ATINER's Conference Paper Proceedings Series
ERT2017-0033
Athens, 12 January 2018

Crustal Models and Active Fault Systems in Western Part of Romania

Andrei Bala

Athens Institute for Education and Research
8 Valaoritou Street, Kolonaki, 10683 Athens, Greece

ATINER's Conference Paper Proceedings Series
ERT2017-0033
Athens, 12 January 2018
ISSN: 2529-167X

Andrei Bala, Senior Research Geophysicist, National Institute for Earth Physics, Romania

Crustal Models and Active Fault Systems in Western Part of Romania

ABSTRACT

First results about crustal models resulted from various geophysical and seismological methods applied in Romania in the last part of XX century. A thorough interpretation of this data leads to the first partial models of crustal structure in the western part of Romania. In the first years after 2000 two regional seismic refraction lines were performed within a close cooperation with German partners from University of Karlsruhe. One of these lines is Vrancea 2001, with 420 km in length, almost half of them recorded in Transylvanian Basin. The interpretation of this line give a first look at the crustal structure in central Romania based on seismic data recorded along the profile. The structure of the crust along the seismic line revealed a very complicated crustal structure beginning with Carpathians Orogen and continuing in the Transylvanian Basin. As a result of the development in the last ten years of the seismic network some 100 permanent broadband stations are now continuously operating in Romania. The data gathered so far is valuable data for seismicity and crustal structure studies, especially for the western part of the country, where this kind of data was sparse until now. Complementary to this national dataset, maintained and developed in the National Institute for Earth Physics, new data emerged from temporary networks established during the joint projects with European partners in the last decades. In the years 2009 – 2011 a temporary network of 33 broadband seismic stations were deployed and autonomously operated in an area covering the western part of Romania. The results 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 at 31-33 km depth. The stations within the Southern Carpathians are characterized by deeper crustal depths of about 33 - 36 km. Three lines crossing the western part of Romania are developed with 2D models of the variation of the seismic velocity in depth and the position of Moho boundary. The Moho boundary coincides generally with the isoline of seismic transverse velocity in depth of about 3.80 km/s.

Keywords: crustal structure in Romania, active faults, strong seismic events.

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 according to Sandulescu, (1984).

Western Carpathians – 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, Fagaras-Sinaia and the Danubian zone - the bend of the Southern Carpathians.

Eastern Pannonian Basin is a depression in Romania's western margin. Neogene filling covers a block system with an uneven basement of Carpathian origin 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 Crisana zones.

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 seismogenic potential, with some events in the west and south-west.

Crustal Structure Assessments in Western Part of Romania

Deep Seismic Sounding on a Fan Shooting in North-Western Part

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 reported in Enescu et al. (1967).

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 (Enescu et al., 1967).

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 seismic 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 (Enescu et al., 1967).

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 (Figure 1) by a group of the Applied Geophysics Institute. Seismic Refraction method was applied along Cris Valley on a Cris - N Bors 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 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 (Radulescu et al., 1976).

It should be stressed that comparing the data with crustal thickness determined in other areas belonging to Carpathian Orogen (Enescu et al., 1992), 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.

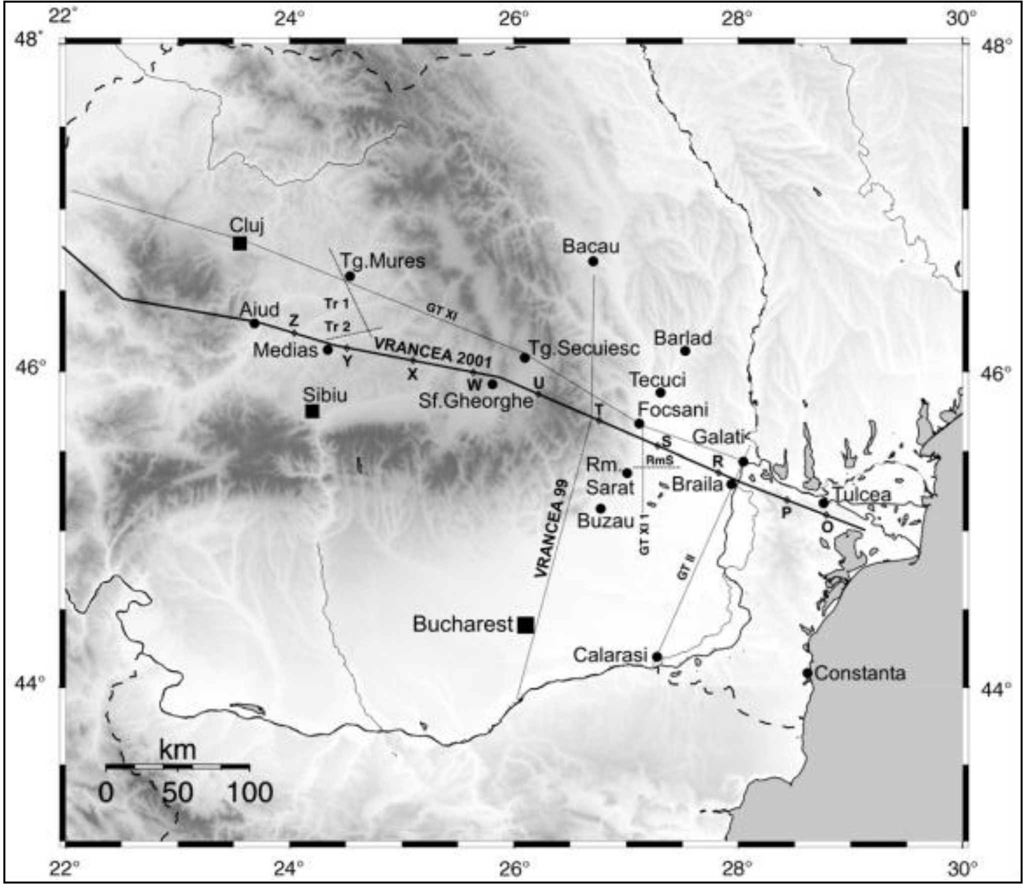
Both set of results are added to the database of the Moho depth in western part of Romania.

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 East Carpathian Orogen and the Vrancea seismic region to the foreland areas with the very deep Neogene Focsani Basin and the North Dobrogea Orogen on the Black Sea. From Aiud town in Transylvania to Tulcea, in northern Dobrogea (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 Focsani 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 Tarnava Basin, (3) the Neogene Focsani 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 Dobrogea Orogen.

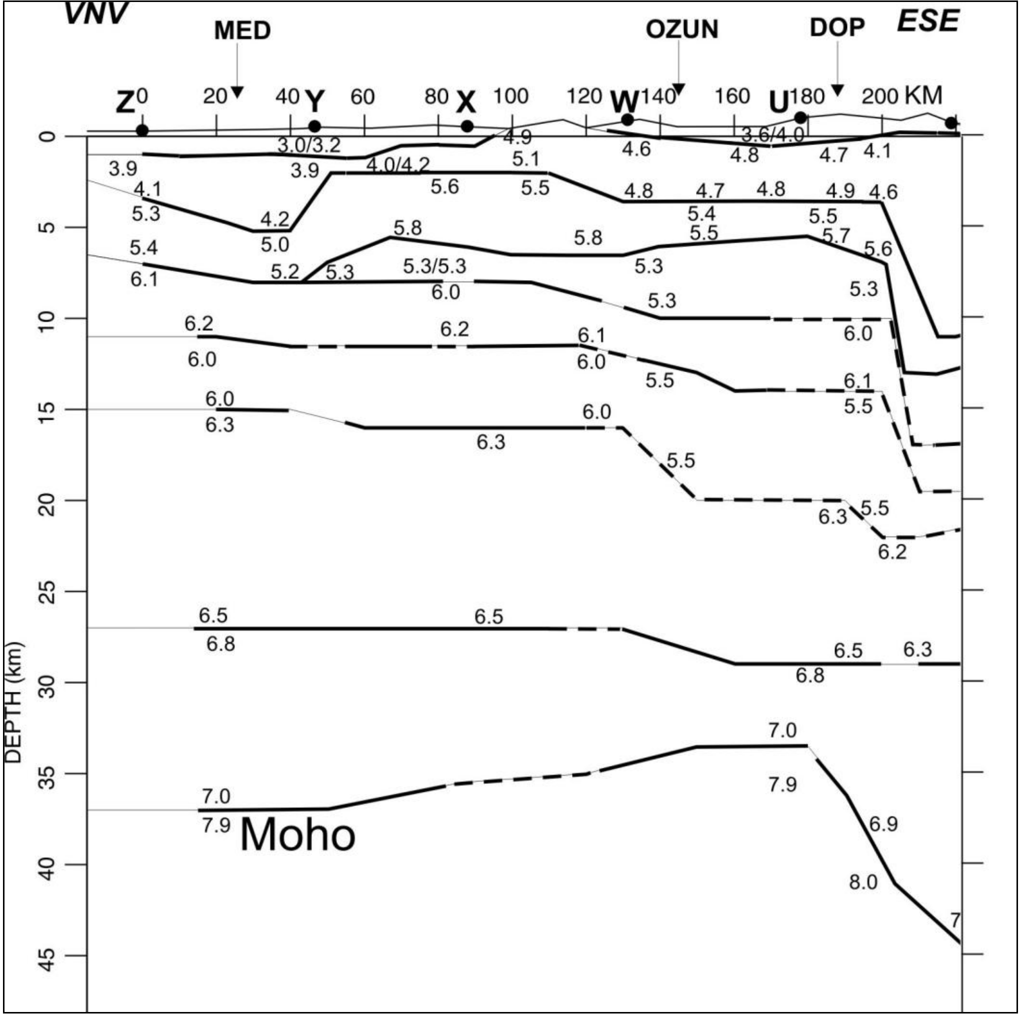
Figure 1. *Topographic Map Showing the VRANCEA2001 Seismic Line (Thick Line O - Z), as well as Older Parallel or Transecting Refraction and Reflection Lines (Thin and Dashed Lines, e.g. GT XI = geo-traverse XI, after Hauser et al. (2007).*



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 Dobrogea 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 Dobrogea Orogen.

A crustal model based on P-wave arrivals is performed and then interpretated in structural terms in Figure 2, after Hauser et al. (2007).

Figure 2. *Crustal Section along the Western Part of the Profile Vrancea 2001, after (Hauser et al., 2007). Z – U: Explosion Points along the Seismic Profile. MED; OZUN; DOP – 3 Permanent Seismic Stations along the Profile. The Numbers Represent the Vp Seismic Velocity at Each Interface, down to Moho Boundary.*



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 (Tesauro et al., 2008), 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 strata having longitudinal (Vp) and transverse (Vs) seismic wave 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 in Carpathian Orogen (Yen et al., 2013).

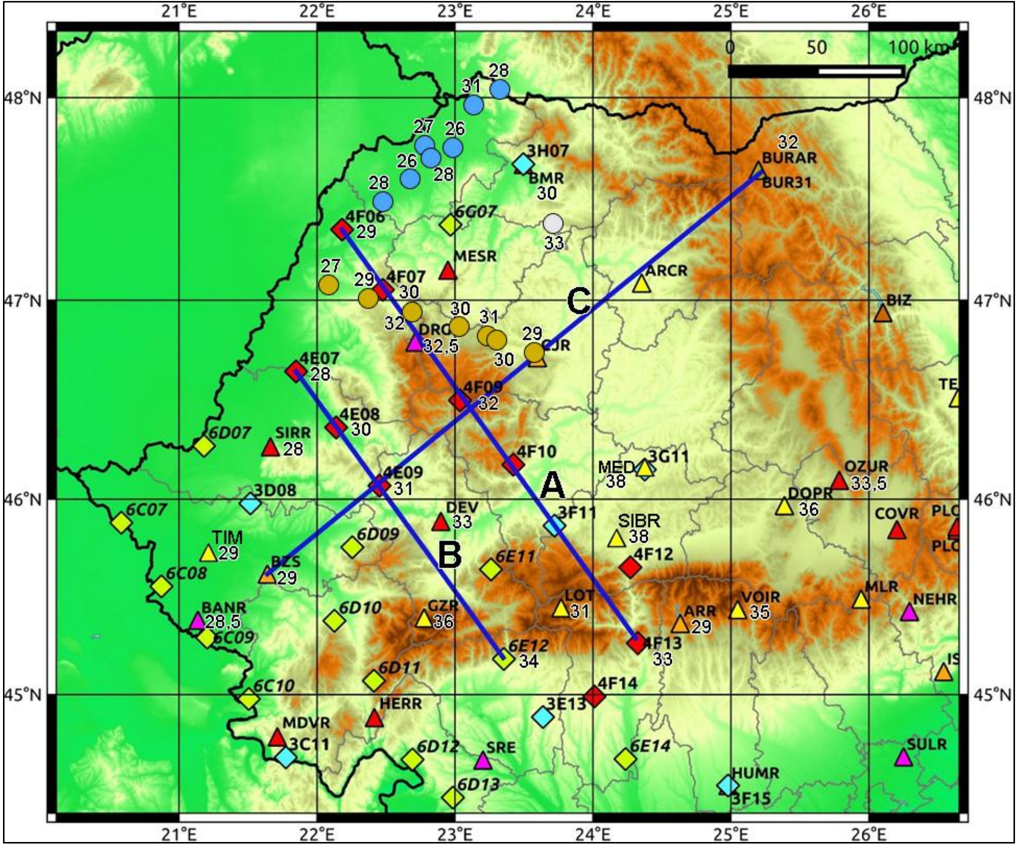
Table 1. *Broadband Stations and Accelerometer Stations in Transylvania and Western Part of Romania. Moho* Depth – Computed from Receptor Functions Method at the Same Location.*

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	45.6167	21.616	260	22	**31**	***29***	BUZIAŞ
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**		MEDIAŞ
OZUR	46.095	25.786	674	28	**33.5**		OZUNCA BAI
SIBR	45.81	24.17	463	26	**38**		SIBIU
TIM	45.736	21.220	134	21	**29**		TIMIŞOARA
SIRR	46.265	21.655	495	21	**29**	***28***	ŞIRIA

Modern Methods used to Assess the Moho Depths - 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 Bala et al. (2016) and Bala et al. (2017), 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 and 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 Bala et al. (2016) and Bala et al. (2017), along 3 lines crossing the western part of Romania. The Moho boundary coincides generally with the isoline of seismic transverse velocity of about 3.80 km/s.

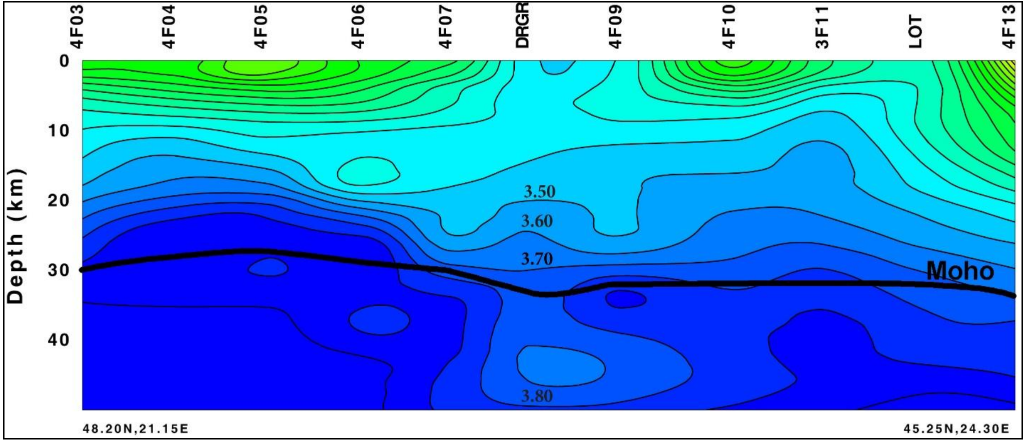
Figure 3. *Punctual Depth to Moho according to First Deep Seismic Surveys in XX Century: the Blue Dots Compiled from Enescu et al. (1967); the Yellow Dots are the Representation of the Profile Cluj Napoca-Oradea, Raulescu et al. (1976). The Triangles are Seismic Station (NIEP) and the Rhombs are the 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 Bala et al. (2016) and Bala et al. (2017). The Values Near Triangles or Dots is the Computed Moho Depth.*



The blue dots in Figure 1 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 used in Enescu et al. (1967). The yellow dots are described in chapter 2.2, and they represent the Moho depth from the seismic profile Cluj Napoca – Oradea, from the Transylvanian Basin to the west, near the border, crossing the northern part of Apuseni Mountains Radulescu et al. (1976) (see Figure 3).

In Figure 4 it is represented the profile through the temporary seismic stations 4F03 – 4F13, profile A, 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).

Figure 4. *Crustal Velocity of the Transverse Waves on the Profile A (4F03 – 4F13). The Moho Boundary is Represented from Joint Inversion of Green Functions and Receptor Functions.*



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) Moho boundary 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.

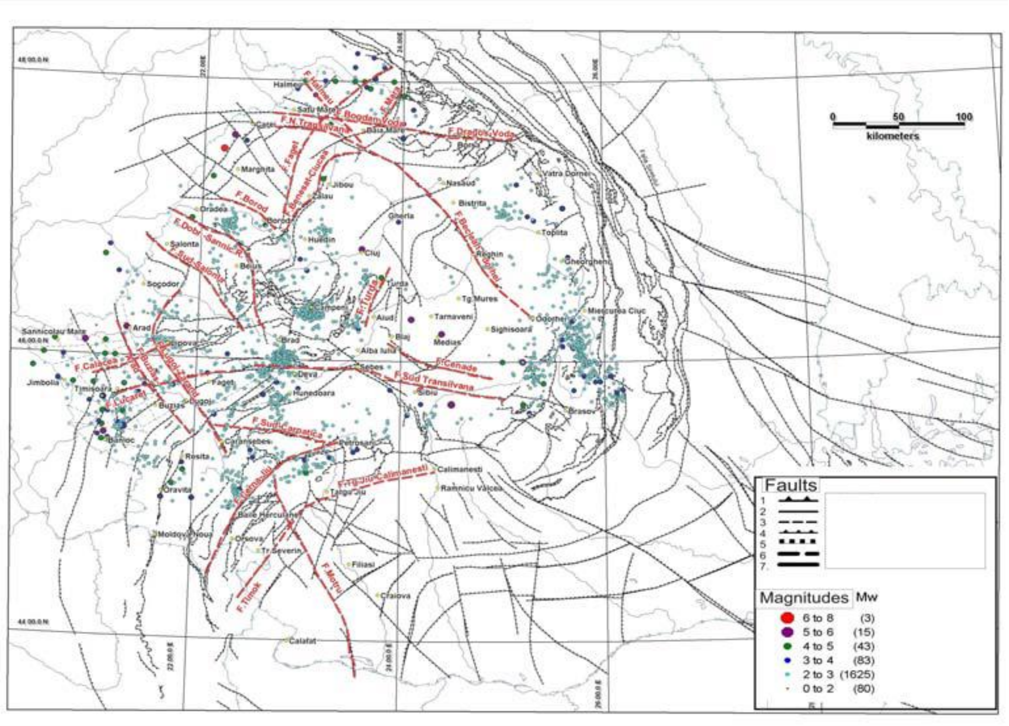
The other two depth profiles to Moho: 4E07 – 6E12 and BZS – BURAR are presented by Bala et al. (2016).

Active Fault Systems in the Western Part of Romania Correlated with Local Seismicity

Region of study involves Transylvanian and Pannonian Depressions, and the Apuseni Mountains Orogen. The above units had a common tectonic evolution stages, interacting with each other, and in time every part took specific features, making them today to be known as distinct and independent units. Seismicity in the west of Romania is linked to the neotectonics evolution of these units. The main areas are active on the edge of Pannonian Basin and at the contact with the basement of the Western Carpathians, Eastern Carpathians or Southern Carpathians.

The map presented in Figure 5 illustrated the structure in blocks and systems for deep faults separating them as different authors have interpreted the available data. Deep faults (faults that extend from the surface to depth at least to the basement, or are developing under shallow sedimentary package) were identified by geophysical (seismic, gravimetric and magnetic), or their supposed existence as a result of geological mapping. Most of them could not be controlled by drilling, at least in the first 1000 m from the surface. Where there was a crustal seismicity, we were able to identify active crustal faults by aligning / grouping epicentres on some active lines. Another aspect of the name associated to a fault, is that in many cases the same fault has acquired different names in different groups, depending of the researchers that has identified them first. Another issue relates to the validation / invalidation or ignoring of a fault identified by an author by the geological community (for lack of sufficient evidence), for inclusion in the regional or national maps.

Figure 5. *Symbols of the Faults: 1. Inverse Fault; 2. Fault; 3. Fault with Uncertain Location; 4. Anticlinal Fold; 5. Normal Fault; 6.Crustal Fault with Uncertain Location; 7. Crustal Fault. Magnitudes Mw of the Earthquakes are Proportional with the Size and Color of the Dots.*



The Tectonic map, Figure 5, illustrates the setting of the systems faults in western Romania. In Pannonian basin there are three fault systems observed. One oriented approximately NW-SE, separating Caransebeş and Sânnicolau Mare grabens, from elevated structures, with faults: Lugoj- Zarand, Sacoşul Mare (Buziaş)-Arad, Nădlag-Jimbolia. Another fault system, roughly orthogonal to the first one, fragmented in secondary blocks the grabens and horsturile oriented NW-SE: the faults Lucareţ, Timisoara, Calacea, etc. A third system, currently in South part of the basin has about E-W orientation.

Earthquake epicentres projected on a crustal tectonic map shows a group of epicentres in several areas. In Banat Plain group appears more evident in Timisoara southwest towards Jebel and Banloc, then north Bega channel in Sânnicolau Mare withers, in the Arad-Vinga-Calacea, and the valley of Timis Faget (Figure 5).

Conclusions

Deep seismic surveys using classic methods were performed in the last part of XX century in the northwestern part of Romania, as well as a seismic refraction regional line (XI) which crosses the entire Transylvanian Basin from Eastern Carpathians to the 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 Bala et al. (2017).

The models of the crustal structure obtained by joint inversion of dispersion curves and receiver functions are presented and described in Bala et al. (2016). 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 chapter 4 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 crustal data and data provided by the Vrancea 2001 seismic refraction experiment Hauser et al. (2007) (Figure 2).

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 Janik et al. (2011) in northeastern Hungary and based on the CELEBRATION 2000 seismic data.

The new data of the crustal structure were introduced in EPcrust, a recent crustal model for the Europe (Molinari and Morelli, 2011).

Transylvanian Basin has a structure fragmented into blocks separated by two fault systems: a NNW-SSE oriented system with fault that crossed the whole depression and an approximately E-W oriented system, with fewer and shorter faults located on the sidewall of the depression (Figure 5). Among the faults the most important are: South Transilvanian fault, Cenade, Turda fault as well as other basement faults that border the most deep zone of the depression. In Apuseni Mountains the structure in overthrusting blades of the main unit seems to generate some weak earthquakes at the contacts between them, e.g. between the Bihor and Biharia nappes.

Acknowledgements

This paper was carried out within NUCLEU Program, supported by ANCSI, project no. 16.35.01.03 and partly in the framework of the project no. 90/2014 supported by UEFISCDI, Program Partnership 2014.

References

Bala, A., Tataru, D., Grecu, B. and Toma-Danila, D. Crustal structure models in western part of ROMANIA using cross correlation of seismic noise and receiver functions. SGEM 2016 Conference Proceedings, 1, vol.3, pp. 443 -450, 2016.

Bala, A., Toma-Danila, D., Tataru, D. and Grecu B. Crustal models in western part of Romania and geodynamics behavior. SGEM 2017 Conference Proceedings, 2017.

Enescu, D., Cornea, I. and Constantinescu, P. The first attempts to assess the thickness of the crust in Romania by punctual seismic surveys. Considerations on the upper mantle structure”, (in Romanian), *Stud. Cercet. De Geol. Geofiz. Geogr., Seria Geofizica*, no. 2/tome 5, pp.185-197, 1967.

Enescu, D., Danchiv, D. and Bala, A. Lithosphere structure in Romania.II. Thickness of Earth’s crust. Depth-dependent propagation velocity curves for the P and S waves. *St. Cerc. Geol. Geof. Geogr., Ser .Geofiz.,* vol.30, pp. 3-19, 1992.

Hauser, F., Raileanu, V., Fielitz, W., Dinu, C., Landes, M., Bala, A. and Prodehl, C. Seismic crustal structure between Transylvanian Basin and the Black Sea, Romania. *Tectonophysics*, vol. 430, pp. 1-25, 2007.

Janik, T., Grad, M., Guterch, A., Vozár, J., Bielik, M., Vozárova, A., Hegedűs, E., Attila, C., Kovács, I. and Randy Keller, G., CELEBRATION 2000 Working Group. Crustal structure of the Western Carpathians and Pannonian Basin: Seismic models from CELEBRATION 2000 data and geological implications. *Journal of Geodynamics*, vol.52, pp. 97–113, 2011.

Molinari, I. and Morelli, A. EPcrust: a reference crustal model for the European Plate. *Geophysical Journal International*, vol. 185(1), pp. 352-364, 2011.

Radulescu, D., Cornea, I., Sandulescu, M., Constantinescu, P., Radulescu, F. and Pompilian, A. Structure de la croute terrestre en Roumanie, Essai d´interpretation des etudes sismiques profondes. *Rev. Roum. Geophys*., vol. 20, pp. 5-32, 1976.

Ren, Y., Grecu, B., Stuart, G., Houseman, G. and Hegedus, E. and South Carpathian Project Working Group. Crustal structure of the Carpathian–Pannonian region from ambient noise tomography. *Geophys. J. Int.*, vol. 195, pp. 1351–1369, 2013.

Sandulescu, M. 1984. Geotectonics of Romania, *Technical Publishing House*, Bucharest, 336 pp (In Romanian).

Tesauro, M., Kaban, M. K. and Cloetingh, S.A. EuCRUST-07: A new reference model for the European crust. *Geophys. Res. Let.*, vol.35, 2008, doi:10.1029/ 2007GL032244.