Abstract. Earthquake mechanism information is fundamental to determine the stress field and to define seismogenic zones. At the same time, it is a basic input to compute seismic hazard by deterministic approach. The present paper extends the catalogue of the fault plane solutions for the earthquakes in Romania, previously completed until 1997, for 1998 – 2012 time interval. The catalogue is limited geographically to the Carpathians Orogeny and extra-Carpathians area located in the south-eastern part of Romania because similar investigations cover the rest of the country. The catalogue comprises 259 intermediate-depth seismic events and 90 crustal seismic events, recorded in the considered time interval with acceptably constrained fault plane solutions. We use specific graphical tools in order to emphasize statistically representative features of the stress field as coming out from our results. The fault plane solutions of the Vrancea earthquakes generated in a confined sinking plate in the mantle reflect the dominant geodynamic process in the study region. The typical features revealed by all the previous studies on the subcrustal seismic activity (predominant dip-slip, reverse faulting, characterizing both the weak and strong earthquakes) are reproduced as well by our investigation. As concerns the earthquake activity in the crust, a few new refined aspects are highlighted in the present work: (1) a deficit of the strike-slip component over the entire Carpathians foredeep area, (2) different stress field pattern in the Făgăraș – Câmpulung zone as compared with the Moesian Platform and Pre-Dobrogean and Bărăsad Depressions, (3) a larger range for the dip angle of the nodal planes in the Vrancea subcrustal source, ~ 40° -70° against ~ 70°, as commonly considered.

Key words: earthquake mechanism; seismogenic zones; fault plane solution catalogue.

1. INTRODUCTION

The present paper is an extension of previous studies dealing with the focal mechanism and related stress characteristics for the earthquakes recorded in Romania (e.g., [1], [2], [3]). Thus, the catalogue of the fault plane solutions built up until 1997 is updated and expanded for the time interval 1998 – 2012 and subsequently analyzed in correlation with specific cluster of events and active faults.
We limit geographically our data set to the Carpathians Orogeny and extra-Carpathians area located in the south-eastern part of Romania. Similar investigations were carried out by [4] and [5], focused on the seismogenic zones located in the western part of Romania: Danubian zone and Banat area. Their results (140 earthquakes mechanisms) can be considered as a complement to our work in order to characterize the earthquake mechanism data for the entire Romania. Seismogenic areas that remains still uncovered includes the Transylvanian Basin and Crisana - Maramures region (north-western Romania) where we could not get enough data to compute reliable fault plane solutions.

The earthquake mechanisms are computed in all cases using the SEISAN algorithm [6] and the polarities of the first P-wave arrivals. The catalogue of fault plane solutions, presented in the Appendix A and accessible online at www.infp.ro, comprises 259 intermediate-depth seismic events and 90 crustal seismic events, recorded in the time interval 1998 – 2012 (see also Table 1). We selected only the solutions with minimum 10 reliable polarities and acceptable stations coverage. The location of the events is presented in Figure 1 together with the seismogenic zones, as they were defined by [7] slightly changed here.

Table 1.

Number of earthquakes recorded between 1998 and 2012, with fault plane solutions available, associated with the study seismogenic zones

<table>
<thead>
<tr>
<th>Seismogenic zone</th>
<th>No. events</th>
<th>Mw</th>
<th>Depth [km]</th>
<th>No. stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moesian Platform – MO</td>
<td>42</td>
<td>2.3 – 3.3</td>
<td>2 – 38</td>
<td>10 - 51</td>
</tr>
<tr>
<td>Barlad Depression &amp; Pre-Dobrogean depression PD-BD</td>
<td>28</td>
<td>2.3 – 4.9</td>
<td>0 – 46</td>
<td>10 - 25</td>
</tr>
<tr>
<td>Fagaras – Campulung area – FC</td>
<td>20</td>
<td>2.3 – 3.3</td>
<td>0 – 25</td>
<td>10 - 34</td>
</tr>
<tr>
<td>Vrancea intermediate depth - VNI</td>
<td>259</td>
<td>2.7 – 6.0</td>
<td>64 – 167</td>
<td>10 - 60</td>
</tr>
</tbody>
</table>

Most of the study crustal earthquakes belong to the background seismicity, with magnitudes Mw below 4, except the event of 3.10.2004 in the Northern Dobrogea with Mw = 4.9. Almost three thirds of earthquakes occurred in the Vrancea region (VRI) in the mantle range (64 to 167 km depth, Table 1). Most of them have magnitudes Mw below 5, with only 5 earthquakes with magnitudes Mw ≥ 5. The largest earthquake was recorded on 27.10.2006 with Mw = 6.

The crustal earthquakes follow closely the areal distribution of the seismogenic zones, which were set on the basis of seismicity trends as covered up by the entire catalogue of earthquakes in Romania and on the basis of geotectonic grounds.

The computed fault plane solutions are plotted in the inset of Fig. 1. For a better graphical presentation/visualization, we kept for the Vrancea subcrustal earthquakes the mechanism solutions only for the larger events (Mw > 4.5), which are 22 subcrustal events out of 259 (Table 1).
Fig. 1. Tectonic map of the south-eastern part of Romania (after [16]) and the epicentre location for the earthquakes considered in this paper. In the inset the focal mechanisms for 90 crustal earthquakes (red circles) and 22 intermediate depth earthquakes with Mw > 4.5 (blue circles) from Vrancea intermediate-depth zone (VNI) are represented.
We can draw some conclusions from a simple visual examination of the figure:
- Prevalence of reverse faulting in the Vrancea subcrustal source;
- A tendency of the nodal planes for the Vrancea subcrustal source to be oriented either parallel or perpendicular to the Carpathians Arc bend;
- A large variety of fault plane solutions for the crustal events both as faulting type and nodal plane orientation.

2. SEISMICITY DISTRIBUTION

Seismicity in Romania is concentrated at the Carpathians Arc bend in the Vrancea region. Here, an isolated lithospheric slab downgoing in the mantle is permanently releasing seismic energy in an extreme narrow volume. In average, three earthquakes with magnitude above 7 were reported each century for a time span of six centuries.

The origin of intermediate-depth seismicity in the Vrancea area is still an ongoing debate. The lithospheric volume which is seismically active can be approximated by a prism vertically oriented between 60 and 170 km depth, with a horizontal cross section of 30 x 70 km². Above 60 km and below 170 km the seismicity is suddenly cut off, although the high-velocity body, as determined by seismic tomography, extends notably beyond these limits ([8], [9]). The most important intermediate depth earthquakes have been analyzed by [10].

The seismic activity in the crust is dispersed over the Carpathians orogeny and foreland with significant enhancements in several seismogenic zones, as defined first by [7].

The crustal earthquakes are commonly small to moderate (M_w < 6). Only in the FC zone a few shocks of magnitude above 6 (M_{max} = 6.5) were reported in the Romanian catalogue, in about one millennium time interval [11]. The crustal seismicity is generally associated with the basement fracture systems [12] and [13].

In the Figure 1 we focus our attention on the seismogenic zones located in the south-eastern part of Romania. The positioning of the other seismic areas in Romania is represented in [7]. Given that tectonically and geologically the seismogenic areas situated in front of the Carpathians Arc, south of the Peceneaga-Camena fault in the Moesian Platform, do not differ notably, we prefer to consider in our subsequent analysis a single area (MO) in this region. In the same way, we combined the Pre-Dobrogean depression and Bârlad depression zones into a single area (PD-BD). The Vrancea intermediate zone (VNI) and Făgăraș-Câmpulung zone (FC) are the same as defined in [7]. We slightly adjusted the Pre-Dobrogean zone, which was extended to the north-west in order to cover also the North Dobrogean Orogeny and to have a common margin with Bârlad Depression zone and to be extended over the southern flank of Sf. Gheorghe fault (Fig. 1). The adjustments relative to the previously defined seismogenic zones are made to include all the earthquakes in the catalogue and to keep at the same time their adherence to a specific tectonic province (Fig. 1).

The eastern sector of the Moesian Platform, located between the Intramoesian fault and Peceneaga-Camena fault is more seismically active as
compared with the sector located west of the Intramoesian fault, which is almost aseismic. The seismicity concentrates close to the Carpathians Arc bend, overlapping to some extend the epicentral area of the Vrancea subcrustal earthquakes (VRI). Quite frequently, the earthquakes are generated in moderate size sequences. Typical sequences were recorded in the Focşani – Râmnicu Sărat and Vranceaia areas ([14]; [15]). Many times, the earthquake sequences in front of the Carpathians Arc bend display alignments parallel to the orogeny, probably in connection to a system of buried faults beneath the Focşani sedimentary basin ([16]; [17]).

The Intramoesian fault crosses the Moesian Platform on the SE-NW direction separating two distinct major sectors with different constitution and structure of the basement. Although the Intramoesian fault is considered a major fault, which extends from the continental platform of the Black Sea to the NW under the Getic Nappe [18] and which is supposed to reach in depth the lithosphere base [19], the associated seismicity is weak and scarce. The prolongation of this fault under the Pericarpathian line and the relations with the Fagaras - Campulung zone is still under debate (Fig. 1).

A scarce seismicity is noticed to the west of the Intramoesian fault, which extends over the entire western part of the Moesian Platform, until it comes into contact with the Southern Carpathians in the Danubian seismic region (not shown in the Figure 1).

For the seismogenic zones located in the western part of Romania, located by [7], some earth sequences are analysed by [20] and mechanism data are examined by [3] as well as in [8] and [9].

The Peceneaga-Camena fault separates the Moesian Platform unit from the North Dobrogean Orogeny. The seismic activity to the northern side of the Peceneaga-Camena fault cover roughly three tectonic units: North Dobrogean Orogeny; Pre-Dobrogean Depression and Bârlad Depression. The Pre-Dobrogean depression lies to the north North Dobrogean Orogen, being separated from it by Sf. Gheorghe fault. The Pre-Dobrogean Depression is continuing to the north-west into Bârlad depression, which is north of Trotuș fault (Fig. 1, after [18]).

The Bârlad Depression is a subsiding depression on the Scythian Platform in contact to the north with the southern edging of the East European Platform (Moldavian Platform). As was also noted by other studies [2], the seismicity and focal mechanism features in the PD and BD zones are similar, and therefore, we can merge them in a single seismic active area (PD-BD), which includes also the North Dobrogean Orogeny.

The Făgăraș-Câmpulung area is the eastern seismic active segment of the Southern Carpathians. It is characterized by strong shocks that reached up to $M_w \sim 6.5$ (the maximum magnitude recorded in Romania for crustal earthquakes). The last major seismic event was recorded on 26 January 1916 ($M_w = 6.4$) and it was followed by a significant aftershock activity which lasted several weeks [21]. The geotectonics of the area is quite complex with relative distinct activities in the central and western side (Făgăraș Mountains and Loviștea Depression) and eastern-south-eastern side (Sinaia area). The earthquakes generated in the south-eastern side could be eventually associated with the north-western edge of the Intramoesian fault. A large sequence started on 4 May 1993 in the Sinaia area and
lasted through the entire year (maximum magnitude $M_w 4.7$), estimated using the seismic moment computed by [22].

### 2.1 Fault plane solutions

We follow the convention of Aki and Richards (1980) [23] to define the nodal plane parameters (strike, dip and rake). Fault strike is the direction of a line created by the intersection of a fault plane and a horizontal surface, measured relative to North (0° to 360°). Strike is defined such as the fault dips always to the right side of the trace when moving along the trace in the strike direction. The hanging-wall block of a fault is therefore always to the right, and the footwall block on the left. This is important because rake (which gives the slip direction) is defined as the movement of the hanging wall relative to the footwall block. Fault dip is the angle between the fault and the horizontal plane (Earth’s surface) measured from the horizontal plane (0° to 90°). Rake is the direction in which the hanging wall block moves relative to the foot wall during rupture, as measured on the plane of the fault. It is measured relative to fault strike, ±180°.

### 3. STATISTICAL ANALYSIS

One of our goals is to determine the main features of the stress field as coming up from the fault plane solutions computed in this paper and to compare the results with previous investigations. For this purpose, we used graphical tools able to emphasize statistically representative features in our data set for each seismogenic area considered in the study. In this way, simple polar diagrams were employed to describe strike and dip behavior of the events in each active area.

In order to classify the type of faulting, we represent the distribution of the principal axes $P$, $T$ and $B$ using Kaverina’s projection [24], which improves the Frohlich and Apperson (1992)’ ternary diagram [25].

A dedicated program is employed for this purpose, which was made available by the author and which is described in [26] and [27].

#### 3.1. Vrancea subcrustal source - VNI

The polar diagrams for the azimuthal distribution of the two nodal planes (A and B) and for the plunge angle are plotted in the Fig. 2. Note the predominance of nodal planes oriented NE-SW, parallel to the Carpathians Arc bend and the plunge angles greater than 40°.

It is worth mentioning that this geometry of the faulting system corresponds with the orientation of the rupture faults for the largest Vrancea events ([28]; [29]; [30]). Taking into account the difference in scale between a moderate earthquake ($M_w = 4-5$) and a major earthquake ($M_w > 7$), it is not trivial such a feature. We may assume that the process of generating moderate earthquakes is controlled largely by the same tectonic forces as for generating the largest shocks.
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The analysis of the Fig. 2 reveals also a secondary tendency for the azimuthal orientation of the nodal planes, roughly perpendicular to the Carpathians Arc bend. This kind of focal mechanism is observed from time to time at moderate-to-large magnitudes ($M_w 5$ to $7$). It looks like the rupture orientation and length scale with the seismicity geometry (elongated along NE-SW, see Fig. 1): the rupture process propagates always along NE-SW plane for the large events, while for the smaller events propagate occasionally along a perpendicular direction (NW-SE).
The distribution of the principal axes $P$, $T$ and $B$, is represented in the Fig. 3 for the entire data set (259 Vrancea intermediate-depth earthquakes) and for the fault plane solutions obtained with minimum 30 polarities (31 events). In order to classify the type of faulting we used the visualization procedure proposed by [24]. Clearly, the reverse faulting is dominating in the Vrancea subcrustal source, independently of depth or magnitude ranges. This is even more evident when plotting only the events with best constraint fault plane solutions (minimum 30 polarities). Practically, none of the events has well-defined normal or strike-slip faulting; two events, located at the bottom edge of the descending seismically active body, are characterized by strike-slip with normal components, and four
events by strike-slip with reverse components. Whereas, most of the events have pure reverse faulting.

### 3.2 Eastern Moesian Platform seismogenic zone

The earthquakes with computed focal mechanism that we consider to fit in the Moesian seismogenic zone are spread over a wide area, both to the south-east and south of the Vrancea region and covering all the eastern Moesian Platform, from Peceneaga Camena fault to Intramoesian fault (Fig. 1). Most of them (36) are in connection with the Vrancea seismogenic area, while a few of them (6) can be rather associated to the Intramoesian fault area. The events are of small-to-moderate magnitude ($M_w \leq 3.3$) belonging to the background seismicity. Four of them are main shocks of local earthquake sequences: 30 April 2004 (15 events), 29 November – 3 December 2007 (41 events), 6 – 30 September 2008 (42 events) and 6 December 2009 (23 events), while the other 38 are single events.

The diagram for P, T and B axes (Fig. 4) shows an equal distribution among normal and reverse faultings and absence of pure strike-slip faulting. According to our results, mechanisms of subsidence and folding are prevailing in the region against transcurrent mechanisms.

### 3.3 Pre-Dobrogean Depression and Bârlad Depressions

The focal mechanisms were computed for 20 events located in the Predobrogean Depression and some 8 events located in the Bârlad Depression. The diagram for P, T and B axes (Fig. 5) shows broadly the same features as for the eastern Moesian Platform (Fig. 4): an equal probability for normal and reverse faulting and almost total lack of pure strike-slip faulting.
Fig. 5. Diagram for P, T and B principal axes distribution for Pre-Dobrogean and Bârlad Depressions.

This result suggests that despite the lateral differences among the tectonic units acting in the foredeep area of the Carpathians the faulting processes are quite similar, with prevalent subsidence and folding mechanisms.

Due to the reduce number of earthquakes in this zone and to the fact that the orientation of the P, B, T axes is very much alike the distribution presented in Fig. 7 for eastern Moesian Platform zone, the polar diagrams are represented for all the crustal earthquakes considered in the two zones, a total of 70 events (Fig. 6).

The distribution of dip angles in Fig. 9 is close to the distribution find for 104 events in the same crustal region after the old catalog of earthquake mechanisms [3], while the strike angles show the same almost equal distribution to all directions.

Fig. 6. Angular diagrams for azimuth and dip angles of the nodal planes – Eastern Moesian Platform area and PD-BD area.
3.4. Făgăraș – Câmpulung seismogenic zone

The catalogue of earthquakes with computed focal mechanism belonging to the Făgăraș-Câmpulung seismogenic area includes 20 events, most of them located in the southern side, towards the contact between Făgăraș Mountains and Moesian Platform. All the events occurred in the 1998 – 2012 time interval belong to the background seismicity (magnitudes no greater than 3.3).

Fig. 7. Angular diagrams for azimuth and dip angles of the nodal planes for the events of Făgăraș – Câmpulung area (FC).

The polar diagrams for the azimuthal distribution of the two nodal planes (A and B) and for the plunge angle are plotted in the Fig. 7. The statistics is too low to provide reliable trends in nodal plane orientation. Apparently, the fault planes are equally distributed on azimuth, while the dip angles have some three principal directions to 30, 60 and 85°.

Fig. 8. Diagram for P, T and B principal axes distribution for the Făgăraș – Câmpulung (FC) seismogenic zone.
The picture shown by the diagram for P, T and B axes (Fig. 8) for the Făgăraș – Câmpulung area, is somewhat different from that pointed out for the other seismogenic areas in the crust. It is closer to the typical distribution of the Vrancea subcrustal earthquakes, with a particular emphasis on reverse faulting component. This result suggests the prevalence of folding processes as a consequence of the convergent contact between Moesian Platform and Carpathians.

4. CONCLUSIONS

The catalogue of the focal mechanism for the earthquakes recorded in Romania, available until 1997 ([2], [3]) is updated for the period 1998 - 2012. Thus, the fault plane solutions for 259 intermediate-depth earthquakes (Vrancea source) and 90 crustal earthquakes (Moesian Platform, Predobrogean Depression, Bârlad Depression and Făgăraș – Câmpulung) are added to the existing catalogue (appendix A). The fault plane solutions are computed in all cases by inverting the polarities of the P-wave first arrivals manually picked up at the seismic stations of Romania, Republic of Moldova, Bulgaria and Ukraine. To this aim, the SEISAN algorithm [6] was applied. Only the solutions with minimum 10 polarities and acceptable coverage on the lower hemisphere are selected.

The seismic activity that took place during 1998 - 2012 time frame was limited to moderate-size events. The largest event was generated on 27 October 2006 (M_w = 6.0) in the Vrancea subcrustal source. The largest event generated in the crust occurred on 3 Oct. 2004 (M_w = 4.9) in the North Dobrogean Orogeny. For this magnitude range, the fault plane solutions of the shallow earthquakes is more likely related to local secondary faults than to the major faults located in the Carpathians foredeep region. We can simply explain on this line the variety of solutions in the Moesian Platform, Pre-Dobrogean Depression and Bârlad Depression zones. The existence of a mosaic of blocks named “buffer plates” or “sub-plates” have been postulated in the area located in front of Eastern Carpathians Bend, between the zone of the major crustal faults like Intramosian fault, Peceneaga – Camena fault, Capidava fault and Trotus fault, which are intersected by a secondary fault system which is roughly parallel with Carpathians. In the sense of [32] these are small blocks situated between major plates, which accommodate the relative displacements, like in a puzzle game.

As a general trend which is statistically consistent, note the deficit of strike-slip faulting. This result suggests the prevalence of subsidence and folding processes as stress release mechanisms in the entire Carpathians foredeep region, as well as in Moesian Platform and Bârlad depression. The hypothesis raised by a few authors in the last century on a trans-current movement along the major faults, crossing the aria situated between the Black Sea and Vrancea ([31]; [32]; [33]) is not supported by our results.

More than that it appears that the seismic activity in eastern Moesian Platform zone is limited to the east by Danube. In Central and Southern Dobrogea, although they are considered to be tectonic provinces belonging to Moesian Platform, there exist just a few earthquakes recorded in ROMPLUS catalogue. Central and Southern Dobrogea are more stable zones.
There is no evidence for strike-slip earthquakes along the major faults in the area, like Peceneaga – Camena fault and Capidava – Ovidiu fault, and they show no signs of mobility for the interval of time considered. More than that in his study of paleostress resulted from a great number of fault observations in Dobrogea, in [34] the author considers that after Paleogene the Peceneaga-Camena fault, as other faults in Dobrogea, were reactivated at certain moments only as reverse faults without any strike-slip component until present. The historic seismic activity along this faults in Dobrogea is clearly reduced, if we compare it to the seismic activity along Sf. Gheorghe fault in Northern Dobrogea (Fig. 1).

To the western part of the Moesian Platform (Wallachian sector), located west of the Intramoesian fault, very few earthquakes were recorded. The seismic events are not clustering along Intramoesian Fault, so there is no evidence that this crustal fault has still an active character. In fact, the Intramoesian fault have been introduced following mostly tectonic considerations (the presence of a large, potentially active fault) and not seismic data [7]. Although the fault is prolonged to the south of Calarasi, in Bulgaria, until Shabla area, there is no seismic activity evidence in this sector, until Shabla area, near the Black Sea.

The crustal seismic activity in this region can rather be seen as a response of the intense processes taking place beneath the Carpathians Arc Bend (Vrancea area) and materialized by a triple number of earthquakes occurred at intermediate depth in the same time interval, almost the same like in the previous catalogue [2]. For the combined seismogenic areas MO and PD-BD (70 events) the distribution of the dip angles is close to the distribution find for 104 events in the same crustal region after the previous catalogue of earthquake mechanisms [3], while the strike angles show the same almost equal distribution to all directions.

Crustal earthquakes appear not to reflect the significant trans-current motions between the tectonic units in the region along the main faults, but they rather express the moving and re-positioning of different blocks in the area, delimited by either the main fault system, which runs parallel to the Carpathians Arc Bend or by secondary faults, distributed to a general direction which is roughly perpendicular to the direction of the main fault system.

The fault plane solutions of the Vrancea earthquakes generated in sinking plate in the mantle are preserving the typical features revealed by all the previous studies on the subcrustal seismic activity in the Vrancea region: predominant dip-slip, reverse faulting, characterizing both the weak and strong earthquakes ([28], [29]). T axis close to vertical and P axis close to horizontal tending to be oriented perpendicularly to the Carpathians arc.

The considerable increase of fault plane solutions accuracy for the earthquakes recently recorded, due to the significant improvement of the Romanian seismic network (www.infp.ro) and of their statistical representativeness, allows us to individualize a few refined aspects not obvious in the previous investigations, such as: (1) deficit of the strike-slip component over the entire Carpathians foredeep area, (2) different stress field pattern in the Făgăraș – Câmpulung zone as compared with the Moesian Platform and Pre-Dobrogean and Bârlad Depressions, (3) a larger range for the dip angle of the nodal planes in the Vrancea subcrustal source, ~ 40°-70° against ~ 70°, as commonly considered.
Acknowledgments

The database for this work is organized in Appendix A (www.infp.ro) and it is part of this paper. The ternary diagrams in this paper are realized with a dedicated program which was kindly made available by the author and which is described properly in Álvarez-Gómez (2014).

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