FOCAL MECHANISM IN CORRELATION WITH SEISMOTECTONICS FEATURES OF EARTHQUAKE-PRONE AREAS IN ROMANIA

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ABSTRACT

A catalogue of fault plane solutions for earthquakes recorded in Romania between 1929 and 1997 is analyzed in order to outline statistical features of the fault plane solutions in correlation with the earthquake-prone areas in Romania. A few solutions recently obtained for the intra-Carpathian region of Romania have been added in order to better cover this area. The catalogue contains both crustal earthquakes (h < 60 km) and intermediate-depth earthquakes (h ≥ 60 km), located beneath the South-Eastern Carpathians arc bend (Vrancea region). Most of the fault plane solutions were computed 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. Only the solutions with minimum 10 polarities and acceptable coverage on the lower hemisphere were selected. In order to evaluate the main features of the stress field as coming up from the fault plane solutions, we used graphical tools able to emphasize statistically representative features in our data set for each seismogenic area. All the available earthquakes mechanisms are examined closely from the point of view of the distribution of the main angles strike, dip and rake and principal deformation axes, B, P and T. The statistical analysis of the diagrams shows the prevalence of the reverse faulting in the Vrancea subcrustal source with predominant vertical extension and horizontal compression. The nodal planes tend to be oriented parallel to the Carpathians Arc bend (along NE-SW direction). The results obtained for the crustal earthquakes generated in the extra-Carpathians and intra-Carpathians areas are close to a random distribution (both in nodal plane orientation and faulting regime), with no preferred alignments. A slight deficit of strike-slip faulting is however emphasized, suggesting the prevalence of subsidence and folding processes as stress release mechanisms in the crust at the scale of the entire study area.

Keywords: earthquake mechanism; seismogenic zones; fault plane solution catalogue.

1. INTRODUCTION

Seismicity in Romania takes place on two levels of depth, in the crust (h < 60 km) and in the mantle (h ≥ 60 km), which appear to be largely decoupled. The subcrustal seismicity concentrates in an extremely narrow active volume, descending almost vertically beneath the continental crust, at the south-eastern corner of the highly arcuate Carpathian Arc, in the Vrancea region. The density of the seismic energy release is very high taking into account the strong clustering in space and relative high rate of producing major shocks (magnitude above 7).

The situation is totally different for the shallow seismicity, which is much more dispersed and significantly smaller as rate of seismic energy release. Zones with increased seismicity are located along the Carpathian orogen, in front of the Carpathians Arc bend and at the contact between the orogen and the Pannonian Basin.

In order to assess seismic hazard of Romania, it is of paramount importance to define as accurately as possible the main characteristics of the seismicity regime in the earthquake-prone areas of the country both in terms of space-time-size pattern and of focal mechanism (e.g., Radulian et al. 2000a).

The present paper reconsiders the catalogue of fault plane solutions of Radulian et al. (2002) in order to

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investigate the specific features of the focal mechanism in correlation with the earthquake-prone areas in Romania. The solutions recently obtained by Oros et al. (2008; 2016) for Banat zone and the intra-Carpathian region of Romania have been added in order to better cover this area. The fault plane solutions are grouped according to the seismogenic zones as defined by Radulian et al. (2000b) and adjusted to some extent in this work. They are represented in the Figure 1.

The catalogue contains fault plane solutions for 590 earthquakes (197 crustal events + 393 subcrustal events) recorded in Romania between 1929 and 1997 with magnitudes ($M_w$) in the range 1.5 – 7.7. The catalogue includes three major Vrancea intermediate-depth events with magnitude above 7: 10 November 1940 ($M_w = 7.7$), 4 March 1977 ($M_w = 7.4$) and 30 August 1986 ($M_w = 7.1$). Most solutions were obtained using the first P-wave polarities. In a few cases the waveform inversion of local or teleseismic waveforms was applied. The investigation carried out by Bala et al. (2003) based on the catalogue of Radulian et al. (2002) was limited to evaluate the focal mechanism features in different depth intervals, one in the crust and three in the Vrancea subcrustal domain. The main conclusion was that the predominant clustering of the principal deformation axes and of the rupture plane orientation are focused in the Vrancea subcrustal source, divided by the authors in three segments: 40-100 km; 100 – 140 km; 140 -180 km. In the same paper, no clear trend of principal axes was noticed throughout the crustal domain (0-40 km).

However, the analysis proposed by the authors is not really pointing on the characteristics for the different seismogenic areas defined in Romania. The main purpose of the present paper is to enlarge the previous investigations in order to identify specific features in correlation with the earthquake-prone areas as well as the active tectonic regions in Romania.

Figure 1. Geological frame and the seismogenic zones defined as polygons (see text). Subcrustal earthquakes of the Vrancea region are plotted by blue symbols.
2. TECTONIC SETTING

The tectonic framework of Romania belongs to the Carpathians-Dinarides orogeny and Pannonian sedimentary basin system. This is a complex system involving shortening and subduction in the Carpathians and Dinarides, formation of contractional and extensional basins, opening of a large continental Pannonian back-arc system. The tectonic evolution of the region consists of extensional processes, subduction followed by volcanism and continental collision.

The seismic activity in Romania is concentrated at the Carpathians Arc bend, at intermediate depths (60 – 180 km) in the Vrancea region (zone VNI in the figure – the epicenters for Vrancea intermediate-depth earthquakes are represented as blue dots in Fig. 1). Here, an isolated lithospheric slab downgoing in the mantle is permanently releasing seismic energy in an extreme narrow volume (40 x 70 km in section and from 60 to 180 km depth). In average, three earthquakes with magnitude above 7 were reported each century for a time span of six centuries.

The seismic activity in the crust is following the Carpathians orogeny and foreland from one hand, and the contact between the Transylvanian Basin and Pannonian Basin and the Carpathians orogeny on the other hand. The seismogenic zones, as depicted in Figure 1, are similar with those defined by Radulian et al. (2000) and Arvidsson and Grunthal (2010), with some adjustments for the zones in the extra-Carpathian area as well as in Banat/Danubian zones. They follow the configuration of the major geotectonic and neotectonic structures, but their final polygonal configuration was tailored to include an optimal number of available mechanisms. For example, the Moesian zone (MO) covers practically the eastern segment of the Moesian Platform (Wallachian sector) situated in Romania, including an extra stripe from the Intramoesian fault to the west (apparently, the seismic activity is not delimiting the contact between the eastern and western sectors of the Moesian Platform, located on the Intramoesian fault, but extends to the west, to the Argeş river). The MO zone also covers part of the Carpathians Arc Bend (Fig. 1), including earthquakes that occur in the crust above the Vrancea intermediate depth zone (VNI). Bârlad Depression (BD) was extended from Trotus fault to the north, up to the Vaslui fault. The Pre-Dobrogean (PD) and Barlad Depression (BD) zones belong to the same tectonic unit (Scythian Platform) and can be considered separately, as well as jointly (Hippolyte, 2002) The seismicity along the Southern Carpathians is enhanced in the eastern sector, in the Făgăraş – Câmpulung zone (FC), and in the western sector, in the Danubian zone (DA). The seismicity in the Eastern Carpathians is too sparse and weak to define a seismogenic zone. Only in the FC zone a few shocks of magnitude above 6 (Mw = 6.5) were reported in the Romanian catalogue, in about one millennium time interval (Oncescu et al., 1999). The crustal seismicity is generally associated with the basement fracture systems (Bala et al., 2015).

The crustal earthquakes are commonly small to moderate (Mw < 6). Only in the FC zone a few shocks of magnitude above 6 (Mmax = 6.5) were reported in the Romanian catalogue, in about one millennium time interval (Oncescu et al., 1999). The crustal seismicity is generally associated with the basement fracture systems (Bala et al., 2015).

The crustal earthquakes with available fault plane solutions are plotted in the Figure 1 with different colors. The colors indicate the affiliation to a particular seismogenic zone. However, some of them are located in areas with exclusively background seismic activity (no well-defined active tectonics). For example, the events located at the eastern border of the Transylvanian Depression along the lithospheric fractures associated with the Neogene volcanic alignment (Calimani-Gurghiu-Harghita). Also, the events in the Apuseni Mountains, limited to sporadic low-magnitude shocks, apparently bearing no relation with geotectonic active structures.

2.1 Fault plane solutions and statistical properties

The fault plane solutions are computed on the basis of the polarities of the first P-wave arrivals using the SEISAN algorithm (Havskov and Ottemöller, 2001). The regional velocity model used in the calculations is common for crustal and subcrustal earthquakes. It was estimated from local tomography data for Vrancea region and surroundings as minimum 1D model (Popa et al., 2001). In the present
approach we adopted as selection criteria for reliable solutions: (1) minimum 10 reliable polarities, (2) acceptable ratio of rejected polarities versus input polarities and (3) non-zero focal depth. Applying these criteria to the databases collected from the existing literature, we come to a database as shown in the Table 1.

Table 1. Number of earthquakes recorded between 1929 and 1997, with reliable fault plane solutions, selected in the present paper

<table>
<thead>
<tr>
<th>Seismic region</th>
<th>No. events</th>
<th>$M_w$</th>
<th>Depth (km)</th>
<th>No. stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moesian Platform – MO</td>
<td>65</td>
<td>2.1 – 5.4</td>
<td>2 - 50</td>
<td>10 - 73</td>
</tr>
<tr>
<td>Pre-Dobrogean Depression - PD</td>
<td>7</td>
<td>3.0 – 5.1</td>
<td>5 - 32</td>
<td>14 - 81</td>
</tr>
<tr>
<td>Barlad Depression – BD</td>
<td>11</td>
<td>2.7 – 3.7</td>
<td>4 - 37</td>
<td>10 - 25</td>
</tr>
<tr>
<td>Fagaras – Campulung area – FC</td>
<td>15</td>
<td>1.5 – 5.2</td>
<td>2 - 50</td>
<td>10 - 38</td>
</tr>
<tr>
<td>Intra-Carpathian area</td>
<td>21</td>
<td>2.2 – 3.9</td>
<td>3 - 28</td>
<td>10 - 87</td>
</tr>
<tr>
<td>Crișana – Maramureș – CM</td>
<td>12</td>
<td>3.0 – 4.7</td>
<td>4 - 13</td>
<td>19 - 82</td>
</tr>
<tr>
<td>Banat and Danubian zones – BA and DA</td>
<td>75</td>
<td>2.0 – 5.6</td>
<td>3 - 20</td>
<td>16 - 70</td>
</tr>
<tr>
<td>Vrancea intermediate-depth source – VNI</td>
<td>393</td>
<td>2.8 – 7.7</td>
<td>60 - 201</td>
<td>10 - 232</td>
</tr>
<tr>
<td>Background events</td>
<td>6</td>
<td>2.6 – 4.7</td>
<td>7 - 35</td>
<td>12 - 22</td>
</tr>
</tbody>
</table>

The size and depth distributions of the events in the catalog are plotted in the Figure 2. The crustal earthquakes are of small-to-moderate size ($M_w < 6$) with the highest number of events around $M_w 3$. The depth range spans the entire crust thickness. The deepest crustal events are located in the Moesian Platform and Făgăraș – Câmpulung region.

Figure 2. Distribution on magnitude (a) and depth (b) for the crustal (top) and subcrustal (bottom) earthquakes.
The dataset for subcrustal events includes three major shocks ($M_w > 7$) and seven earthquakes with magnitude between 6 and 7. The depth distribution shows two significant features: a strong increase around 140 km depth and a sharp cut off below 160 km depth (more than 10 times from above to below 160 km depth). Note the location of a single isolated event below 200 km depth.

In order to emphasize the statistically representative features of the parameters of the fault plane solutions we employ simple polar diagrams to describe strike and dip behavior of the events in each active area and ternary diagrams for the distribution of the principal axes in order to classify the predominant type of faulting, if this exists. The projection proposed by Kaverina et al. (1996) to improve the ternary diagram of Frohlich and Apperson (1992) is applied using the software described in Álvarez-Gómez (2014 and 2015). According to this procedure, we can classify earthquakes in seven classes represented by specific rupture types: 1) Normal; 2) Normal – Strike-slip; 3) Strike-slip – Normal; 4) Strike-slip; 5) Strike-slip – Reverse; 6) Reverse – strike-slip and 7) Reverse (Figure 3).

![Classification diagram](image)


The diagrams for the azimuth and plunge angle distributions of the two nodal planes of the Vrancea intermediate-depth events are plotted in the Figure 4. They show a preference for a NE-SW nodal plane orientation (parallel to the Carpathians Arc bend) which coincides with the orientation of the rupture plane for the largest Vrancea earthquakes. The plunge angles concentrate in the interval from 45° to 75°.

![Nodal planes azimuth and plunge distribution](image)

Figure 4. The nodal planes azimuth and plunge distribution on polar diagrams for the Vrancea subcrustal earthquakes.

The same diagrams for the crustal earthquakes considered as a single set except the earthquakes in the Banat (BA) and Danubian (DA) zones is represented in the Figure 5. This time, the orientation of the nodal planes is quite homogeneous with a slight enhancement on E-W direction, while the plunge angles
show a maximum around 45° (normal faulting). Some reverse faulting is still present (especially in the outer side of the Carpathians Arc bend) as suggested by larger plunge angles, while strike-slip faulting (lower plunge angles) is significantly less representative.

Figure 5. The nodal planes azimuth and plunge distribution on polar diagrams for the crustal earthquakes occurred in extra Carpathians area.

The polar diagrams for the earthquakes in the BA-DA zone are plotted in the Figure 6. They show quite similar homogeneous orientation of the nodal planes with a slight enhancement on E-W direction. The plunge angles cluster around 45° - 70° suggesting the presence of significant reverse faulting component in the focal mechanism.

Figure 6. The nodal planes azimuth and plunge distribution on polar diagrams for the earthquakes occurred in the Banat and Danubian zones.

The distribution of the principal axes P, T and B for the Vrancea subcrustal earthquakes is represented in the Figure 7 for the entire data set (393 Vrancea intermediate-depth earthquakes) and for the events with magnitude $M_w \geq 5.0$ (47 events). Clearly, reverse faulting is dominating in the Vrancea subcrustal source, independently of depth or magnitude ranges. This is more evident when plotting the events with best constraint fault plane solutions (right diagram in the Figure 7).

We plot in the Figure 8 the distribution of the principal axes P, T and B for the crustal earthquakes distributed on five seismic areas considered in this paper (we merged in a single area the PD and BD zones since they belong practically to a single tectonic unit – Scythian Platform). The diagrams corresponding to the Banat and Danubian zones are plotted in the Figure 9.
Figure 7. Ternary diagrams for P, T and B principal axes distribution for Vrancea subcrustal zone (VNI). Left: all the events; right: only events with magnitude above 5. The dots are proportional to Mw magnitude; to the right, the color scale represents the depths of the events in km.
Figure 8. Diagrams for P, T and B principal axes distribution for the seismic areas generating characteristic crustal events: (a) Moesian Platform; (b) Pre-Dobrogean and Barlad zones; (c) Făgăraş – Câmpulung zone; (d) Transylvanian zone; (e) Maramures zone.

Figure 9. Diagrams for P, T and B principal axes distribution for the Banat and Danubian seismic areas generating characteristic crustal events. Top: all solutions (75 events); bottom: solutions with at least 30 stations (43 events).
For Banat region, the distribution of principal axes is less uniform, with a deficit for the reverse type of faulting. Combination of predominant strike-slip faulting and all the intermediate sectors to the normal faulting is present. The ternary diagrams characteristic for the Banat area (Fig. 9) might be similar to the diagram in the Crisana - Maramureș zone (Fig. 8e), although the last one refers to 22 events only. The diagrams of the focal mechanism for the crustal events occurred in the inner Carpathians region (Fig. 10a) and in the outer Carpathians region (Fig. 10b) are presented comparatively in Figure 10. The ternary diagram for the crustal earthquakes generated in the inner side of Carpathians (33 events), except Banat region, shows a rather uniform distribution with a slight deficit for the strike-slip and normal type of faulting (Fig. 10a). The focal depth is limited for this region down to 25 km. The diagram in Fig. 10b for the outer Carpathians region (98 events) shows a uniform distribution of mechanisms, with no preferred type of faulting. But this zone is characterized by a much dense distribution of events and the focal depth can reach the lowest crust (48-50 km depth). At any rate, the focal mechanism for the crustal earthquakes clearly differs from the predominant reverse faulting in the Vrancea intermediate-depth source.

![Diagram showing principal axes distribution](image)

Figure 10. Diagrams for P, T and B principal axes distribution for: a). seismic regions in the inner part of Carpathians (Transylvania, Apuseni Mts., Crisana - Maramures); b). in extra Carpathians seismic areas: Moesian region (MO) and Barlad and Predobregean Depression (BDPD) generating characteristic crustal events.

3. IMPLICATIONS ON SEISMIC HAZARD ASSESSMENT

Seismic hazard depends on the ground motion characteristics that we expect for a given site as a result of the occurrence of a significant earthquake and on the way such earthquake is produced in space and time. We can predict characteristic ground motion applying probabilistic or deterministic approaches. In any case, it is crucial to define as accurately as possible the seismogenic areas or active faults able to generate destructive earthquakes and the predominant features characterizing the associated seismic sources. One element that can notably influence the ground motion parameters is the focal mechanism, and for this reason it is considered as input parameter both in probabilistic and deterministic approaches. At the same time, the focal mechanism provides important information that should correlate with geotectonic features (active faults).

As concerns seismic activity in Romania there are two distinct types of seismic source: subcrustal source (Vrancea) and crustal sources. The source located at intermediate depth (60 – 180 km) beneath the Vrancea region is well-defined and constraint in space and preserves a dominant rupture process along an alignment NE-SW (tangential to the Carpathians Arc bend) within a compressional tectonic setting (reverse faulting). The results of the present paper validate these features and show that they can be extended over the entire scale of seismic activity, from small to major events. The parameters of this particular source, which controls the seismic hazard level over 2/3 of the Romania territory and parts of Bulgaria, Republic of Moldova, Serbia and Ukraine, are well determined based on the available observation data and can predict ground motions in site of interest acceptably realistic from engineering point of view.
4. CONCLUSIONS

The fault plane solutions presented by Radulian et al. (2002) for the earthquakes recorded between 1929 and 1997 in Romania are reconsidered together with recent fault plane evaluations by Oros et al. (2016) for the intra-Carpathian region and Banat and Danubian zones in order to investigate specific statistical features in correlation with the earthquake-prone areas. Except a few events, the fault plane solutions were computed on the basis of the polarities of the first P-wave motion. Only the events with at least 10 reliable polarities, acceptable ratio of rejected polarities versus input polarities and non-zero focal depth were selected. In total, 197 crustal events and 393 subcrustal events are analyzed.

The seismicity in the subcrustal domain (upper mantle) concentrates in a well-defined cluster of earthquakes beneath the Carpathians Arc bend (Vrancea region). The focal mechanism for these events shows predominant reverse faulting with a nodal plane (assumed to be rupture plane) oriented mainly parallel to the mountain belt (NE-SW). This orientation preference is noticed both for small-to-moderate events and for major shocks and expresses the existence of strong tectonic alignments in the high-velocity body descending in the mantle.

Figure 11. Seismogenic zones defined as polygons and dots with mechanism events. Ternary diagrams with at least 12 event mechanisms are represented for all the seismogenic zones.
A summary figure on the statistical analysis of the resulting fault plane solutions carried out for the study seismogenic zones using ternary diagrams for the principal axes is given in the Figure 11. The earthquakes produced in the crustal domain are scattered over wider areas, related to some extent to the contact between the tectonic units, but showing no clear alignments. Also, they are less significant as energy release. The crustal seismicity follows on the one hand the configuration of the Carpathian orogen, and on the other hand concentrates in front of the Vrancea region in the eastern sector of the Moesian Platform. It is worth to mention that the western Moesian Platform and Moldavian Platform are stable and practically aseismic. Hence, the earthquakes here are sporadically generated and can be included in the background seismicity. We removed these events from our analysis. Some of the events in the in eastern sector of the Moesian Platform and in the Făgăraș – Câmpulung zone are presumably in connection with the Vrancea seismogenic area. Other crustal events can be linked to the active faults identified in Romania, such as Peceneaga Camena fault and Intramoesian fault crossing the Moesian Platform from Black Sea to the Carpathians Arc bend.

The polar diagrams for the azimuthal distribution of the nodal planes and for the plunge angle do not suggest any preferential orientation. The variety of fault orientation and inclination indicates the complexity of the system of faults. The ternary diagrams for P, T and B axes show an equal distribution among normal and reverse faulting and a slight deficit for pure strike-slip faulting for the earthquakes along the Carpathians, in the platform regions located south-east of Carpathians and in the inner side of the Carpathians. According to our analysis, mechanisms of subsidence and folding are prevailing in the crustal range in these areas, wherever the earthquake is produced, while the transcurrent mechanisms are less encountered. A different regime is noticed for the Banat region, where the reverse faulting is less observed relative to strike-slip and normal faulting, indicating an extensional deformation field. A slight tendency to align up around a E-W orientation could be attributed to the reactivation of the system of faults bordering to the north and south the Transylvanian Basin in an extensional stress regime and the reactivation of reverse faulting characterizing the system of faults along the Eastern Carpathians and in the Carpathians foredeep area, adjacently to the Vrancea region (Radulian et al., 1990; Oros et al., 2017), see Fig. 11.

Generally, our results are only partially compliant with the major geotectonic units and the major faults system that cross or bound these units. The present-day first order stress field (Cloetingh et al., 2002) reflects the movement of the Adria plate through Dinarides into Pannonian Basin on a NE-SW direction causing a general shortening (about 1-2 mm/yr) and a gradual change toward E-W towards Eastern Carpathians and WNW-ESE towards Southern Carpathians (Bada et al., 2007). The stress model of Heidbach et al. (2010) is somewhat more complicated, but reflects grossly the same features. The fault plane solutions determined in our paper indicate important local variations of the regional stress tensor orientation and stress regime. We assume that local stress sources create additional stresses manifested through local seismicity. These can be caused by varying topography, lithosphere flexure and stress perturbations due to active faults and mainly intersections of faults generate the observed variations in the regional stress field pattern. In conclusion, local tectonic features, like intersections of some kind of brittle structures, faults systems, geotectonic structures with particular geodynamic history, weakness zones can be local stress concentrators able to change the regional tectonic regime and control the local seismic activity.

4. ACKNOWLEDGMENTS

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5. REFERENCES

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APPENDIX

The database for this work is organized in Appendix A (www.infp.ro) and it is part of this paper.