ASSESSING OF THE CRUSTAL MODELS AND ACTIVE FAULTS SYSTEMS IN WESTERN PART OF ROMANIA WITH APPLICATIONS IN SEISMIC HAZARD

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Abstract. Seismicity in western part of Romania is the result of tectonic evolution, which created a fragmented structure at the crystalline basement level, with blocks that have suffered differential movements due to general tectonic stress in the area, and due to secondary factors such as erosion or lateral variations in density. Some of the faults formed during development of the units under survey were reactivated later in recent periods of stress and became seismogenic faults.

The present paper is an analysis of tectonics and seismicity in western part of Romania (Pannonian depression and Transylvanian Basin, and the Apuseni Mountains Orogen). Several maps interpreted by different Romanian authors on local tectonics are presented and a final map with active faults in the region of study is constructed.

The first part is a summary of the stress field in the Earth crust and tectonic evolution of the Carpathian area with particular reference to the units analyzed. Each unit is analyzed based on published sources, finally emphasizing the peculiarities of each area and tectonic fault lines known in particular. In a later chapter is a summary of information on the behavior of the stress field of study areas and seismicity zone, the range of magnitude and hypocenter depths registered with mention of the most significant events occurring over time and relative to areas where they were concentrated.

In the last chapter fault systems in the study region are presented, their peculiarities as they appear in the available studies projected on the local tectonic structure for each of the areas under examination. Results are reported using the tectonic map of Romania, on which epicentres of earthquakes in the catalog ROMPLUS (NIEP Catalog) by the end of 2010 are projected.

Key words: fault types; stress field in the Earth crust; stress field in western part of Romania; faults systems; active faults from persistent earthquake activity.

1. INTRODUCTION

The outer shell of the Earth, lithosphere, consists of a series of hierarchically organized structures from micro-scale (minerals and rocks) to macro scale (plate
tectonics). Separations of the different types of structures are either welded, especially at micro-scale, or in the form of cracks and fissures. *Cracks and faults* are discontinuities resulting from brittle behavior of minerals/rocks under the action of stress fields acting upon them. While the *cracks* are micro-scale fissures with zero displacement, *the faults* have a component of movement parallel to the separating surface. Most of the cracks and fissures are formed by *fracture*, a phenomenon that requires the development of cracks on the when the local cohesion disappears. If the initial stress disappears, cracks and faults can be partially or fully welded [1].

A *fault* can be imagined as a discrete area or an area of discrete surfaces, between two masses of rock, along which a mass slipped compared with the rest [2] or a planar surface between blocks of rock which, in the past, have been moved relative to one another in a direction parallel to the discontinuity [1]. A fault zone is a tabular region that may contain numerous parallel faults.

The present paper is an analysis of tectonics and seismicity in western part of Romania (Pannonian depression and Transylvanian Basin, and the Apuseni Mountains Orogen). Several maps interpreted by different Romanian authors on local tectonics are presented and a final map with active faults in the region of study is constructed.

On the eastern rim of Pannonian basin (in Romanian sector) there are mainly two to three fault systems: a parallel system to the mountainous frame, a second approximately transverse to the first, and the third which has an angle to the first two, observed in Banat. Active faults that separate basement blocks have differential movements. The main fault in this sector are: Lugoj–Zarand, Sacașul Mare (Buziaș)–Arad, Nădlag–Jimbolia, Lucareț, Calacea, nord Timișoara, sud Transilvă, sud Salonta, Dobrești–Sânnicolau Român, Borod, nord Transilvă, Dragoș/Bogdan Vodă, Halmeu, Mara, Făget şi Benesat–Ciucea.

## 2. STRESS IN THE EARTH CRUST

### 2.1. FAULT TYPES

Depending on the relative movement of the two blocks, faults can be classified into three categories: *normal fault*, *reverse fault* and *strike-slip fault*. Displacement vector joining the starting points of the adjacent sides of the fault is called the total *jump of the fault*. Components of the total jump are the *jump on the direction* and the *jump on the declination* (slip) of the fault.

Strike-slip faults involve travel direction of the blocks in the horizontal direction, most often the slip plane is vertical or slightly tilted. Normal and reverse faults involve a displacement of the blocks vertically, along the right oblique plane.
to the horizontal and vertical planes. The blocks situated above and below the fault plane are called the **roof compartment** and **bed compartment** respectively. In case of **normal faulting**, the roof compartment went down in respect to the bed compartment. In the case of **reverse faulting** the roof compartment went up in respect with the bed compartment. The slip faults can be distinguished by **dextral slip faults** (moving to the right of the block in front of an observer located on the reference compartment) and **senestral slip faults** (moving to the left of the front compartment). Normal and reverse faults may have a larger or smaller angle to the 45° in the horizontal, being the **high angle fault** or **low angle fault** [1]. Because most of the time the shift component along the fault are not pure, only vertically or horizontally, there is a predominant component which is either horizontal or vertical, and a second component which is low vertical, respectively low horizontal. When a trough in the central part is lowered in relation to its flanks, generally affected by normal faults, relatively high angle, that is called a **graben**. An elevated block in respect with its flanks is called a **horst**. Low angle reverse faults are called the **subduction faults**.

The concept of active faults involves a recent activation of a slip process along a fault, process which is likely to occur in the future. Active faults are the sites in which contemporary elastic deformation occur, accompanied by active seismicity or aseismic the fault displacement [2]. Deduction of the active nature of a fault is performed by surface geological observations, seismic sections, or seismological observations.

As shown above, the faults are the result of stress fields acting on rock masses. The state of stress in the lithosphere is determined by forces acting in the lithosphere and upon it [3]. If one knows the size and distribution of these forces, a series of limitations can be applied, imposed by the mechanical, thermal and rheological of the rocks, in order to examine the processes occurring in the lithosphere during deformation.

Lithosphere exhibit shear stress resistance, resistance size being a function of depth. Naturally the lithospheric strength increases linearly with depth, according to the law of Byerlee [4], and its size is proportional to the lithostatic load. In the first 15 to 20 km of depth, the mechanical behavior of rocks is elastic, and it might become brittle in boundary conditions. In parallel with the increasing lithostatic pressure, temperature increases with depth. At a temperature of about 350°C, at which point the quartz mineral (one of the main minerals that make up the upper crust) becomes ductile, shear strength begins to decrease, controlled by lithology and temperature, after a nonlinear law. The interval depth where the maximum
resistance to the shearing stress occur, followed by a drop, it is known as the transition zone from brittle to ductile behavior.

2.2. STRESS IN THE EARTH

Stress is defined as a tensor which dimension is determined by the density of forces acting on all surfaces passing through a point. The stress tensor is defined by the nine components. Any component of stress is a force that acts in a specific direction on a unit area, with a given orientation. There are three orthogonal components normal to the faces of a cube containing the point elemental analysis and the other six components of shear stress, which acts in the planes of the three pairs of orthogonal sides, two components perpendicular to one another in each plane and parallel to the sides of the cube face. Because the axes to which the elementary cube is defined is arbitrary, one can find three orthogonal directions, for which the shear components become zero, in this case the stress is described by only three main stress components, being in a ratio $S_1 > S_2 > S_3$ [3]. The significance of this concept in the nature is the fact that the earth surface is in contact with a fluid (air or water), which does not support shear stress and which has become one of the main plane of stress. Thus, one of the main stress will be normal to the surface of the Earth and the other two will operate approximately in a horizontal plane. Data from focal mechanism solutions have suggested that this remains true in the upper crust, until the brittle-ductile transition zone [3]. Starting from this premise are sufficient only four parameters that completely describe the state of deep stress: stress orientation, which usually is taken as the azimuth of maximum horizontal compression ($S_{H_{\text{max}}}$) and three stress values: vertical ($S_V$), corresponding to the weight of the lithologic column, horizontal maximum principal stress ($S_{H_{\text{max}}}$) and horizontal minimum principal stress ($S_{H_{\text{min}}}$). To apply this concept to the crust are considered maximum principal stress sizes ($S_i$), intermediate ($S_i$) and minimum ($S_i$) in terms of $S_V$, $S_{H_{\text{max}}}$, $S_{H_{\text{min}}}$ (Fig. 1).

The two principal horizontal stresses, $S_{H_{\text{min}}}$ and $S_{H_{\text{max}}}$ may be described in function of the vertical principal stress $S_V$, the size of which is given by the height of the lithostatic column, which mathematically corresponds to an integration of the density ($\rho$) from the surface to the depth $z$.

$$S_V = \int_0^z \rho(z) \cdot g \cdot dz \approx \bar{\rho} \cdot g \cdot z,$$  \hspace{1cm} (1)

where: $g$ – gravity acceleration, and $\bar{\rho}$ is the average density of the lithologic column down to the depth $z$. 
Main horizontal stresses are almost never equal, but may be higher or lower than the vertical stress. The relative sizes of the three principal stresses are related to faulting mechanism of a region (Fig. 1). Characterization of a region through normal faulting type, strike-slip or reverse can be done by defining the size of the two horizontal stress in relation to the vertical. When the vertical stress is prevailing in regions with extensional deformation ($S_1 = S_V$), then gravity leads to a normal faulting. When horizontal stresses exceed the vertical stress ($S_3 = S_V$), then the deformation accommodates to shortening by a reverse faulting. Strike-slip fault is an intermediate state of stress ($S_2 = S_V$), in which the maximum horizontal stress is greater than the vertical stress and horizontal minimum stress ($S_{lm} \geq S_V \geq S_{hmin}$).

To incorporate the influence of the pore fluid pressure caused by rocks at depth, the term of effective stress was introduced. A component of effective stress ($\sigma_{ij}$) is linked to the total stress ($S_{ij}$) by the relationship:

$$\sigma_{ij} = (S_{ij} - \delta_{ij} P_P),$$ (2)

where: $\sigma_{ij}$ are Kronecker coefficients and $P_P$ is the pressure of fluid in pores. Laboratory studies have shown that faulted rock friction resistance is described by the criterion of Coulumb. That is, the fault is slipping when:
\[ \tau = \tau_0 + \mu \sigma_n, \]  

where: \( \tau \) is the shear stress acting on the fault, \( \tau_0 \) is cohesion of the fault, \( \mu \) is the coefficient of friction on the fault, \( \sigma_n \) is effective normal stress acting on the fault plane. The maximum shear stress is equal to \( \frac{1}{2} (S_1 - S_3) \).

Simplified theory of 2D faulting Mohr–Coulomb supposed that faulting is a function only of the difference between maximum effective principal stresses (\( \sigma_1 \)) and minimum (\( \sigma_3 \)), the formula being given by Jaeger and Cook (1971):

\[ \frac{\sigma_1}{\sigma_3} = \frac{(S_1 - P_p)}{(S_3 - P_p)} = \left( \frac{\mu^2 + 1}{1 + \mu} \right)^{\frac{1}{2}}. \]

The conclusion is that the sizes of the three principal stresses at any depth are limited by the strength of the crust on the same depth. Thus, in the case of normal faulting, stress sizes are controlled by \( \sigma_v \) and \( \sigma_{\text{min}} \), corresponding to the \( \sigma_1 \) and \( \sigma_3 \), and \( \sigma_{\text{max}} \) corresponds to \( \sigma_2 \), which is an intermediate value between the first two and does not affect the faulting.

Coulomb’s theory demonstrate that the frictional slip occurs when the ratio of shear stress to normal stress effectively on pre-existing fault planes is equal to the coefficient of friction. Because friction coefficients are determined relatively well for most rocks [4], being in the range 0.6–1.0, equation (4) takes on values between \( \frac{\sigma_1}{\sigma_3} = 3.1 \div 5.8 \). For the case of hydrostatic pressure, friction coefficients are \( \approx 0.6 \), which means \( \sigma_{\text{min}} \approx 0.6 \sigma_v \) in extensional areas affected by inverse faulting, and \( \sigma_s \approx \frac{1}{2} \left( \sigma_{\text{max}} + \sigma_{\text{min}} \right) \), \( \sigma_{\text{max}} \approx 2.2 \sigma_{\text{min}} \) in areas affected by strike-slip faulting. These values were confirmed by in situ stress measurements at depths of about 8 km in super-deep borehole KTB in Germany and in a number of locations in intra-plate areas [3].

### 3. Behavior of the Regional Stress Field in Romania

Stress field in Romania must be defined in the context of regional stress field and intra-plate tectonics existing in our country.

Recent edition of the World Stress Map [5] has compiled a large database of information of contemporary tectonic stress in the crust. Previous editions of world stress map proved the existence of the first order scale stress fields in the tectonic plate, controlled by forces on the boundary of the plates (boundary forces), and the second order stress fields at the regional scale, controlled by intra-plate stress sources such as mountain belts and widespread areas of lifting as a result of glacier melting (glacial rebound). A 2005 edition of the same maps made it possible, for areas with a higher density of information, to study the variations in the tertiary order stress fields, i.e., locally variations, highlighting the nature of the forces that control these stresses: active faults, local inclusions, horizons detachment...
(detachment horizons) and density contrasts. These forces act as major controls on stress field orientation when horizontal stresses sizes are close to the isotropic model (equal in all directions). The substantial increase in the volume of data on the state of stress in different regions of the world has shown that there are additional factors that control stress patterns regionally and locally.

Stress Map Edition 2007 [5], stress presents data in a standardized format. Minimum information provided for each data record of maximum horizontal stress orientation stress is $S_{H}$, data quality that provided orientation (Class A has errors $\pm 150$, class B $\pm 200$, class C $\pm 250$ and class D $\pm 400$), the type of indicator of stress (focal mechanism, out of roundness boreholes-breakouts, horizontal stress-induced fractures by the drilling process, images taken from the well bore caliper, hydraulic fracturing, in situ testing of the stress in mine galleries (overcoring) or drilling (borehole slotter), the fault slip data, etc.), location and depth measurement, tectonic stress regime (normal faulting, reverse direction or unknown type of faulting), as well as the reference source.

Stress Map of Western Europe, which includes Romania is shown in Fig. 2. The key findings made by [6] in the stress models of the first order, indicated a predominant orientation NW and NNW directions $S_{H}$ blamed on forces from the plate border, in particular by pushing the North Atlantic Plate and African/Eurasian plate collision. These conclusions were supported by several large-scale models made by finite element method. Although meanwhile the amount of data stress in Europe has doubled compared to 1992, today the first order models are clearly visible smoothed stress field (smoothed stress).

The main $S_{H}$ direction is parallel to the orientation of the relative motion of the African plate against the Eurasian plate. Large-scale deviations from this trend are found in Aegean Arch and western Anatolia region, where the back deviation of the subducted lithosphere fragment (slab rollback) in Hellenic Arch induced $S_{H}$ in a E–W direction in the region (back arc) opposite to the basin and to the subducted plate. In the Pannonian Basin, the NE–SW orientation of $S_{H}$ is probably due to a collision with Dinaridele.

The smoothed field stress orientation in Italy is similar to that of Western Europe, showing a trend of large-scale orientation NW–SE, which was due to the convergence of African and Eurasian plates. Local deviations near the coastline and the Alps and Dinaride could be the result of local density contrasts, topography, rotation in the opposite clockwise rotation of the Adriatic block relative to the Eurasian plate and the collisional resistance along the Dinaric mountains on a NW–SE direction.

Forces from the plate edges are identified as having the main control board for stress model extended to the first order model of Western Europe [5].
Fig. 2 – Stress map ($S_H$ component) in Western Europe after [5]. The symbols are explained in the upper right box. NF = normal faulting, SS = faulting in direction, TF = reverse faulting, U = unknown faulting mechanism. The parameters, on which the smoothing of the $S_H$ was done, are: investigating radius $r = 600$ km, the minimum number of data $n = 3$, smoothing factor $\lambda = 12$.

3.1. STRESS FIELD IN ROMANIA

Stress Map of Romania is cut from the World stress map 2007 [5]. A first map is presented in Fig. 3, where visible trends of the smoothed field as well as the anomalies of this field are revealed.
In Fig. 3 two major trends of $S_{hh}$ orientation are observed: one from an E–W direction, dominant in the east, which is maintained north of 46° N and another toward the NE–SW, in the SE part of Romania. In contrast to the stress model’s proposed by [8], indicating a homogeneous orientation stress field $S_{hh}$ on a WNW–ESE direction, the current model of stress does not clearly indicate these trends. This fact could be explained by considering three factors: (1) possible inclusion in the Bada data set of the focal mechanisms of subcrustal earthquakes in Vrancea area, while current map only consider mechanisms crust up to 40 km deep; (2) the parameters used by Bada for smoothing have filtered only the first order model at a large-scale plate; (3) the number of local data of stress at that time, was too low in order to highlight the intricate pattern of existing stress. Great variability of the $S_{hh}$ orientations outlined in detailed in the Stress map of Romania (Fig. 3) cut out from world map [5] is most likely the result of the small size and relatively isotropic horizontal stress field removed. According to the research of [9], the net stress field as a result of overlapping local and regional stress depends on the size of the main stresses regional, local stress component size, and difference angle of the main directions of regional stress and local stress.
sources. Additional local stress non-parallel to the regional stress field orientation, will drive that net stress will not be identical with the main stress, also that being the cause to change the style of faulting at local scale, for example from direction faulting to normal faulting. These localized stress disturbances are considered to be low horizontal stress and/or isotropic, being seen also outside Romania, in the Permian Basin and in the North Sea.

By analyzing the map of Fig. 2 and Fig. 3, which illustrates a wide variety of orientation and changes of tectonic stress on small spatial scales, it can be concluded that the contribution of forces on the edges of plate tectonic on the stress size is small, and the stress tensor eigenvalues are similar, i.e. a state of stress close to the isotropic model [5]. This observation suggests an influence of third order sources on both $S_H$ direction and kind of tectonic regime. Among possible sources of local stress can include: relief (topography), lateral contrasts of density and strain in Focsani Basin, with 11 km thickness of Neogene sediments, Carpathian Vorland, Moesian platform, basin subsidence due to the subducted lithosphere fragment, and rotating stress direction at the ends of faults. The overlapping of these different sources of stress leads to a complex stress field with direction of $S_H$ changing a in a few kilometers, as can be seen in the focal mechanisms of local earthquakes.

The wide variation in local stress patterns in Romania determine the upper limits of regional potential sources of stress in the area and the degree of coupling of lithosphere fragment subducted in Vrancea area. The authors in [5] presume that the lithosphere fragment does not transfer large amounts of stress to the stress crust over, and the coupling is probably weak. A strong coupling regional would produce a signal higher in the stress model, which is not yet found in the observations of stress.

3.2. STRESS FIELD AS RESULTED FROM SEISMICITY RECORDED IN WESTERN PART OF ROMANIA

A more recent stress Map of Romania cut from the map of Europe 2008 [10] shows a small number of determinations stress regime for Transylvanian Basin and the Romanian part of Pannonian basin. In Banat and Maramures determinations are based on focal mechanisms of local earthquakes and in the eastern rim of the Transylvanian Basin they are based on drilling data. In Banat maximum horizontal stress occur oriented on an approximately east–west direction, with deviations toward NW–SE or SW–NE. The predominant type is slip faulting in the direction (SW–NE) and reverse (about E–V). A normal faulting event of NNE–SSW direction appeared too. In Maramures there are reported normal faulting type and
reverse faulting on the direction E–V. In the SE Transylvania Depression compressive stress directions appear relatively in parallel to the mountains frame with normal faulting in the Persani mountains and Baraolt (NE–SW), and of unknown type, on the western edge of Gurghiu–Harghita mountains (NW–SE).

In [11], a comparative study of geophysical and geological data led to the development of the configuration patterns and geodynamics major lithospheric compartments in Romania (Fig. 4). In order to determine the current stress field the authors use stress tensors deduced from focal mechanism solutions of the crustal earthquakes. Based on seismicity and deep structure geodynamics authors make three subdivisions: European plate in the east and northeast, Moesian Microplate in the south, and Intra-Carpathian microplate in the center and north–west, over which they overlap a map of the main stress tensors.

![Fig. 4 – Geodynamic compartments and principal maximum stress tensors in Romania: I – European plate; II – Moesian microplate, a – Moesian Central block, b – Black Sea block; III – Intra-Carpathian microplate, a – the Pannonian block, b – Geto-Danubian block, c – Transylvanian block; 1 – crustal fault, 2 – fault, 3 – strike-slip fault, 4 – maximum principal stress tensor, 5 – geodynamic polygon, 6 – average orientation of the maximum principal stress, 7 – hypocenter with determined focal mechanism. (After [11]).](image)

In Intra-Carpathian microplate the authors found a NW–SE oriented compressional stress, due to displacement of the Pannonian block toward
Transylvanian block along some latitudinal strike-slip faults, dextral in the south and senestral in the north. The direction of this movement, that determines the orientation of 128°02′ of the maximum principal stress tensor, leads to a process of reverse faulting.

In the papers [12] and [13] the authors made an inventory of the seismic areas in Romania, and analyses the crustal seismicity of seismogenic areas including Banat, Crisana and Maramures and conclude that in this sector predominates reverse faulting and strike-slip type. Along the eastern edge of the Pannonian Basin there is a compressional stress regime with a maximum horizontal compressional stress axis oriented E–W, and indicating the compression of the contact between the Pannonian Basin and Carpathian Orogen.

A study of focal mechanism solutions for 140 crustal earthquakes ($M_w = 2.8–5.6$) in Banat in the period 1985–2006 show the following distribution of the type of faulting: 50 events with oblique normal faulting, 6 events with normal faulting, 37 events with displacement on the direction, 45 with oblique reverse and 2 with inverse faulting [14]. The fact that only 37 events (26%) of 140 indicate a shift in the horizontal direction and the rest up to 140 events indicate a vertical component, suggests that stress is predominantly vertical, which is expected due to the structure of the unleveled blocks of the crystalline basement.

### 4. SEISMICITY IN THE WESTERN PART OF ROMANIA

The region is seismically active in local seismic areas, more frequent in the Pannonian basin. A map of crustal and intermediate depth distribution of earthquake is given in Fig. 5, based on the epicentres in ROMPLUS catalog [15] until 31.12.2010.

Seismic areas can be seen on the western rim of Pannonian Basin from Banat up to Maramures, in Apuseni Mountains and sporadic in Transylvanian Depression. The magnitudes of the earthquakes recorded did not exceed $M_w = 5.6$ in Banat, $M_w = 6.9$ in Transylvanian Depression, and $M_w = 6.2$ in Crisana and Maramures [13]. The distribution of recorded magnitudes show that most recorded magnitude are low ($M_w = 2.00–3.0, \sim 90\%$), and the remaining 5% ($M_w = 3.0–4.0$), or 2% ($M_w = 4.0–5.0$ and $M_w = 0.0–2.0$) or < 1% ($M_w > 5.0$). In the category of events with $M_w < 3.0$, an important part may be suspected to be industrial explosions in quarries, especially in some areas of Western and Eastern Carpathians, parts of Transylvanian frame. The largest earthquakes seem to have registered in Banat, Crisana and SE Transylvania.

If we analyze the depth distribution of events in the region studied, with the exception of intermediate depth earthquakes in SE (Vrancea region), however, all the hypocenter in the first 50 km, *i.e.* crustal level and first subcrustal part. Among the 1647 events located in the first 50 km, 239 (15%) are the in first 5 km, of which
a part is suspected to be the nature of explosions blasting, 1086 (66%) are within 5–15 km depth, 207 (12%) between 15–30 km depth and 115 (7%) between 30–50 km depth.

In Banat there is a dispersion of epicentral areas. Earthquakes with magnitudes \( M_w > 5.0 \) were recorded in Banloc with \( M_w = 5.6 \) (07.12.1991) and \( M_w = 5.5 \) (12.02.1991), these are the most powerful local events in recent decades. Two historic earthquakes with magnitudes estimated \( M_w = 5.0 \) listed near Arad on 19.10.1797 and 15.10.1847. The same magnitude had the earthquakes north of Periam (10.17.1859), west Foeni (Meda, Serbia, at 02.04.1901) and Peciul Nou (05.27.1959). On 17.04.1974 an earthquake occurred in Satchinez, with \( M_w = 4.9 \). Three events were recorded with \( M_w = 4.8 \) near Banloc (10.19.1915), Peciul Nou (06.09.1936) and Jimbolia (30.08.1941). Another series of earthquakes with \( M_w = 4.7 \) are reported in area near Sănnicolau Mare and Mocrin of Serbia (10.31.1879), north Teremia (11.01.1879) and north of Timișoara (19.11.1879).

South of Vinga there were two seismic events with \( M_w = 4.7 \) (07.10.1887) and \( M_w = 4.6 \) (01.29.1900). Other two events took place at the Ciacova SV, \( M_w = 4.6 \) on 27.10.1915 and between Biled and Peciul Nou, \( M_w = 4.5 \) on 21.02.1960. Another series of earthquakes occurred with \( M_w = 4.3–4.2 \) near Banloc (10.09.1915), NW of Vinga (07.08.1938) and NW of Ciacova (22.10.1960).
At Liebling and south Foieni two earthquakes occurred with $M_w = 4.0$ on 07.20.1903 and 28.09.1927. Several events have magnitudes $3.5 \leq M_w < 4.0$: NW Lucareţ, $M_w = 3.9$ (11.29.1988); Recaş, $M_w = 3.8$ (21.01.1902); Ciacoava–Rudna $M_w = 3.8$ (03.10.1907); Banloc, $M_w = 3.8$ (01.10.1956); Peciu Nou, $M_w = 3.8$ (09.22.1957); SE Lucareţ, $M_w = 3.8$ (19.12.1991); NW Făget, $M_w = 3.7$ (13/07/1991); $M_w = 3.7$ NW Zam (07.19.1991); between Lucareţ–Lugoj, $M_w = 3.5$ (04.16.1913) and Voitec–Ghilad, $M_w = 3.5$ (03.24.1996). Series of earthquakes with $M_w < 3.5$ continues with numerous earthquakes in the above areas.

Focal mechanisms of Banat show that two types of faulting are prevailing: sliding on a direction type, more or less combined with reverse faulting and one can see the two types in almost all areas: Banloc, Foeni, Ciacoava, Liebling, Peciu Nou, Timisoara, Vinga, Calacea.

In [17] the authors consider earthquakes in Banat as multiple replicas (polikinetik events) for large events. A typical example is the sequence of seismic events between October 1879–April 1880. Another example is an earthquake in Timisoara area from 05.27.1959, $M = 5.0$ and just 5 km deep hypocenter, which was followed by two aftershocks in 1960. Some earthquakes are obviously related to seismotectonic alignments, as well Orşova–Terego line, that extends northward with the depression of Caransebeş. This alignment is assumed to be linked to a fracture that led to the formation of the Neogene depression. Another line, Moldova Noua–Oravita–Dognecea, oriented NS, is linked to the western edge of the sinclinal Resita–Moldova Noua and Supragetic Thrust. In the above cases the transmission of seismic energy is asymmetrical, and mainly to the NE, where the crystalline formations are on the surface. In western Banat known epicenters are in Rudna, Pardani, Vinga, Timişoara, in the areas of intersection of fractures of the foundation on the Pannonian basin, in areas where under the Neogene cover, there are some extending structures on the Mureş corridor, and to the south are extending fractures which delineate horsts and grabens formations in Serbia, in massive Vrset and Moraviţa area.

As a conclusion of crustal seismicity in Banat, this might be grouped into several areas: the area around the localities Banloc–Liebling–Peciu Nou–Banloc–Foeni; in the zone Periam–Jimboia–Teremia Mare–Sânnicolau Mare; the perimeter near Arad–Vinga–Calacea–Satchinez–Arad; in Timisoara–Buziaș perimeter Lugoj–Lucareţ–Bencecu Upper–Timişoara, and in some isolated locations, like Faget or Zam.

As noted above, in the year 1991 it was a special seismic activity, marked by earthquakes epicenter July 12, $M = 5.7$ in Banloc, July 18 at Herculane, $M = 5.6$, August 14 with Voiteg epicenter, $M = 4.6$ and December 2 with the epicenter at Voiteg, $M = 5.6$ and their sequences of aftershocks. Relatively intense seismic activity manifested in Banat in 1991, with the main shocks followed by numerous aftershocks of moderate magnitude, shallow seismic foci ($5 < h < 10$ km) led to significant damage in the epicentral area, and vulnerability due to higher buildings.
In the area between Arad and Oradea moderate seismic activity is known both from present and historical data. The paper [18] cites the Cris area near Elek (5+ intensity earthquake in 1905, on the Romania/Hungary border, north of Arad), Oradea areas, Barcăului Hills, Petreni and Apuseni Mountains. In Oradea area it is described the earthquake in 1886 that caused damage, with estimated 5+ intensity and $M_w \sim 4.1$. An event occurring further south, to Cefa, had the same intensity. It highlighted a probable Oradea–Cefa seismic line. In the Bârgăului Hills, near Cubulcut an earthquake occurred in 1906, with the intensity of 5+, with izoseismal lines oriented N–S. The assumption was made that the marshes south of Săcuieni were an “obstacle” in the energy propagation of the earthquake. Here it is suggested the presence of a seismic line in the direction Poclușa – Cubulcut – Târgușor. In Apuseni Mountains is recorded only one significant earthquake with intensity of 5+, with the epicenter between Baita and Sudrigiu on 07.11.1911. Another earthquake occurred the next day in Moneasa–Sudrigiu area.

In the Arad–Oradea area, crustal structure consisted of blocks of horsts and grabens which are not at the same level at crystalline basement and present differential movements that induce a moderate magnitude seismicity. The main epicentral areas are at Socodor, where earthquakes are produced: with $M_w = 3.8$ at 02.08.1905; with $M_w = 4.3$, at 08.08.1910; with $M_w = 3.0$ at 11.07.1910; with $M_w = 3.0–4.6$ at 6.22.1978; in Oradea with $M_w = 4.1$, 12.04.1886 and with $M_w = 4.2$ at 29.01.1906.

Seismic activity in the area Oradea–Carei is generated by normal epicentres, which had a maximum activity in the period 1829–1834. In the paper [19] the authors analyzed 54 earthquakes grouped into 12 epicentral areas, among which the most important are the Galoșpetreu, Andrid, Piscolt, Carei, Tarcea and Valea lui Mihai. The earthquake of 1.07.1829 ($M_w = 6.2$ after ROMPLUS) has produced large area of destruction near Galoșpetreu–Vășad–Andrid–Dindești–Irina with the epicenter likely at Andrid. The same epicenter appears to have had the earthquake of 15.10.1834 ($M_w = 5.6$). Contemporary documents record that seismic events were accompanied by geological phenomena like cracks in the ground from which artesian water has been sprinkled, gas fumes and streams of sand, and they heard noises underground. The maximum intensity reached was 8 degrees at Andrid–Dindești area where apex of the system is activated by a number of earthquake faults. Numerous aftershocks of magnitude smaller occurred in the days following the main shock. At Dindești a crack of about 3 km in length occurred, which emitted water vapor during the earthquake and later during the aftershocks.

The strongest earthquake occurred in Sânnicolau graben 29.04.1906 ($M_w = 4.2$) had its epicenter at Cubulcut. Izoseismal line configuration overlaps the direction of the earthquake fault bordering the lowered part of the Sânnicolau depression. In Oradea–Carei area there was a seismic positioning of epicentres both in the lowered compartments of tectonic blocks and along the faults which separate these blocks.
Other paper [17] from 1980 mention the existence of active seismic zones on the western edge of the Pannonian Depression around Oradea and Carei, at the intersection of some NE and WE fracture oriented toward N–E and E–W. The active character of faults is sustained by the presence of thermal waters that creeps along fault planes in the area Petreni–Carei.

In the studies [12, 13] the authors show that historical data in Crisana and Maramures suggested that potential earthquakes with magnitudes greater than 6 degrees might occur, although only a $M_e = 5.0$ event was reported in the last century. In this sector predominates reverse faulting and strike-slip type. Although the orientation of P axes is not sufficiently constrained, it seems that a horizontal compressional stress field at regional scale is predominantly from on a E–W direction.

For the large earthquakes in Crisana area some events are: 07.01.1829 ($M_s = 6.2$), 15.10.1834 ($M_e = 6.5$) and 23.03.1939 ($M_e = 5.1$).

Area Maramures (Baia Mare) is marked by a moderate crustal seismicity manifested around a few places. At Sighet have been highlighted some frequently active seismic foci [18]. In 1876 three events occurred with a felt intensity of about $I = 4$ degrees; in 1886 another event $I = 5+$ occurred at Niz Neresnice (Ukraine); in 1888 an earthquake of grade 5+ occurred in Coștiui; in 1902 an earthquake was felt at Tereșva (Ukraine); another one at Sarasau in 1911, $I = 5+$, followed a few days of weaker aftershocks; in 1926 an earthquake of $I = 4+$ with a maximum intensity along Sighet–Ocna Șugatag line. After how different the localities were affected, seismic lines are suggested to Sarasau–Teceu, Sighet–Ocna Șugatag and Coștiui–Strâmtura. The author mentioned that during 66 years (1876–1940), for which information was not felt intensities greater than 5, so seismic activity was relatively weak.

In the Maramures have been recorded earthquakes of up to $I = 5$ degrees in the period from 1876–1926, often with numerous aftershocks [17]. Earthquakes have occurred on a latitudinal alignment from Sighetul Marmătiei, westward along the Tisza, and the two alignments NW–SE between Sighet–Ocna Șugatag and Coștiui–Strâmtura. Earthquake of 30.06.1978 and three shocks were felt in March 1979 at Baia Mare with an intensity of 5–6 degrees. The two alignments Sighet–Ocna Șugatag and Coștiui–Strâmtura are parallel with the structures of Eastern Carpathians dipping fractures and reflected in the basement stage and lifting the base crystalline crust into contact with Neogene vulcanites. Baia Mare area is located upon a deep fracture in which there were injected the hydrothermal mineralization from Baia Sprie and Cavnic, then to the east the fracture zone corresponds to Poiana Botizei and further the fault borders the Rodnei Mountains to the north. Hypocentres of Baia Mare area are about 10 km deep, being located along a basement fracture, probably of Cretaceous age and reactivated in Neogen.
In [21] some 77 events are recorded with magnitude between 2.0–4.7, in 1662–1980, Fig. 6. The main epicentral areas are:

1. Sighetul Marmatiei – 23.01.1784, $M_w = 5.3$; 5.01.1823, $M_w = 5.0$; 1.03.1902, $M_w = 4.0$; 10.08.1926, $M_w = 4.0$; 28.03.1979, $M_w = 3.5$;
2. Baia Mare – 7.01.1896, $M_w = 3.5$; 14.09.1937, $M_w = 4.3$; 30.06.1978, $M_w = 4.0$; 8.03.1979, $M_w = 3.2$; 30.03.1979, $M_w = 4.5$;
3. Halmu – 11.03.1893, $M_w = 4.7$; 12.12.1901, $M_w = 3.7$; 24.10.1965, $M_w = 3.7$;

A local seismicity map shows the existence of several areas of maximum seismic energy density, corresponding to the main epicentral areas: Halmu, Sighetul Marmatiei, Crucisor, Borlești, Baia Mare, Cavnic and Firiza. These areas appear along directions E–W and NW–SE and overlap some of the faults known in the area.
In Transylvania seismic activity is sporadic (Fig. 6).

Historical data [18] shows that between 1840 to 1961 is known one earthquake localized in the basin: 3.10.1880 earthquake with an intensity of 5+ felt over an area of a parallelogram shape with peaks located around settlements Bazna–Târgu Mures–Turda–Alba Iulia. The earthquake was felt over a wide area of about 62,000 km² to Câlimani–Harghita eruptive complex, but not beyond the Carpathians. Surface shaken with an intensity of 5+ or higher exceeded 5,000 km². This earthquake had an epicenter which seems to be diffuse (which suggests a deeper source), one seismic shaking and a relatively large macroseismic area compared with the epicentral area. ROMPLUS catalog assessed this event with a magnitude $M_w = 5.3$. The culmination areas observed during the earthquake of 1880 were observed also during other earthquakes, such as from 10.11.1940, in Vrancea area. Such lines were maintained culmination Bazna–Băgaciu, Medias–Dumbrăveni partly superimposed on the line Medias–Sighisoara, Sibiu–Meşendorf, Ozd–Ogra, Turda–Cluj, Huedin–Şimleul Silvaniei. Tg. Mureş–Reghin–Teaca–Bistrita climax zone coincide with an anticlinal fold of Neogene deposits of in Transylvanian Basin.

Archives mention a relatively strong earthquake in Bistrita in 1800, but it had not been felt in Brasov, Sibiu and Bucharest, suggesting a local epicenter occurring on the Reghin–Teaca–Bistrita line [18]. In the same way it is mentioned an earthquake in Brasov, 1715, without being felt in Sibiu and Bucharest, or at Cluj in 1786, which has “ruined” four churches in the city. At the edge of the Transylvanian Basin was an earthquake in Jibou, on 26.05.1885, felt in the north of Transylvania on about 14,300 km², with an intensity of at least 5+ degrees, with a maximum of $I = 6$ at Domnin. Here it was defined the culmination of Jiboului line extended on a NNW direction. On the same line seems to have manifested the earthquake of 22.01.1830 regarded as “strong”.

Another earthquake having besides the main shock several aftershocks, occurred at Deva in the interval 29–30.04.1886. The earthquake was rated as weak, with $I = 4$. Radulian et al., (1999 and 2000) record Transylvanian Basin 11/19/1523 earthquakes ($M_s = 5.3$) and 10/26/1550 ($M_s = 5.3$).

At the heart of Transylvanian Depression a secondary epicentral area is located between the two Târnava rivers, most important earthquake is generated here on 3.10.1880. A recent earthquake occurred on 12.11.1978 with $M = 3.3$. Hypocenter was estimated at about 10 km depth. The earthquake must have had a tension mechanism [17].

5. 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 Fig. 6 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 km from the surface. Where there was a crustal seismicity, we were able to identify active crustal faults by aligning/group 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.

In the present paper, the authors were have used as the name of the faults, those names recognized by several group of researchers, or as they appear on geological maps nationwide. Based on this principle, crustal faults identified as active, were marked with a red line on the maps in Figure 7. Of course, in addition to those marked fault, there are other active crustal faults, but in the absence of information on their name, we skipped marking and “baptizing” them with new names, in order to reduce confusion among those who will read this study.

The Tectonic map (Fig. 7) 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, Sacoșul Mare (Buziaș)–Arad, Nădlag–Jimbolia. Another fault system, roughly orthogonal to the first one, fragmented in secondary blocks the grabens and horsts oriented NW–SE: the faults Lucareț, Timisoara, Calacea, etc. A third system, currently in South part of the basin has about E–W orientation.

In the west of Southern Carpathians, contact lines between the units Danubian, Getic and Supragetic, have an approximately NE–SW orientation. Here must be mentioned South rift Carpathian fault and Cerna fault, and Timocului fault and Tg. Jiu–Călimanesti fault, all horizontal moving dextral. Further north, South-Transylvania fault with horizontal displacement dextral, which limited the extent of Supragetic domain to the north, both in Banat and north of Masifs Poiana Rusca [16]. In the Poiana Ruscă the fault seem to be active, judging after a concentration of epicentres ($M_w = 2.0–3.0$) on one side of it (Fig. 7).
Besides these faults, it may be included a number of seismic lines: Caransebeş–Orşova, Bocşa–Dognecea–Anina–Moldova Noua [16].

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 (Fig. 7).

In the southern area there is Borod fault which border to the south the block of the same name.

Fig. 7 – Crustal earthquakes on the background of main tectonic units and fault systems from the western part of Romania, projected on the simplified Tectonic map.

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.

To the north and east of Carei, two major faults separated the depression of Satu Mare from the southern and eastern units: Bogdan/Dragos Voda fault and Halméu fault.

The main seismogenic areas are in Sighet Marmatiei on the fault Mara, at Baia Mare on the fault Dragos Voda, at Halméu on Halméu faults and satellites, at Jibou on Benesat–Ciuc fault, at Valea lui Mihai–Carei on the Galos–Petreu graben and Pişcolt raising, and north of Oradea on the Sânnicolau graben (Fig. 7).
Dragos Voda fault has been active from Neogene to Quaternary, by allowing distinct movements of the two compartments, a subsidence of the northern compartment compared to the southern compartment. Seismic events were localized along this fault Moara Borsa, Baia Mare and Crucișor ($M \leq 4.7$). An earthquake on 03.30.1979 at Moara Borsa had normal faulting mechanism type, with horizontally tension stress [21].

Overthrusts movements along Halmeu fault are weak as a result of compression of the eruptive block Satu Mare on the Baia Mare depression to the west. Focal mechanism of the earthquake in Rașca of 08.03.1979, $M = 3.9$, produced by a satellite fault of the Halmeu fault, suggest a subduction-type movement with horizontal compressive stress.

In Apuseni Mountains area of epicentres concentration is observed in the seismic area Câmpeni with $M_w = 2.0–3.0$, related to the contact between the Bihor unit in the north and Biharia nappes in the south. Small magnitude events makes us suspect at least some of them to be the nature of local blasting explosions.

In Transylvanian Depression the most significant seismicity is located in the Medias–Târnăveni area, north of Cluj or in the SE of depression at the contact with Carpathian Orogen. The main fault systems are south Transylvanian fault and north Transylvanian fault (dextral movement) with its extension towards the SE, Beclean–Odorhei fault (Fig. 7). Cenade fault in SW and Turda fault in the west have active character. The map in Fig. 7 shows two fault systems that are at the basement level: one NNW–SSE oriented system, with fault that litters the whole depression and the second with shorter lines, oriented on a E–W line, fewer and located on the sidewall of the depression. The most significant seismic zone is located between the two Târnava rivers, with a normal fault mechanism [17].

6. CONCLUSIONS

The present paper is an analysis of tectonics and seismicity in western part of Romania (Romanian sector of Pannonian depression, Transylvanian Basin and the Apuseni Mountains Orogen). Several maps interpreted by different Romanian authors on local tectonics are presented and a final map with active faults in the region of study is constructed.

The first part is a general presentation of fault types, which is intended to make the connection between faults as they are seen by geologists in the field and faults that are expressing the earthquake mechanisms, as they are seen by seismologists. The stress field in the crust is presented, with general presentation of the stress field in Romania.

In a later chapter is a summary of information on stress field of study areas and seismicity zone, the range of magnitude and hypocenter depths registered with
mention of the most significant events occurring over time and relative to areas where they were concentrated.

In the last chapter fault systems in the study region are presented, their peculiarities as they appear in the available studies projected on the local tectonic structure for each of the areas under examination. Results are reported using the tectonic map of Romania, on which epicentres of earthquakes in the catalog ROMPLUS (NIEP Catalog) by the end of 2010 are projected.

Seismicity in western part of Romania is the result of tectonic evolution, which created a fragmented structure at the crystalline basement level, with blocks that have suffered differential movements due to general tectonic stress in the area, and due to secondary factors such as erosion or lateral variations in density. Some of the faults formed during development of the units under survey were reactivated later in recent periods of stress and became seismogenic faults.

On the eastern rim of Pannonian basin (in Romanian sector) there are mainly two to three fault systems: a parallel system to the mountainous frame, a second approximately transverse to the first, and the third which has an angle to the first two, observed in Banat. Active faults that separate basement blocks have differential movements. The main faults in this sector are: Lugoj–Zarand, Sacoşul Mare (Buziaş)–Arad, Nădlag–Jimbolia, Lucareţ, Calacea, north Timișoara, south Transilvănă, south Salonta, Dobreşti–Sânnicolau Român, Borod, north Transilvănă, Dragoș/Bogdan Vodă, Halmeu, Mara, Făget and Benesat–Ciucea.

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. 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.

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