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CRUSTAL SEISMICITY AND ACTIVE FAULT SYSTEMS IN ROMANIA

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Abstract. The most significant seismicity in Romania is located in a relatively small area – the Vrancea seismogenic zone, where 2–3 intermediate depth strong earthquakes (Mw > 7.0) occur in a century. Although the crustal seismicity is dispersed in several zones of country, only in a few areas the observed magnitudes exceeded Mw = 6.0. Nevertheless some crustal earthquakes that occurred in the past have resulted in damages and even casualties. These facts imposed the taking into account of crustal seismicity in the seismic hazard mapping. Crustal seismicity in Romania is distributed within some belts located along of Carpathians and the Pannonian depression having a more significant concentration in the Vrancea crustal area and in the front of Eastern Carpathians bend, in the Fagaras Mountain area, in the Danubian area, Banat, Crisana, Maramures and North Dobrogea regions. A summary on the crustal seismic activity beneath the Romanian is presented pointing out the most significant events known from both historical and instrumental records. The observed crustal seismicity did not exceed M_w = 5.6 excepting the Fagaras area where the strongest events reached up to M_w = 6.5. For each crustal seismogenic zone the main fault systems which can account for the local seismicity are presented.
This study presents a correlation of seismicity data with the local tectonics. A special attention is focused on foreland of the Carpathian orogen and on the Pannonian sector where a correlation of seismicity with deep structure is better documented.

Key words: crustal seismicity in Romania, epi- and hipocenters, faults, crustal blocks, focal mechanism.

1. INTRODUCTION

Romanian tectonic units comprise both pre-alpine platforms and alpine orogen units: W margin of the East European Platform, known as Moldavian platform, Scythian and Moesian platforms, Eastern, Southern and Western (Apuseni Mountains) Carpathians, North Dobrogean orogen, foredeep of Eastern and Southern Carpathians, Transylvanian depression and Eastern margin of Pannonian depression. The tectonic units come in contact along some major crustal fractures, many of them generating crustal earthquakes. A sedimentary cover with a variable thickness from a few hundred meters up to 10 km or more overlies the crystalline basement over the platforms. The platform areas are superposed by the external units of Carpathians, resulting in gradually sinking of platform basement underneath Carpathian orogen, along some faults parallel to the Carpathians. Other crustal fractures relatively transverse to the Carpathians have created an unleveled block structure. Many of the crustal fractures have proven to generate a low to moderate seismicity [1].

Observed crustal seismicity in Romania did not exceed $M_w = 5.6$, excepting the Fagaras zone. The crustal seismicity in Romania is mainly concentred along the external side of Carpathian orogen and Pannonian depression, with a significant occurrence in Vrancea area and in front of Eastern Carpathians bend, as well as in Fagaras Mountains area, in Danubian, Banat, Crisana, Maramures and North Dobrogea regions (after [2, 3, 4]).

Most of the hypocenters are located in the upper crust (in the first 20 km depth), while the events localized deeper do not exceed 20% of the total.

2. TECTONIC FRAMEWORK OF ROMANIA

Tectonic of Romania includes both pre-alpine platforms and Alpine orogenic structures (Fig. 1). The pre-alpine platforms are: Eastern European Platform, with its western margin in Romania – Moldavian platform; Scythian platform; Moesian platform. The Alpine Orogen 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].

Platforms in front of the Carpathian Arch are of different ages, structure and lithology. The contacts between them are along deep crustal faults, often seismogenic. A sedimentary cover with variable thickness overlies the fractured basement blocks. The platform areas are overlapped by the external units of the Carpathian Orogen, resulting in the sinking of basement and fracturing the crust along some directions parallel to the Carpathian Arch. Other relatively transverse fractures to the general direction of the Carpathian Arch create an uneven basement blocks system, especially in the Moesian platform. Many of crustal fractures are active, generating a moderate to normal background seismicity. Scythian Platform includes two seismogenic structures: Bârlad Depression and Predobrogean Depression (Fig. 1).

Eastern Carpathians as well as ***Southern*** and ***Western Carpathians*** 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. Outer edge of the Carpathians is marked by Carpathian foredeep, whose outer side is a young depression superimposed largely on the platforms developed in front of the Carpathians [1]. In the Foredeep have been outlined two major depressions:

Focsani Depression and Dacian Basin (south of the Southern Carpathians), both having a basement with seismogenic potential. 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.

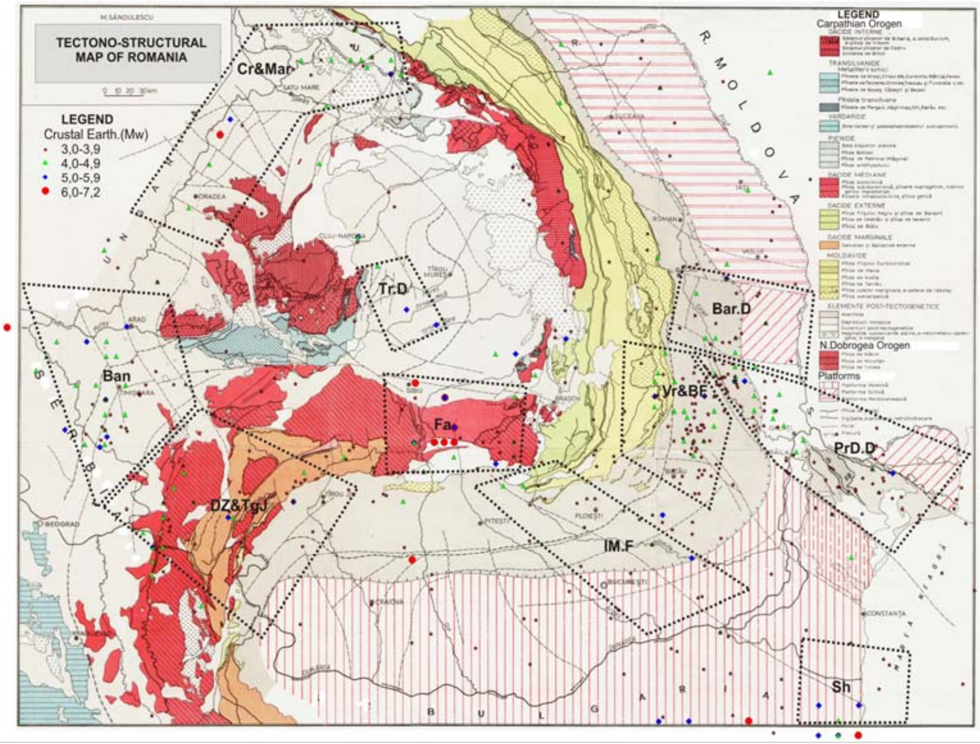

Fig. 1 – Map of tectonic units in Romania (Săndulescu, 1984), with increased crustal seismicity zones. Bar.D = Bârlad depression, Vr&BF = Vrancea crustal zone and Focşani basin, PrD.D = Predobrogean depression and North Dobrogean promontory, IM.F = Intramoesian Fault, Sh = Shabla zone, Fa = Făgăraş-Câmpulung-Sinaia zone, DZ&TgJ = Danubian zone and West Oltenia, Ban = Banat zone, Cr&Mar = Crişana and Maramureş zone, Tr.D = Transylvanian depression.

North Dobrogean Orogen is an intracratonic unit that evolved till the Cretaceous time [1], later joining in the Vorland units of the Carpathians. It extends west of the Danube under Neogene deposits and forms North Dobrogean promontory. Seismogenic potential is more pronounced in the north-eastern edge, in contact with Predobrogean Depression.

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 [5]. Compared to other tectonic units Romanian, Transylvanian Depression has weaker seismogenic potential, with some events in the west and southwest.

3. CRUSTAL SEISMICITY IN THE SE PART OF ROMANIA

Barlad Depression is known by a moderate seismicity with some earthquakes having $M_w \leq 5.6$ (Fig. 1). A prevalently horizontal extensional regime with a basic normal component is suggested by the fault plane solutions [2, 3]. An important role in the seismicity of area is played by the Trotus fault and satellites.

Another seismogenic zone is located at the border of ***Predobrogean Depression*** with ***North Dobrogean Orogen*** (Fig. 1). Taking into account the seismicity and focal mechanism solutions this area has many similarities to the Barlad depression: an extensional faulting regime and moderate magnitude events ($M_w \leq 5.3$). Most of events are groupped along the Sf. Gheorghe fault. An earthquake ($M_w = 3.7$) occurred on October 3, 2004 at NW of the Tulcea town was felt up to Constanta, Braila, Galati towns and even at Chisinau city (Republic of Moldova).

Vrancea zone is marked by a moderate crustal seismicity with $M_w < 5.0$ and relatively rare events in comparison with the ***Focsani Basin***, where more frequent earthquakes grouped in swarms and clusters occured, with small to moderate magnitudes $M_w \leq 5.6$. In the Focsani basin as much as 20 sequences of swarms and clusters were recorded during the last four decades, some of them lasting for several weeks, the main shock being followed by tens of aftershocks. Some of them were analyzed by [6]. Recorded sequences indicate a systematic alignment of the breaking directions parallel to Carpathian orogen in the area, on a NE-SW direction. Hypocenters are gathered in two depth intervals: 5 to 20 km and beneath 30 km. The NE-SW basement fault system at the bottom of Focsani Basin accounts for the seismicity of the two above mentioned areas.

In the areas of Focşani–Rm. Sărat and Vrâncioaia the epicentres are aligned along two lines linked to the deep crustal faults in front of the Carpathian Arc bend: the Capidava-Ovidiu fault with its prolongation toward NW and a fault system oriented N-S or NE-SW, such as Zarnesti–Focsani fault and Valea Salciei fault [7, 8]. The hypocentres are in 3 main depth intervals: 5–10 km; 10–25 km; 30–40 km.

The Braila-Galati-Marasesti seismogenic area, situated to the NE and E of Focsani, is known by a relatively large number of weak to moderate events, sometimes with $M_w > 4.0$. Most of events are aligned on the Peceneaga-Camena fault and its sattelites, which separates the Moesian platform from the North Dobrogean Orogen [7].

3.1. THE SEISMIC SWARM IN GALATI ZONE IN 2013

South of Barlad Depression a seismogenic zone is identified. It lies on the border of South-Western edge of the North Dobrogean Orogen and Predobrogean Depression: Sf. Gheorghe fault. Local seismicity and focal mechanisms are similar to those mentioned for Barlad Depression: moderate seismic activity ($M_w < 5.3$), clustered mainly along the Sf. Gheorghe fault and extensional regime of the deformation field. This reflects that both tectonic regions belong to the same tectonic units (Scythian platform). From this point of view they may be regarded as a single seismogenic zone.

Ivoarele village is pegged to the north by St. Gheorghe fault and to the south by Peceneaga-Camena fault. In between there is another fault with the same orientation, namely Pechea fault. Izvoarele village is located along a normal fault (developed in the sedimentary cover and the crystalline basement) along the Suhurlui river and with the orientation NE-SW [9]. On the eastern side of the fault and also the Izvoarele village, an oil reservoir is located which supports undergoing extraction operation.

After analyzing the seismic data recorded during the period 23 September to 15 October 2013 in the Galati area, the following conclusions appear. The sequence of earthquakes produced in Galati area during the investigation period belong to a seismic swarm type, with all specific characteristics of these seismic processes. One can not distinguish an event with magnitude significantly different from the other events. Release of tectonic energy during a seismic swarm can vary from a few days to several months. Alternation of periods of calm with periods of seismic intensification can occur.

It is difficult to forecast accurately the duration of the seismic swarm, as there is no known relationship between the magnitude scale and time duration.

Seismic swarm phenomena is rather common, being recorded in many parts of the world, as well as and in Romania (Sinaia zone in Carpathian foredeep [11]). In Romania, however, from the instrumental data, the seismic cluster in Galati area is significantly higher, both in duration and number of events compared to similar swarms in other areas.

Table 1

List of the earthquakes from the seismic swarm in Galati county (Izvoarele village), with Mw greater than 3.0 [10]

Date	Origin time	Lat.	Long	Mw
2013/10/03	04:37:39.3	45.54	27.83	3.0
2013/10/04	21:08:10.0	45.53	27.83	3.0
2013/10/03	09:27:40.8	45.54	27.90	3.1
2013/10/04	14:29:26.5	45.53	27.88	3.1
2013/09/30	05:01:56.8	45.53	27.8	3.0
2013/09/29	18:10:49.8	45.54	27.85	3.2

The occurrence of earthquakes with such different depths of hypocenters, *i.e.* at depths of 25.8 km to a depth of 0.3 km, is consistent with the interpretation that they occur after some rearrangement of rigid blocks playing the direction of a major fault oriented NE-SW. These earthquakes are aligned along a new fault, with the same orientation as the known one that is crossing Izvoarele village [9], it has the same orientation NE-SW and plunge toward NW. It is worth to mention that the fault presented without a name in a tectonic sketch by Visarion *et al*., 1990, is a new one because its extremities cut out both major faults: Peceneaga-Camena to SE and Sf. Gheorghe to NE, as well as Pechea fault near Izvoarele Village.

Maximum recorded accelerations in Izvoarele village (20–37 cm/s^2) indicate macroseismic intensity V on the Mercalli scale. Expected macroseismic intensity in the area of Galati following the seismic hazard map is VIII (Mercalli) under the map of seismic zoning (STAS 11-100/93). This can be caused only by deep Vrancea subcrustal earthquakes [12].

4. CRUSTAL SEISMICITY IN THE SOUTHERN PART OF ROMANIA

Pontic earthquakes have foci occuring along and close to the shore of the Black Sea, within the Constanta-Mangalia-Cavarna-Balcic area (the latter two in Bulgaria). They include the historical events occurred in 1869, 1870 and 1892, as well as the catastrophic earthquake of March 31, 1901 from Shabla (Bulgaria) with $M_w = 7.2$ [13]. Their sources are located to certain faults of the Moesian platform and their extensions under the Black Sea. ***Kimerian earthquakes*** [13] are situated in the Dobrogean sector of the Peceneaga-Camena fault and its satellites, with events having up to $M_w = 4.9$. A moderate seismic activity is recorded in ***Central Dobrogea*** on two directions parallel to the Capidava-Ovidiu fault.

Romanian Plain hosted about 300 events between 1872–2005, with $M_w \leq 5.4$. Most of them have a low magnitude $M_w < 3.0$ and are located east of the Arges river. A series of weak and moderate events located around the Bucharest were well felt in the city. Some remarcable events occurred subsequently to the

Vrancea major subcrustal earthquake, March 4, 1977 ($M_w = 7.4$), although they rarely exceeded $M_w = 3.0$. Between the Intramoesian and Capidava-Ovidiu faults a rare and weak-to-moderate seismic activity was observed. The most significant earthquakes occurred NE and E of Bucharest in 1967 ($M_w = 5.0$ at Cazanesti) and in 1960 ($M_w = 5.4$ at Radulesti), on some basement faults of the Moesian platform. The southern events were located on the Oltenita-Turtucaia fault [14]. From W of the Intramoesian fault to the Olt river some weaker earthquakes ($3.0 < M_w < 3.9$) occurred on several basement faults of the Moesian platform.

Around the Sinaia town a significant crustal seismicity with small and moderate magnitudes was also put into evidence. The $M_w = 3.4$ event occurred in 1993 was followed by some 350 small aftershocks [15]. A breaking plane solutions on SE-NW suggests prolongation of some basement faults underneath the Carpathian orogen. There are two alignments of the epicentres NNV-SSE: the first one is W of Sinaia, while the second is S of Moroieni. The two alignmnets are superimposed most probably on some faults of the cristalline domain which are transverse to the direction of Carpathian Orogen.

The ***Fagaras-Campulung*** zone (Fig. 1) have generated the strongest Romanian crustal earthquakes known until present. They reached a magnitude up to $M_w = 6.5$. The last major event occurred in January 26, 1916 with $M_w = 6.4$. A more recent event on April 12, 1969, with $M_w = 5.2$, was followed by about 500 aftershocks. Out of 271 events known between the 1550–2001 years, 15 occurred before 1900 out of 5 had $M_w = 6.2$–6.5. Other 21 weak to moderate events were recorded from 1900 to 1980. The earthquakes occurred in the southern area could be generated on NE deep old Hercyninan fractures and on NE younger Alpine fractures [16], while the seismicity in the northern area could be connected to the fault system which separate the north flank of the Southern Carpathians from the Transylvanian Depression.

5. CRUSTAL SEISMICITY IN THE SW PART OF ROMANIA

A moderate crustal seismicity was observed west of Olt river, but events with $M_w > 5.0$ are known only as exceptions. Some epicenters of moderate events ($M_w = 3.0$–4.9) are located in the neighborhood of Targu-Jiu town. In the south of Dolj county a few moderate earthquakes were felt between Craiova and Caracal towns.

In the west part of Oltenia and within the ***Danubian zone*** (where Danube river is crossing the passage between Southern Carpathians and Balkans) were observed events up to $M_w = 5.6$ (Fig. 1). Earthquakes with $M_w > 5.0$ are known at ***Mehadia-Baile Herculane*** ($M_w = 5.6$ in 1991), ***Moldova Noua*** ($M_w = 5.3$, in 1879) and nearby ***Tismana*** ($M_w = 5.2$ in 1943). Other lower magnitude seismic events ($M_w = 4.0$–5.0) were located at Moldova Noua (1879–1880), Oravita (1984), Targu-Jiu (1912, 1963), Anina (1909), Sasca Montana (1927), Baile Herculane (1910), Resita (1912), Bozovici (1922), all presented by [13].

The significant earthquakes from Oltenia and ***Danubian zone*** suggested by their focal mechanism a reverse faulting in S Turnu-Severin and NW and SE Targu Jiu and a normal faulting near Baile Herculane and S Craiova [17, 18]. The earthquakes are generated either by the transverse fault systems of the platform or by the E-W fault systems along which the platform sink underneath the Carpathian orogen. Other earthquakes could be generated at the contact of Getic and Danubian domains of Southern Carpathians, on the Timok and Jiu faults or in the Cerna graben. The earthquakes occurred on the Orsova-Baile Herculane-Teregova line could be connected to a fracture extending towards N in Caransebes depression, while the Moldova Noua-Oravita-Dognecea seismic line is overlapping the western edge of Resita-Moldova Noua syncline.

Banat region (Fig. 1) has a larger dispersion of epicenters observed. The most significant and recent earthquakes occurred at Banloc (M_w = 5.6 and M_w = 5.5 in 1991). Other events ($M_w \sim 5.0$) are known nearby Arad (1797, 1847), Periam (1859), West Foeni (1901), Peciul Nou (1959). Earthquakes having $4.9 < M_w < 4.0$ were recorded at Satchinez (1974), Banloc (1915), Peciul Nou (1936), Jimbolia (1941), Sannicolau Mare, N Teremia and Timisoara (1879), S Vinga (1887, 1900), Ciacova (1915, 1960), Biled (1960, Vinga (1938), Liebling (1903) [13].

A strike slip faulting combined more or less with thrust faulting is pointed by the focal mechanisms of the significant events [18]. Banat earthquakes are occurring to the contact between Carpathian and Pannonian basement (from Timisoara to Banloc, and to N of Timisoara), as well as to the contact between unleveled basement blocks (like horsts and grabens) from Sannicolau Mare, Nadlag-Jimbolia, Arad-Vinga-Calacea, and on the Timis Valley at Faget [19].

6. CRUSTAL SEISMICITY IN THE NW PART OF ROMANIA

In NW part of Romania in the ***Crisana***, ***Satu Mare*** and ***Maramures*** areas (Fig. 1) some moderate magnitude earthquakes were observed. Also some historical data mention an event with $M_w \sim 6.2$ (1829). Nevertheless, during the last century only an event of $M_w = 5$ was recorded [3].

From N Arad to Oradea, two moderate epicentral areas were located at Socodor (M_w = 4.6 in 1978) and Oradea (M_w = 4.2 in 1906).

North of Oradea, several epicentral areas are known at Sighetul Marmatiei (M_w = 5.3 in 1784 and M_w = 3.5 in 1979), Baia Mare (M_w = 4.5 in 1979), Halmeu (M_w = 4.7 in 1893 and M_w = 3.7 in 1965), Jibou (M_w = 4.1 in 1835), Valea lui Mihai-Carei (M_w = 5.6 in 1834) after [18]. The epicentral areas are mainly overlapped along the crustal fractures which separate some unleveled basement blocks of the local horsts and grabens: Sighetul Marmatiei on Mara fault, Baia

Mare on Dragos-Voda fault and its satellites, Halmeu on Halmeu fault and satellites, Jibou on Benesat-Ciucea fault, Valea lui Mihai-Carei on Galos-Petreu graben and Piscolt uplift, and N Oradea on Sannicolau graben [7]. Although the ***Transylvanian Depression*** (Fig. 1) is thought as a low seismicity area, a moderate event occurred in 1880 (M_w = 5.3) between the two Tarnava rivers. A more recent one in 1975 was weaker (M_w = 3.3).

7. CORRELATION BETWEEN THE CRUSTAL SEISMICITY AND KNOWN FAULT SYSTEMS

7.1. ACTIVE FAULT SYSTEMS IN SOUTH AND EAST PART OF ROMANIA

The study area overlaps two major tectonic units: the ***Moesian Platform*** and ***Carpathian Orogen***. The two units are in contact at the south on a EW line, covered by the ***Dacian Basin*** sediments.

Moesian Platform is characterized by an uneven foundation blocks separated by fractures, some of them extending to crustal base. Two fault systems have been mapped: the first is parallel to the Carpathian arch that accommodates the sinking of the platform; the second fault system, which is relatively transverse to the first system and have a general direction oriented transverse to the Carpathian arch.

Carpathian Orogen structure is complicated, consisting of a complex system of overlapping fractured nappes. While the structure of the ***Moesian platform*** was investigated by geophysical methods at regional to local details in many areas, Southern Carpathians have not benefited from such investigations, except in some isolated sites. Gravimetric, magnetic or electrical methods provided information on a regional scale. This is why the knowledge is limited to geologically mapped surface structure, while the deep structure is less documented.

The two tectonic units generate different seismogenic potential, the Moesian Platform has a limited potential to M_w = 5.6, while the Carpathian Orogen has a limit of up to M_w = 6.5. The occurence depths of the crustal earthquakes shown a concentration in the first 20 km, but they are relatively common as well in the range 20–40 km. In areas with high geothermal gradient, the hypocenter depths are grouped in the shallow crust in the first 5–10 km, while in the areas with low geothermal gradient the hypocenter depths are deeper, extending down to the base of the crust. In the east of the Moesian platform, where geothermal gradient is low, hypocenter depths are dispersed over a wider range; this is the case of the NE of Bucharest area, where the measured heat flow is over 20–30 mW/m^2 and hypocenter depths extend to depths of 40 km.

The Focsani-Rm. Sarat and Vrâncioaia areas show distributions of earthquakes on alignments related to crustal fault system buried in front of the Carpathian orogen: Capidava-Ovidiu fault, with its northwest extension and crustal fault system oriented N-S or NE-SW, such as the Focsani-Zarnesti and Valea Salciei faults [7, 8, 20]. Hypocenters are grouped into three depth ranges: 5–10 km, 15–25 km and 30–40 km. In the Barlad Depression, the crustal earthquakes are located on the Trotuş fault and along some local faults. Hypocenters are clustered between: 6–10 km, 16–22 km and about 30 km deep.

Seismogenic zone Braila-Galati-Mărăşeşti located on North Dobrogean Orogen is crossed by the fault Peceneaga-Camena fault and other local crustal faults that branch from it [21]. To the south, the Danube fault could be an active source of local earthquakes. A depth distribution of hypocenters show a concentration in several ranges: 5–10 km, 15–23 km and 30–35 km.

Tulcea area, located in North Dobrogean orogen contact with Predobrogean depression is linked to Sf. Gheorghe fault and other systems of local crustal faults. Seismicity is grouped for the most part in the depth range of 15–20 km.

In the epicentral area ***Campulung-Fagaras-Sinaia*** (Fig. 2) local faults that generate earthquakes are covered by the Carpathian flysch system. It is estimated that an extention of the Intramoesian fault and associated fault fields are responsible for earthquakes produced in this area. Grouping a large number of low magnitude epicenters on two NNW-SSE alignments, west of Sinaia, suggests the presence of two relatively parallel and transverse faults relatively to Carpathian Orogen. Earthquakes in the south of Făgăraş mountains are aligned approximately on a north-west direction on deep fractures that could be inherited hercynian directions, and on the north-east direction of Alpine origin [16]. Seismicity of the northern fault system may correlate with the step fault system that separates the Southern Carpathian Orogen from the Transylvanian depression.

A number of more than 200 earthquakes with magnitude $2.5 \leq M_w \leq 3.5$ have been identified since 1980 due to the improvement of seismicity monitoring system in INCDFP. In the absence of a convincing evidence, a general hypothesis is that these earthquakes occur on an extension of Intramoesian fault under the Carpathians. Focal mechanism solutions determined on more recent data indicate a strike-slip fault type as predominant, with a normal component [3]. The Southern Carpathians crustal seismicity appears to be significantly higher compared to that in the Eastern Carpathians, suggesting a more active contact of Carpathian orogen with the Moesian Platform, in comparison with the contact of Eastern Carpathians with Eastern European Platform which is frozen now. In the Fagaras-Campulung over 900 earthquakes are identified from 1517 until present, in recent decades the detected events having magnitudes $M_w \leq 3.0$.

Central and Southern Dobrogea are crossed by faults systems having relatively different preferential orientations. In central Dobrogea there is a group of weak earthquake epicenters ($M_w \leq 3.0$) along the NW-SE faults such as Capidava-Ovidiu fault or a fault oriented towards Palazu Mic-Hârşova. Southern Dobrogea main field fault is predominantly NW-SE direction. There are some events with $M_w \geq 3.0$ which located precisely on the alignment of secondary faults, in a NW-SE direction [20]. Earthquakes at Cape Shabla (Bulgaria) seem to be related to the prolongation of Intramoesian fault and/or other local faults with NS direction extended into the Black Sea.

In Dobrogea the crustal seismic activity is low to moderate magnitude in the center, increasing to south. In Central Dobrogea the seismic activity is concentrated for earthquakes with lower magnitudes ($2.0 \leq M_w \leq 3.0$), some events are suspected to be blasting in existing quarries in the area. Some outbreaks are grouped on two parallel SE-NW, the first direction being parallel to the Capidava-Ovidiu fault, which confirms its active atribute, and the second extends from the Black Sea (Palazu-Mare) to Hârşova. Earthquakes with magnitude $3.2 \leq M_w \leq 4.9$ are more rare and they concentrate along the Camena-Peceneaga fault, north of Cogealac, near Hârşova, between Adamclisi and Cobadin and in offshore area, about 25 km ESE of Mangalia. Earthquakes with magnitude $M_w > 5.0$ are located south of the border with Bulgaria, the latest earthquakes occured between 1960–1981 and more recently, in August 2009. The main type of fault is strike-slip that often has a vertical component.

Romanian Plain crustal earthquakes are controlled by deep geological structure, by the major tectonic accidents and differential movements of crustal blocks [7]. Intramoesian fault, Capidava-Ovidiu fault and the other in between parallel faults appear to be the site of crustal earthquakes with small and moderate magnitudes. A series of earthquakes with $M_w \geq 3.0$ are localized along faults oriented approximately east–west: the faults Videle-Balaria, Belciugatele-Ileana, Periş-Pogoanele, resulting from differential neotectonic movements of the basin subsidence movements and lifting of the Carpathians [14].

In Romanian Plain there were identified more than 300 earthquakes from 1872 until present. Here the earthquakes with magnitudes $M_w \leq 3.0$ are prevailing, distributed mainly east of the river Arges. Around Bucharest, south, north and east, a series of earthquakes were felt in the last century, some of which are subsequent to major intermediate earthquake on March 4, 1977. The majority of them have magnitudes $M_w \leq 3.0$, and a few exceed $M_w > 3$, which are located along Oltenita-Turtucaia fault [14].

In between Capidava-Ovidiu fault and Intramoesian fault there is a significant seismic activity with many low magnitude earthquakes (2.0–3.0), and just a few with magnitudes $M_w > 3$, north and east of a line Bucharest-Ploiesti, with epicenters at Tomşani, west Urziceni, Baba Ana. An earthquake of $M_w = 5.4$ occurred at Căzăneşti on April 1, 1960 [14].

West of Intramoesian fault to Olt River, some events occurred west of Gaesti between Olteni and Drăgăneşti-Vlaşca, south of Alexandria, as well as on Olt Valley, south of Draganesti Olt and Slatina.

7.2. ACTIVE FAULT SYSTEMS IN SOUTH-WEST, WEST AND CENTRAL PART OF ROMANIA

Oltenia earthquakes are related either to the fault systems that cross the platform, either to the east-west fault system along which the platform margin descends under the orogen (Fig. 2). Some of the Craiova-Slatina earthquakes may be related to the massive intrusive Bals-Optaşi. Others may be related to the contact between the Getic and Danubian units, on the Timoc and Tg.-Jiu faults, or Cerna graben on the line Vârciorova-Baia de Arama. Earthquakes on the line Orşova-Herculane-Teregova are related to the fracture that extends to the north towards the Caransebeş depression. Seismic line Moldova Noua-Oraviţa-Dognecea overlaps on the western margin of the sincline Resita-Moldova Noua. A number of seismic lines can be found at: Călimăneşti-Horezu, Râmnicu Vâlcea-Govora-Turceşti, Topeşti-Tismana-Glogova [13, 16].

In western part of Oltenia and in Danube area were recorded earthquakes with magnitudes up to $M_w = 5.6$. Earthquakes that exceeded $M_w = 5.0$ were located in the Mehadia-Herculane ($M_w = 5.6$, from July 18, 1991) at Moldova Noua ($M_w = 5$, March 10 şi July 11, 1879) and east of Tismana ($M_w = 5.2$ from June 20, 1943). There were more frequent earthquakes (Fig. 2) with $M_w = 4.0$–5.0 [13].

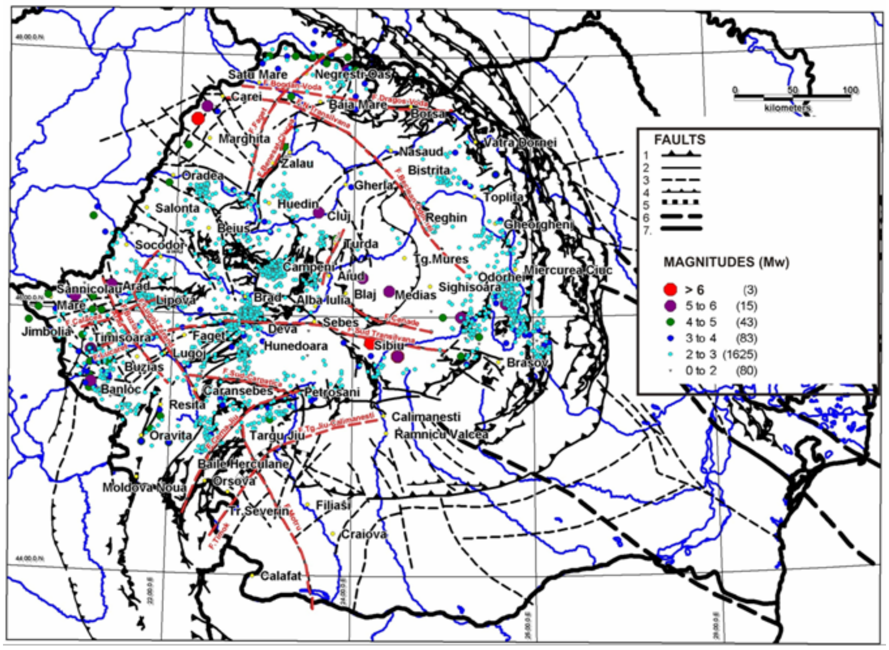

Fig. 2 – Crustal earthquakes on the background of main tectonic units and fault systems in western and central part of Romania: 1 – inverse fault; 2 – fault; 3 – fault with uncertain location; 4 – anticlinal fold; 5 – normal fault; 6 – crustal fault with uncertain location; 7 – crustal fault. Moment magnitudes are according to the legend.

A sequence of 11 earthquakes occurred in Moldova Noua, from September 1879 to March 1880, with an estimated magnitude $M_w = 4.7$.

Focal mechanisms in West Oltenia and the Danubian zone does not indicate a unique type of faulting. Reverse faulting is observed south of Craiova, about 25 km south of Tr.-Severin, East and North-West of Tg.-Jiu, while in Herculane and about 50 km east of Tg.-Jiu normal faulting occur. Earthquakes are related either to fault systems crossing the platform or fault systems oriented east-west along which the margin of the platform sinks under the orogen. Some of the Craiova-Slatina earthquakes may be related to the intrusive massive Bals-Optaşi. Others may be related to the contact between the Piedmont and the Danube, the faults Timocului and Tg.-Jiu, or Cerna Graben-Vârciorova line – Baia de Arama.

In conclusion, in the Danube and in west Oltenia earthquakes occurred in the following areas: Baia de Arama-Tismana-Tg.-Jiu, extending toward northeast to south Petrosani, or to south (Dragoteşti, the Mehadia-Baile Herculane).

Focal mechanism solutions for earthquakes in SW Romania show reverse faulting and strike slip, or a combinations of the two. Normal faulting is rare. Focal depths of earthquakes in western Oltenia and Banat Danube area are in the range 5–33 km, with an increased frequency between 5–10 km depth [17, 18].

The Banat sector of the Pannonian Basin (Fig. 2) has a rough structure of unleveled blocks at the crystalline level (Fig. 2), bounded by several fault systems: (a) one NW-SE oriented, with Lugoj-Zarand, Sacoşul Mare-Arad and Nădlag-Jimbolia faults that separate the grabens Caransebes and Sânnicolau Mare from the higher structures; (b) a transverse fault system with Lucareț, Timisoara and Calacea faults, that fragmented the large blocks into secondary units oriented NW-SE, and (c) an E-V oriented system, present in the southern Pannonian basin [18]. The Banat earthquakes occur at the contact between the Carpathian and Pannonian fundament (from Timisoara to SW Jebel and Banloc and north of Bega channel), and the contact between uneven fundament structures, horsts and grabens: Sânnicolau Mare, Nădlag-Jimbolia, Arad-Vinga-Calacea and Timis Valley to Faget [23].

Neotectonic activity in NW Romania is manifested by an uplifting motion of Western Carpathians in relation to the Pannonian basin. Focal mechanism solutions indicate a predominantly compressive stress. Correlation of seismicity with tectonic elements indicate groups of crustal earthquake epicenters concentrated around some faults separating different crustal block: Zarand and Beiuş grabens south of Oradea, the grabens Borod Sânnicolau and Galoșpetreu or the major horst Salaj, Satu Mare and the block depression Oas-Gutai, north of Oradea. Two major faults are active in these sectors: Dragos Voda fault and Halmeu fault [19, 22]. The main epicentral areas are at Sighet, along the Mara fault, at Baia Mare along Dragos Voda fault, and Halmeu fault and sattelites, at Jibou on Benesat Ciucea fault, Valea lui Mihai-Carei on the graben Galoş-Petreu and raising Piscolt, and N Oradea on the Sânnicolau Graben. Hypocenters depth is between 3–33 km (Fig. 2).

Western part of Romania is seismically active with local seismicity zones, mainly in Pannonian Basin. A map of the distribution of epicenters from intermediate crustal ROMPLUS catalog up to 31.12.2010 is shown in Fig. 3. Seismic areas can be seen on the western frame of Banat-Maramures to the Apuseni and sporadically in Transylvania. Magnitudes of earthquakes recorded did not exceed $M_w = 5.6$ in Banat, $M_w = 6.5$ in Transylvanian Depression and $M_w = 6.2$ in Crisana-Maramures [3]. The analysis of the magnitude distribution show that most of earthquake have M_w = 2.0–3.0 (~ 90 %), and the remaining events having M_w = 3.0–4.0 (5%) and M_w = 4.0–5.0 (2%) and M_w = 0–2.0 (2%) or $M_w > 5.0$ (1%). In the category of events with $M_w < 3.0$, a part may be suspected to be industrial explosions in quarries, especially in some areas in Apuseni Mountains and eastern part of Transylvania. Largest earthquakes seem to be recorded in Banat, SE Transylvania and Crişana.

8. CONCLUSIONS

If we analyze the depth distribution of events in the region, with the exception of intermediate depth earthquakes in SE (Vrancea region), all other have hypocenters in the first 50 km, *i.e.* at crustal and maybe slight under crust. Of the 1647 events located in the first 50 km depth, 239 (15%) are in the first 5 km (some of them being suspected to be quarry explosions); 1086 (66%) are in the range 5–15 km depth; 207 (12%) between 15–30 km depth; 115 (7%) between 30–50 km depth.

Most significant seismicity of Romania is located in the bending zone of the Eastern Carpathians Arch, known as the Vrancea, where 2–3 intermediate depth earthquakes with great potential destructive ($M_w > 7.0$) occur per century.

Crustal seismicity is spread almost throughout the country, and the magnitudes only exceptionally have exceeded $M_w = 6.0$. However a number of crustal earthquakes caused over time a number of destruction or loss of life, which require to consider their effects on seismic hazard maps. We have considered as crustal seismicity all events located from surface down to 40–50 km depth. It manifests with moderate magnitudes, along the external margin of the Carpathians and Pannonian Basin, with a significant concentration in the Vrancea crust in the bending Eastern Carpathians area, in the Fagaras Mountains, in the Danube and Bannat provinces, Crişana, Maramures and Dobrogea.

On the basis of some large concentrations of epicenters, mainly of low magnitudes events, some presumed faults are drawn with red dashed lines on the map in Fig. 3. A few of them coincide with some already known faults but most of them are suggesting still unknown or undetected fractures.

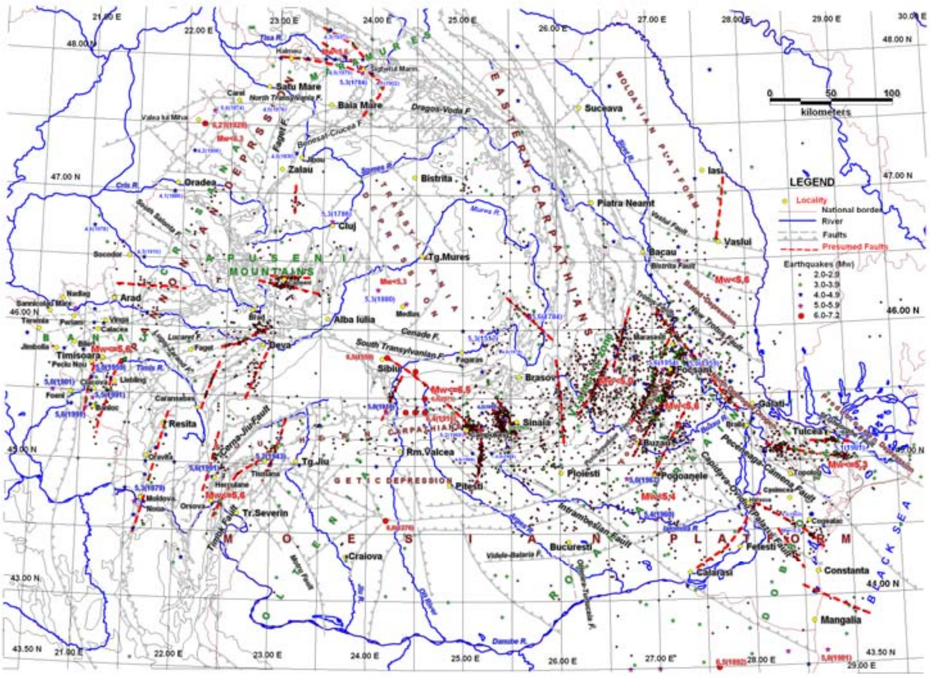

Fig. 3 – A distribution of crustal seismicity for events with $M_w \geq 3.0$ is drawn. Besides the known faults (light grey lines), some new presumed faults or faults systems (dashed red lines) are drawn based on a high concentration of epicenters along the lines.

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