(NIEP) and one temporary seismic network (SCP). They are added to the database,

being the new contribution to the crustal structure obtained in different national projects in the last years.

For Romania, last general model of the crustal structure is presented in the last chapter and it is relying on all the available data existing at that moment. Basically, it is a compilation of data from old and new seismic refraction data, deep seismic reflection data and seismology data recorded by the broadband stations belonging to the Romanian seismic network. It also takes into account the previous compiled Moho maps sketched for the south-eastern half of Romania using also previous 1D and 2D crustal models, as well as data provided by the Vrancea 2001 seismic refraction experiment [5] (Figure 2).

The EPCrust model, which was available in digital form after [11] and later improved by [15], constitute the general grid on which the new points, described in the database, were added in order to obtain an improved and upgrade image of the crustal structure for the western part of Romania.

The obtained crustal models are presented in Figure 5 for midcrustal interface and in Figure 6 for Moho discontinuity. The midcrustal interface is not changed much by the introduction of new rather few points, because they were almost the same values as in the original map.

As for the Moho discontinuity, some inflexion on the isolines of the depth can be seen in the Pannonian Basin (near the border) and also on the Apuseni Mts., but there is no circle of maximum depth here. The image of the Moho depth in Transylvania have the same generally features as the map presented by [6]. There are however some differences noted especially in the Pannonian Basin (Romanian sector).

Deep seismic survey data in Pannonian basin made on both sides of the Romanian-Hungarian border shows a thinning crust to the west. Structural map at Moho boundary shows decreasing thickness of the crust from ~35 km south of Timisoara, to ~30 km in Arad area and ~27,5 km near Oradea. The upper crustal layer has normal thickness of about 17-19 km and the lower crust is about 5-8 km thick. Active fault systems of differential motion occur between the different blocks, which eventually became grabens and horsts.

However, the new data obtained by receiver functions show that depths to Moho of 26- 28 km might exist in the north-western corner of Pannonian Basin. They are consistent with the Moho depth map obtained by [16] in north-eastern Hungary and based on the CELEBRATION 2000 seismic data.

In the research region the crustal earthquakes are commonly small to moderate ($M_w < 6$). The crustal seismicity is generally associated with the basement fracture systems [17] and [18].

In this new proposed model of the crust there were selected regional and local models, derived from active seismic experiments, surface-wave studies, noise correlation, receiver functions. Because of its characteristics, the new crustal model is most suited for use at the regional scale for a variety of research topics, including: wave propagation modeling at continental scale, crustal correction in tomography, regional gravity studies.

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