*Romanian Reports in Physics, Vol. 64, No. 2, P. 539–554, 2012*

# CRUSTAL MODELS IN ROMANIA – I. MOESIAN PLATFORM

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*Received July 26, 2011*

*Abstract.* A set of crustal data collected in the last decades across the Moesian platform are processed in order to derive a crustal model. New crustal model comprises maps with depths to the top of lower crust and Moho and thicknesses of the crystalline upper and lower crust. Some ranges of mean P-wave velocity in the upper and lower crust are assigned for the eastern and western sectors of platform.

*Key words*: Moesian platform, upper and lower crust, P-wave velocity, top of lower crust, Moho.

## 1. INTRODUCTION

Moesian platform (MP) is a tectonic unit bordered by the Carpathians and Balkans mountains and the Black Sea shelf. Its geologic evolution is preserved in the present crustal/ lithosphere structure. MP was intensively investigated in the last 5-6 decades due to hydrocarbon resources as well as to hosting of the most dangerous Romanian earthquakes in the Vrancea zone.

Many studies attempted to provide crustal models taking into account the available data at each time.

Based on gravimetric data Socolescu et al. [1] built up for the first time a crustal thickness map for the whole country. Since 1970 the seismic crustal investigations have begun to provide crustal information in the NE part of MP (geotraverses XI and $XI_1$ [2, 3, 4]), in East (Geotraverse II, [3]) and west (Geotraverse XII, [5]). Relying on deep seismic data Radulescu [6] built up in 1988 two structural sketches for the Moho and Conrad (top of lower crust) discontinuities across the Romania. Enescu et al. [2] launched in 1992 a new version of Moho map where both seismic crustal and earthquake data were included. A decade later, Martin et al. [7] sketched a new Moho map for the SE half of Romania using previous crustal information and new data consisting of large angle seismic data: Vrancea99 and Vrancea 2001 seismic experiments [8,9] and receiver functions by the CALIXTO experiment [10]). The work of Raykova and Panza [11] using surface wave tomography in SE Carpathians resulted in a crustal model for Moho and S-wave velocity distribution in crust and upper mantle with a low resolution of $1^0\times1^0$ degrees. Tesauro et al [12] have built up a crustal model (Eu-CRUST-07) for the most of Europe (including Romanian territory) with maps for the top of basement, the top of lower crust and Moho and the mean P-wave seismic velocity-Vp in the upper and lower crust with a finer resolution of $0.25^0$x$0.25^0$ degrees. A more elaborated and extended in surface Moho map of Europe (ESC Moho) is launched in 2009 by Grad et al [13] with $0.2^0\times0.2^0$ degrees. The newest crustal model of Europe was compiled on the basis of all available models and data in the European Seismology Reference Model (EPcrust) by Molinari and Morelli [14] with $0.5^0\times0.5^0$ degrees and with maps for the top of basement, the top of lower crust and Moho and the mean P- and S-wave velocities and densities in sedimentary cover, upper and lower crust. Recently, a local model for Moho within the SE Romania based on local earthquakes was built up by Ivan [15].

All the above crustal models that cover Romania are based on seismic refraction data and partially on earthquake data collected in the last decades, but before 2010. For those models many areas of country had no data (e.g. mountain areas) and only extrapolated data were assigned. The crustal model of the MP presented in the next pages is a regional model based on a larger data base that includes refraction data and in addition to previous models, the reflection and earthquake data in mountain area (S and SE Carpathians) and in Central and South Dobrogea. The study perimeter is delimited between $43.4^0$–$45.5^0$N and $22.7^0$–$28.9^0$E and covers the Moesian platform and its neighbourhoods (North Dobrogea orogen and partially S and SE Carpathians).

## 2. GEOLOGICAL AND GEOPHYSICAL SETTINGS

The Moesian Paltform is a Precambrian block integrated in the Epi-Hercynian European platforms [16, 17]. It is bordered by Carpathians in N and NW, Balkans in S and SW, the shelf of Black Sea in East and Scythian platform and North Dobrogea orogen in NE. A major crustal fracture-Intramoesian fault-splits the platform in two: the Dobrogean sector to N and E of the fault and Vallachian sector at S and W. The two sectors had a different evolution and display a series of specific peculiarities, Fig.1. The Dobrogean sector is flanked by the Intramoesian fault at SW, Peceneaga-Camena fault in NE and it is extended towards E on the continental shelf of the Black Sea. The dense network of faults having a composite style (with sliding on the both horizontal and vertical directions) points out two preferential directions: NW-SE and NE-SW, the latter being more recently and crossing the former. The Vallachian sector displays a different basement from the Dobrogean sector. The northern margin is marked by the Targu Jiu-Calimanesti fault and its prolongation to the W – the Timok fault. Two fault systems cross this sector: an about N-S system which breaks the platform in a suite of unleveled blocks and the second on E-W direction which accommodates the sinking of platform under the foredeep stack.

The Basement of platform is heterogeneous both age and lithology. Its tectonics displays a structure of unleveled blocks separated by faults. The sunken zones looks like some elongated depressions. They are located on crustal blocks that supported subsiding movements and favored the accumulation of thicker and complex piles of sediments in respect with the uplifted zones.

The sedimentary cover of platform was settled during four cycles from the Ordovician or Cambrian to the Upper Neogene or Pleistocene times having a series of gaps [16]. In each cycle large piles of detritic and carbonatic sediments were accumulated. Sometimes the eruptive rocks have penetrated through sediments, e.g. in the western part of platform during the Permo-Triassic times.

Magnetic and gravimetric data revealed some major structural lines delimiting tectonic areas with different basement or unleveled blocks. The Bouguer anomaly displays a decrease of isogals from south to north with a significant negative anomaly in the front of Southern Carpathians. Seismic prospecting data found out details of local structures and displayed a complex tableau of both sedimentary structures and partially for the crust. The thickness of sediments varies from N to S (~4 km around Calarasi town to 6–7 km in the Bailesti zone, ~14 km in the Getic depression and ~20 km in the Focsani depression) and from E to W (~1 km around Eforie and Braila towns, to 6-7 km around Bucharest and ~10 km in the Alexandria depression) [18].

Deep seismic soundings have been performed preponderantly in the eastern part (XI, $XI_1$, II geotraverses [3] and Vrancea 99 and Vrancea 2001 [8, 9] refraction lines) and occasionally in the western part (XII refraction line, [5]) of platform. Along with the deep seismic reflection line of near-vertical angle they brought into the light new data on the crustal structure. Seismological data have completed the crustal information that was unavailable from former sources [19]. The thickness of crust is increasing from south (~30 Km) to north (38–40 km) and from west (30–35 km) to east (~40 km). Some crustal models of the Moesian platform were sketched in the last decades by Socolescu [1], Radulescu [6], Enescu [19], Martin [7].

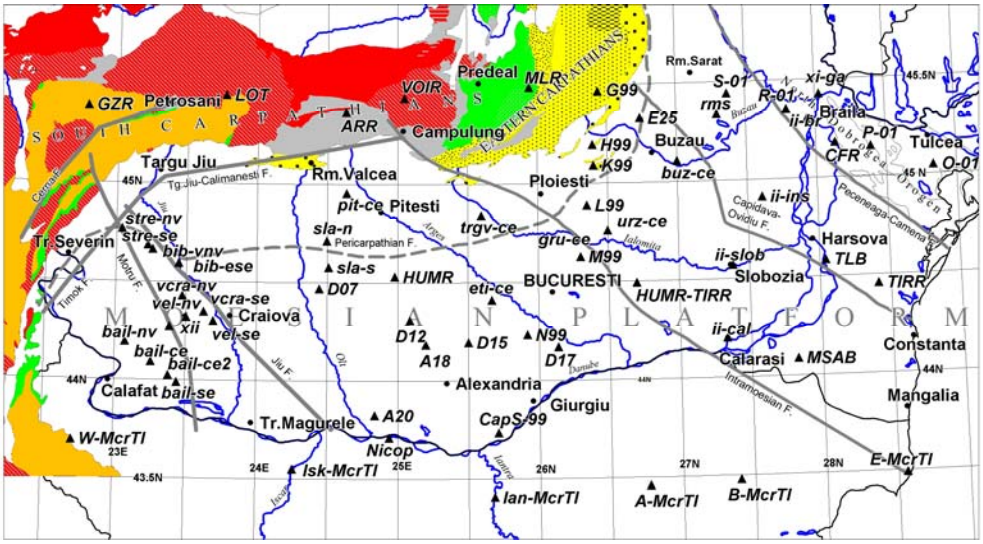


Fig. 1 – Layout of Moesian platform to N of Danube, with the main faults (grey lines) and location of data points used for crustal mapping (full black triangles). The grey (coloured) tones mark the tectonic divisions of the Carpathians orogen based on tectonic map of Romania [16].

## 3. CRUSTAL MODEL OF THE MOESIAN PALTFORM

### 3.1. DATA BASE

Since the beginning of 1970's the subsequent crustal information is being based on seismology data: seismic (reflection&refraction) prospecting or earthquakes data.

Seismic data were collected along of some lines with larger lengths for refraction studies (50–600 km) and shorter for reflection studies (10–40 km). Field data were processed resulting in 2D seismic sections. Their use for mapping the crustal parameters (e.g. depth to Moho or to top of lower crust, P-wave velocity in upper and lower crust, etc) means a sampling in 1D crustal models along the seismic sections at distances of ~50 km, taking into account the present level of coverage with seismic data of the Moesian platform, Fig. 1. Earthquake data collected by the individual stations provided 1D crustal models ready for use in crustal mapping. This is the reason why we will present in the following only the data points that are sampled along the seismic lines. Each 1D crustal model comprises coordinates and the depth to the main crustal interfaces: top of the crystalline basement, top of the lower crust and Moho and the mean P-wave velocity in upper and lower crust.

*Seismic refraction data* were provided by the refraction lines recorded in the 1970's (XI, $XI_1$, II and XII geotraverses, [2, 3, 4, 5]) and in the 1999 and 2001 (Vrancea 99 and Vrancea 2001 [8, 9]), Fig. 1. Geotraverse XI provided data for only the *xi-ga* point located on the easternmost end of line. To the west the geotraverse exceeds the study area. Geotraverse II is part of an international crustal line which runs from NE (Ukraina) through Galati to Calarasi and ends over the Danube river in Bulgaria. 4 data points are sampled along this line: *ii-br, ii-ins, ii-slob, ii-cal* [3]. Geotraverse XII [5] located in the west of platform and with a relatively short crustal section ( ~40 km) resulted in a single data point used in our study: *xii*. More crustal data were provided by the Vrancea 99 [8]: *G99, H99, K99, L99, M99, N99* and *CapS-99* and Vrancea 2001 [9]: *O-01, P-01, R-01* and *S-01*. Because the crustal data along the left side of the Danube river (from the Turnu Severin to Calaras sector) are lacking or very poor, some available crustal data provided by the Markesh-Tiulenovo seismic refraction line [20] has been used for the south sector of river: *W-McrTl, Isk-McrTl, Ian-McrTl, A-McrTl, B-McrTl*, *E-McrTl* and an additional point at *Nicop* on the Petrich-Nikopol seismic refraction line. The refraction data brought into the light information on both the geometry of main crustal discontinuities and seismic velocities across the crust. The uncertainties of depth on the newer lines (Vrancea 99 and Vrancea 2001 [8,9]) is from ±0.5–1.0 km for shallower layer (top of basement) to ±1.0–1.5 km for deeper interfaces (e.g. Moho) while for P-wave velocity they are ± 0.1 km/s for upper and middle crust and ±0.15–0.20 km/s for lower crust and upper mantle.

*Seismic reflection data* completed the data base for our study. A few tens of seismic reflection lines designed for oil prospecting industry were recorded with prolonged times (10–17 s) since 1976 to 1993 across the Moesian platform and its adjacent areas [21–24]. Their length varies from 10 km to 40 km. Many seismic sections illustrate the crustal structure displaying the geometry of the crystalline basement, middle crust, lower crust and Moho with a significant reflectivity and coherent wave trains observable on several km lengths. This kind of data provided only structural information (geometry of discontinuities) and less seismic velocity data.

On the reflection sections we correlated the top of crystalline basement, top of the lower crust and Moho in terms of two-way-travel times. To transform the position of the main interfaces from travel-times in terms of depths we used more P-wave velocity models. In the eastern part of platform the Vrancea 99 and Vrancea 2001 seismic refraction lines [8, 9] gave confident information on crustal P-wave velocity. Their velocity models were used for location of crustal interfaces in the depth terms, Fig.2. We used in the west part of platform due to the lack of more accurate data a more general velocity model derived from seismological data, Fig. 2 [19].

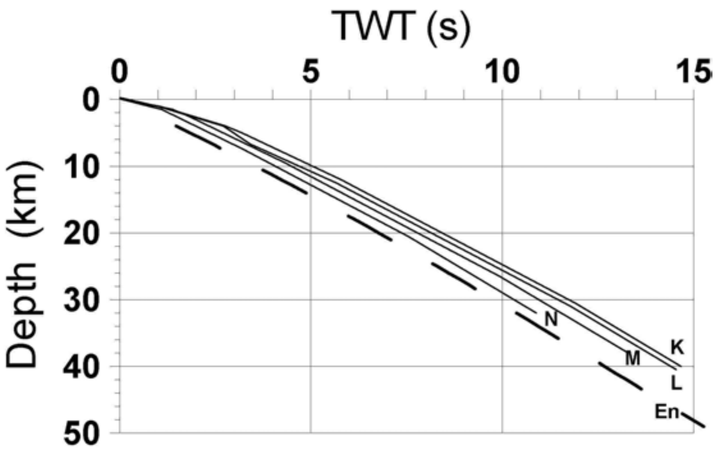


Fig. 2 – Velocity models -two way travel times (TWT) versus depth- derived from 1D models for the K, L, M and N points along the Vrancea 99 seismic refraction line (solid lines) and for En (dashed line) [19].

Under these circumstances the uncertainties of depth for lower crust and Moho are greater than for refraction lines, that is > ±1.0–1.5 km.

Due to the short length of seismic reflection lines we assigned only (a) one 1D model for very short lines (< 20 km), (b) two 1D models for a medium length (20–30 km) and (c) three 1D models for lengths ≥ 40 km. Each 1D model was assigned to the middle of seismic lines for (a), to the ends of lines for (b) and to the ends and middle for (c).

Among the seismic reflection lines used in the present study are the following, Fig. 1: East-Ramnicu Sarat (*rms*), East-Buzau (*buz-ce*), NW-Urziceni (*urz-ce*), Gruiu (*gru-ce*), East-Titu (*eti-ce*), SE-Targoviste (*trgv-ce*), NW-Pitesti (*pit-ce*), Slatina (*sla-n, sla-s*), Bailesti (*bail-nv, bail-ce, bail-ce2, bail-se*), Vela (*vel-nv, vel-se*), West Craiova (*vcra-nv, vcra-se*), Bibesti (*bib-vnv, bib-ese*), North Strehaia (*stre-nv, stre-se*).

*The earthquake data* brought crustal information in areas without other previous knowledge on the deep structure like the Southern Carpathians or as redundant information in other areas (e.g. North Dobrogea). Two techniques of data processing and interpretation are used: receiver functions (RF) and surface wave inversion (SuW). The RF technique uses teleseismic events arrived in a certain epicentral window. The time difference between P-wave and S-converted wave through the Moho discontinuity gives a measure of crustal thickness and of P- and S-wave velocity ratio across the crust. An inversion technique provides a 1D crustal/upper mantle model. The SuW technique uses noise records from two distant stations. The larger is the distance between stations the deeper is the investigated depth. The cross-correlation of the seismic noise recorded at two stations yields the Rayleigh Green's function of the medium between the two stations. A crustal model is derived by applying an inversion technique to the dispersion curve if the Green's function. The resulted 1D model displays an averaged structure between the two stations and we refer this model to a point located at the half distance between the stations.

The following permanent stations belonging the National Seismic Network were used for deriving some 1D crustal models by RF techniques, Fig. 1: *GZR, LOT, ARR, VOIR, MLR, HUMR, CFR, TLB, TIRR* and *MSAB* [25, 26]. Data provided by several temporary stations deployed during the CALIXTO 99 seismic experiment [7, 10] have been also taken into account: *A18, A20, D07, D12, D15, D17, E25*.

The main parameters which define a crustal model are the depths to the top of crystalline basement, top of the lower crust and Moho. In addition the mean P- and S-wave velocities in upper and lower crust complete the crustal model data.

Our study for the Moesian platform was focused on mapping of two major interfaces: top of the lower crust and Moho and the distribution of mean P-wave velocity in upper and lower crust. We gave up to the top of crystalline basement mapping because the existing map of the crystalline basement [18] is based on a larger data base (seismic prospecting and well data) in respect with our data base used in this study. Nevertheless we used our data set for the top of crystalline basement derived from seismology and earthquake data for the assessment of the upper crystalline crust thickness.

### 3.2. BUILDING UP OF THE CRUSTAL MODEL

For each of the above locations of the refraction/reflection lines and seismology stations the following data are assigned: geographic coordinates, depths to the top of lower crust and Moho, mean P-wave velocity in upper and lower crust. As it can be seen from Fig. 1 there are about 60 data points with an uneven distribution across the platform. The poorest coverage is in the southern-central part of the platform from East Craiova to West Bucharest. In order to obtain the maps of crustal parameters two procedures have been applied: a linear Kriging method for interpolation [27, 28] and a filtering of the resulted grid by a spatially Gaussian filter with 50 km wide [29].

Four maps for the top of lower crust, Moho and the thickness of the upper crystalline and lower crust were built up, Fig. 4, 5, 6, 7.

The seismic velocities assigned for the upper crystalline and lower crust are mainly based on refraction data [8, 9]) and earthquake data [19, 25, 26], Fig. 1. Each of the two main crustal layers are defined by a range of P-wave velocity ($V_p$): from 5.8 km/s to 6.7 km/s for upper crust and from 6.7 km/s to 7.5 km/s for lower crust [30, 31, 32]. Taking into account the $V_p$ uncertainties in refraction data

(±0.1 km/s for the upper and middle crust and ±0.15–0.20 km/s for the lower crust [9]) any map of the mean $V_p$ in the two major crustal layers will have uncertainties at least equal or rather greater than the basic data. The Vrancea 99 [8] seismic line displays $V_p$ in the upper crust from 5.9 km/s on top to 6.2 km/s on base of the upper crust along the whole profile. A mean $V_p$ in the upper crust is 6.05±0.1 km/s. In the lower crust $V_p$ varies from 6.7 km/s (top) to 7.0 km/s (bottom) with no lateral change; a mean $V_p$ in lower crust is 6.85±0.2 km/s. The Vrancea 2001 seismic section [9] displays for the O-T shot points segment a relatively larger range of $V_p$ in upper crust: from 5.8 km/s to 6.4 km/s with a mean $V_p$ = (6.0–6.2)±0.1 km/s; in lower crust $V_p$ varies between 6.7–7.1 km/s with a mean $V_p$ = 6.9±0.2 km/s. The two seismic lines are representative for the eastern part of Moesian platform. In the western part of platform no P-wave seismic velocity model derived from refraction data is available. Only the P-wave velocity model derived from quarry blasts and crustal earthquakes [19] for the whole platform is available (Fig. 8). This was used to transform the travel times from seismic reflection section in depth data. As can be seen in Fig. 8, $V_p$ is increasing with the depth from 5.8 km/s at ~8 km depth to 6.5 km/s at ~21 km and 7.0 km/s at ~38 km. Taking into account the fact that the author [19] did not give any uncertainties on P- and S-wave velocity models we think that a lower threshold of at least ±0.2 km/s towards ±0.3 km/s is realistic. All the above reasons regarding uncertainties in P-wave velocities do not allow us to built up a map with a continuous distribution of mean $V_p$ across the platform but we are able to provide some ranges of $V_p$ for smaller sectors in the upper crystalline and lower crust layers.

### 3.3. DISCUSSIONS

The four maps (Figs. 4–7) illustrate some of crustal peculiarities of the Moesian platform at the north of Danube river.

Fig. 4 shows that the depth to top of lower crust is increasing from ~17 km in south to 25–30 km in North-East. The isobaths have a NW-SE general trend with a light inflexion to east of Bucharest city. A comparison of our map with the most recently and updated model for the top of lower crust – EuCRUST-07 – [12] shows some differences only in the shape of contour lines but not in their magnitude. This is due to the fact that we had a better coverage with data (mainly reflection and RF data) in the west of MP where the EuCRUST model had to extrapolate the refraction data from east (Vrancea 99) and possible other data outside our study area.

Fig. 5 displays the Moho map. One can remark the trend of sinking of Moho discontinuity from S-SW to N-NE direction from 30-32 km in south to 35-40 km or more in N and NE.

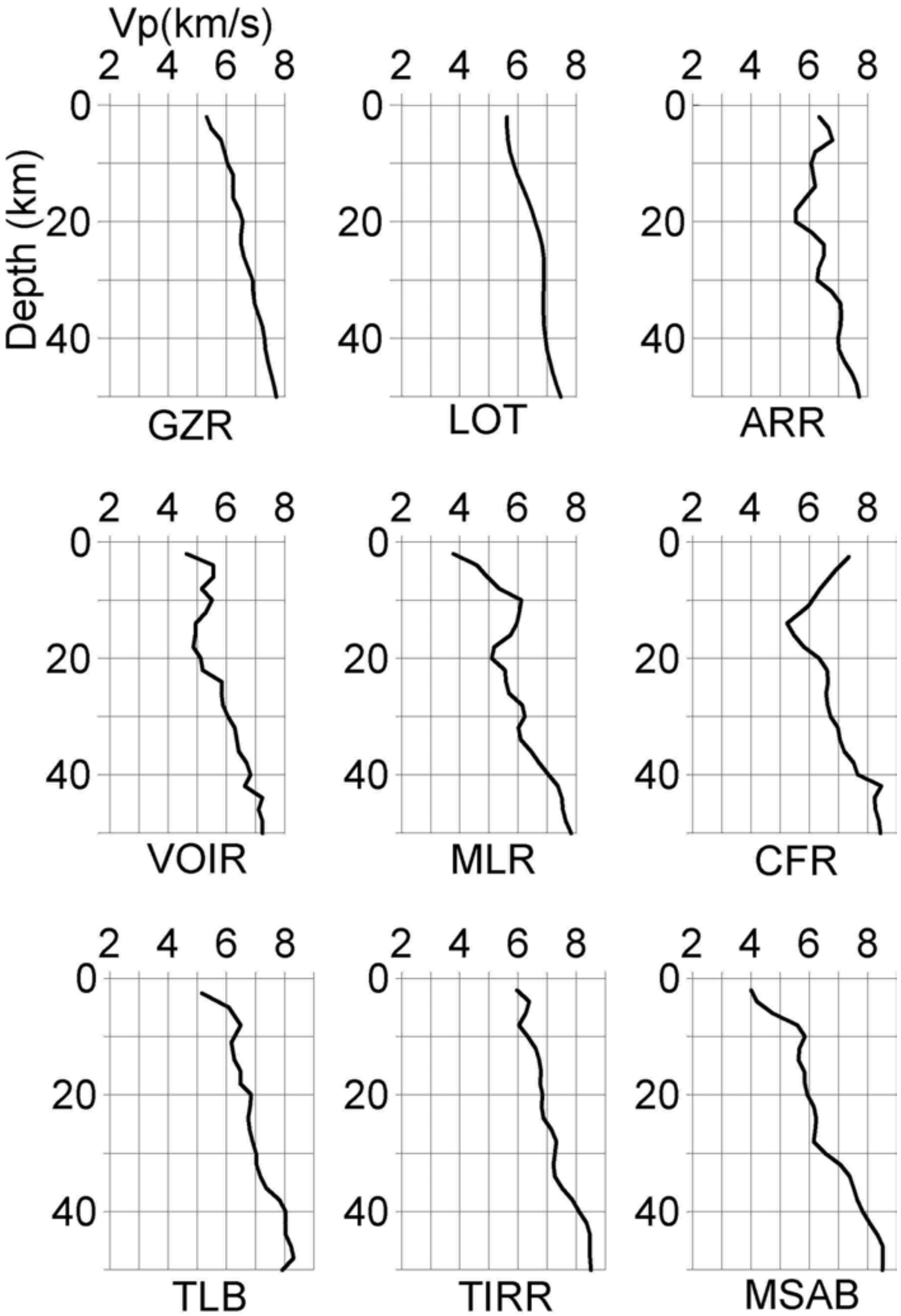


Fig. 3 – P-wave velocity models for seismology stations: GZR, LOT, ARR, VOIR, MLR, CFR, TLB, TIRR and MSAB derived by [25], for location see Fig. 1.

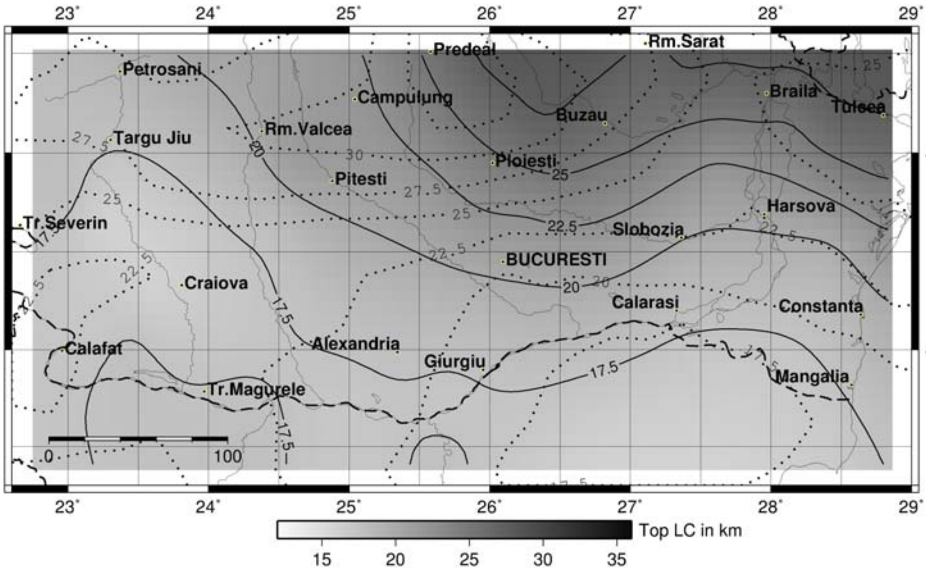


Fig. 4 – Depth in km to the top of lower crust across the Moesian platform from our data (solid line) in comparison with EuCRUST-07 (dotted line) [12].

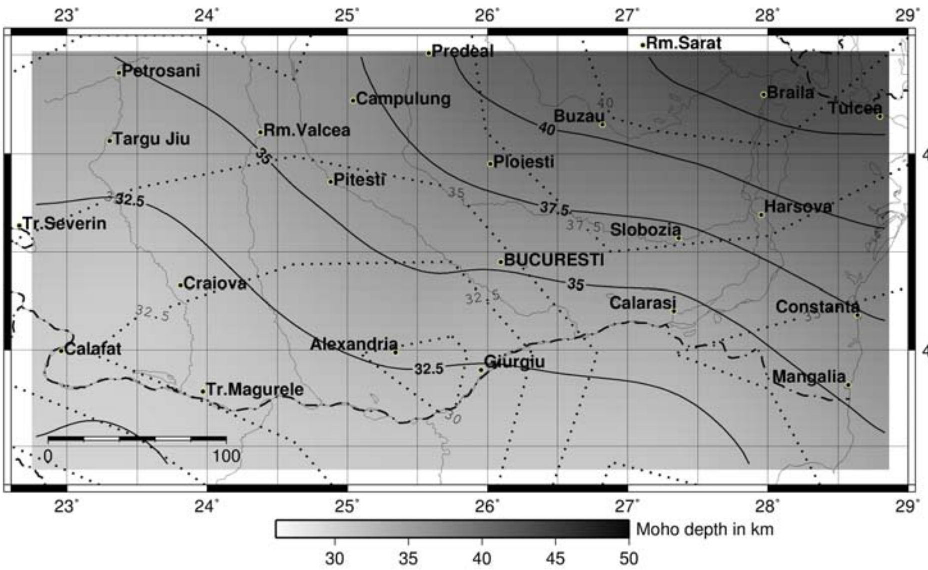


Fig. 5 – Depth in km to the Moho discontinuity across the Moesian platform from our data (solid line) in comparison with ESC model (dotted line) [13].

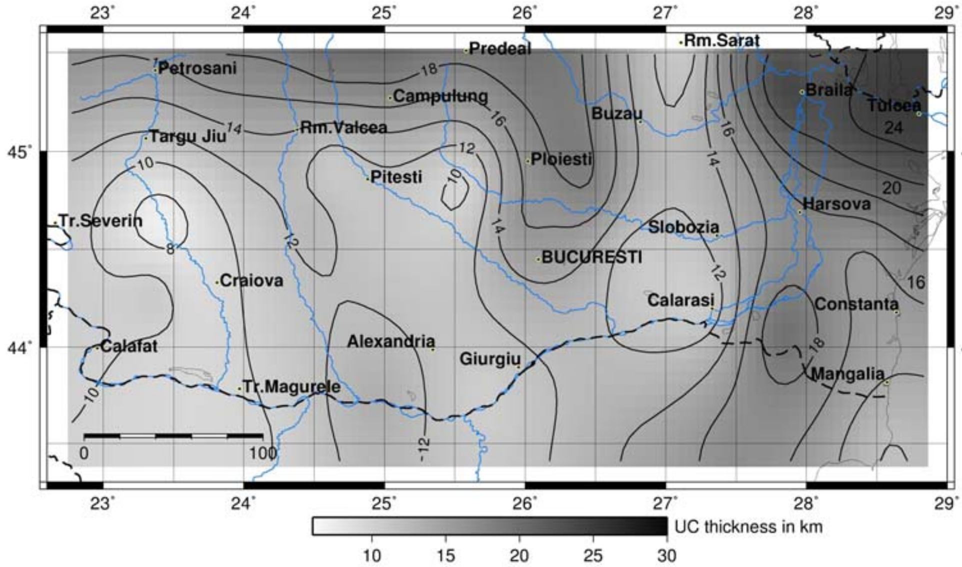


Fig. 6 – Thickness of the crystalline upper crust across the Moesian platform.

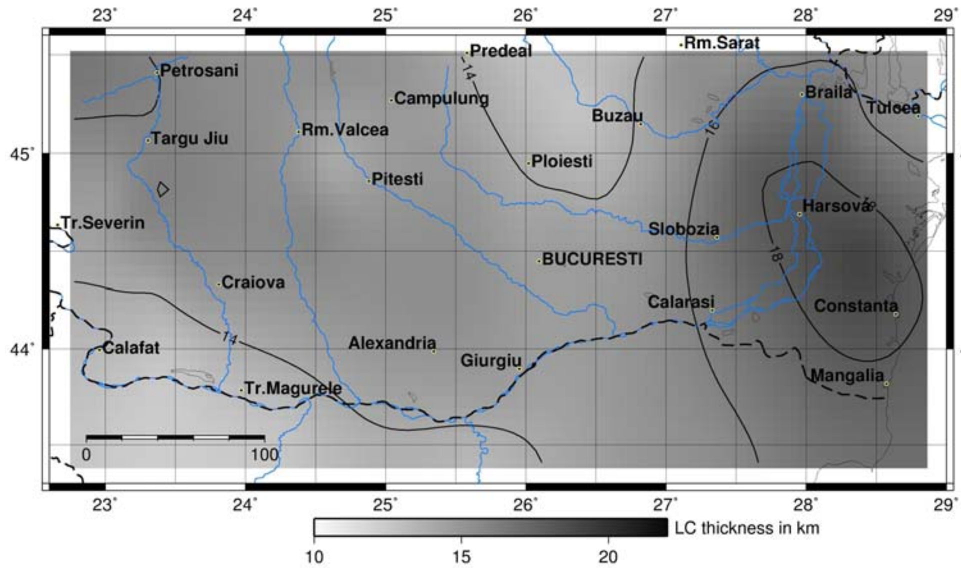


Fig. 7 – Thickness of the lower crust across the Moesian platform.

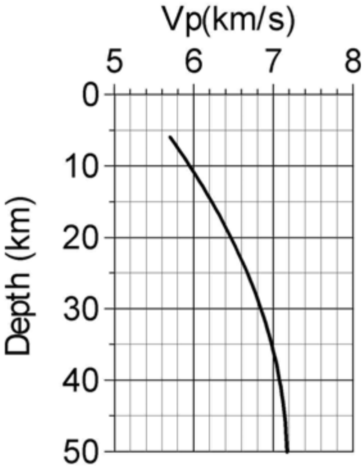


Fig. 8 – P-wave seismic velocity model in the crystalline crust of the Moesian platform derived from traveltimes data of the quarry blasts and crustal earthquakes [19].

This trend is partially confirmed by the ESC model [13]. The same cause account for the differences between the two models: MP model is based on a larger data base (additional reflection and earthquake data) in comparison with ESC model which that used at least for this sector only refraction data, while the western part of platform is lacked of this kind of data.

The thickness of crust found in the study region is in according with data from other similar region in Europe or across the world [33].

A pertinent observation on the above crustal model of MP is the distinction of two sectors with different thicknesses: a thinner crust in west and a thicker in east which seem to be coincident to the two tectonic sectors of platform: the Vallachian in west and Dobrogean in east. This is the new evidence for the existence of two tectonic sectors of platform which are different one from other in both evolution and tectonics.

Based on the two above maps and on the information regarding the top of crystalline basement provided by the same data set (refraction, reflection and earthquake data) two maps with the thickness of the crystalline upper crust (from base of sediments to top of lower crust) and of lower crust were built up and displayed in Figs. 6, 7. Thickness of the crystalline upper crust, Fig. 6 shows a increasing from south to north and from west to east. The uncertainties of the mapped data are at least ±1 km. In the western part the upper crust thickness riches 8-10 km in south and increases in north to ~18 km. In eastern part the upper crust thickens from 16–18 km in south to 24 km in north. The contour line inflexions are the result of sedimentary structures: depressions with thicker pile of sediments or uplifted areas with a thinner stack of sediments. A second map, Fig. 7 was built up to give the extent of lower crust thickness. Here the uncertainties are larger:

±1.5–2.0 km. This map shows a narrow range of thicknesses from ~14 km in the western half of MP to 16–18 km in the eastern part as we have expected relying on the Vrancea 2001 seismic data [9].

A P-wave velocity model of MP is available not as a map with continuous lateral variation of Vp but only as range of velocities in local sectors. This kind of model is imposed by lack of the measured Vp in the western sector of MP. Taking into account the Vp distribution the MP is split in 2 sectors: one in east and second in west.

In the eastern sector the Vrancea 99 and Vrancea 2001 [8, 9] provided mean $V_p$ in upper crust $V_p$ = (6.0–6.2)±0.1 km/s and in lower crust $V_p$ = 6.9±0.2km/s. Velocity models derived from RF data, Fig. 3, point out some mean Vp in a larger range [24, 25]: 5.5 km/s in upper and 6.7 km/s in lower crust – for MLR station, 6.2 km/s and 7.1 km/s – CFR, 6.2 km/s and 7.1 km/s – TLB, 6.3 km/s and 7.1 km/s for TIRR and 5.5 km/s and 6.7 km/s – MSAB. Even if the confidence of RF data is lower than of refraction seismic data we can consider the mean Vp provided by RF as a local information. A remark for MLR and CFR velocity models, Fig. 3: a velocity inversion is pointed out at the the mid crustal level but that was not detected by Vrancea 2001 seismic line, CFR station being situated close to P shot point, Fig.1. This evidence suggests a complicate crustal tectonics with low velocity layers that alternate with higher velocity layers.

In the western part of MP, to west of $25^0$E meridian only the Enescu's $V_p$ model, Fig. 8 [19] and $V_p$ models for GZR, LOT, ARR and VOIR stations could be used. Figs. 4–5 display depths to top of the lower crust of 17–20 km and for Moho of 30–37 km. For those depth ranges a mean velocity in the upper crust is $V_p$ = 6.1±0.1 km/s and in the lower crust $V_p$ = 6.7±0.2 km/s. RF models, Fig. 8, provide the mean $V^p$ as following: 6.0 km/s in the upper crust and 6.7 km/s in the lower crust – GZR, 6.0 km/s and 6.9 km/s – LOT, 6.0 km/s and 6.7 km/s – ARR and 5.5 km/s and 6.3 km/s – VOIR. All station show the mean $V_p$ in the range of Enescu's model [19], except the VOIR station. This station shows a smaller mean $V_p$ than for the others with about 0.5 km/s. In addition a velocity inversion is remarked for this and ARR station. The two facts suggest once again the very complex tectonics of South Carpathians and the high difficulties in constraining such tectonics in a simplified model.

A comparison of the above crustal model with the local lithosphere models provided by sesimology data [34, 35] resulted in a good agreement of our model with seismology data.

## 4. CONCLUSIONS

A data set provided by deep seismic investigations in the Moesian platform and its adjacent areas allowed us to build up a crustal model for this major tectonic unit of Romania. Seismic refraction and reflection data along with earthquake data acquired in the last decades until 2010 delivered information on the major interfaces and P-wave velocity in the crust. About 60 data points distributed relatively unequal across the platform allowed to mapping the top of lower crust, Moho and thickness of upper crystalline and lower crust. Some mean $V_p$ ranges in the two major crustal layers were as well derived.

The top of the lower crust is sinking from ~ 17 km in south to 25–30 km in north-east with an orientation of isobaths from NW to SE. The Moho surface displays a descending from SW (30–32 km), to NE (35–42 km) with a trend of isobaths from NW to SE. The thickness of the upper crystalline crust is in a range of 8–12 km in SW and 12–24 in NE while the lower crust thickness is in a narrower range from about 14 km in the western half of MP to 16–18 km in the east.

The mean P-wave velocity in the upper and lower crust is based on seismic refraction data in the eastern part and on earthquake data in the western part of platform. The upper crust is characterized by a range of mean $V_p$ = (6.0-6.2)±0.1 km/s and in the lower crust the mean $V_p$ = 6.9±0.2 km/s. Some exceptions are noticed locally in the upper crust for VOIR, MLR and MSB stations with a mean $V_p$~5.5 km/s and while for VOIR station a mean $V_p$~6.2 km/s is observed for the lower crust. A velocity inversion in the upper crust for ARR, VOIR, MLR and CFR stations suggests a complex tectonic in S and SE Carpathians and North Dobrogea orogen.

***Acknowledgements***. This paper presents a part of results obtained by the VELOROM project (contract 32153/2008) of the Partnership Program and of the project number PN II-RU 120/2010 of the CNCSIS-UEFISCDI Human Resources Program, the both funded by the Romanian Ministry of Education, Research Youth and Sport. Authors thank Professor Marian Ivan for his constructive discussions which help to the improvement of paper.

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