



# Revised catalogue of earthquake mechanisms for the events occurred in Romania until the end of twentieth century: REFMC

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## Abstract

The purpose of this paper is to present the most comprehensive catalogue of focal mechanisms for Romanian earthquakes which occurred between 1929 and 2000 in the Carpathian Orogen, the Moesian and Moldavian Platforms, and the Transylvanian Basin. The present catalogue (REFMC) is a first step toward creating a centralized and continuous database of earthquake mechanisms in Romania by revising and updating existing data for the twentieth century, which together with the Romanian earthquake catalogue (ROMPLUS)—continuously updated by the National Institute for Earth Physics, provides the fundamental information for any seismicity or seismic hazard assessment. In order to produce a close-to definitive version compatible with more recent and less uncertain focal mechanisms solutions, we revised multiple sets of data (some of which newly found), recalculated and corrected some of the fault-plane solutions and reached a consensus. The catalogue comprises 250 crustal events and 416 intermediate-depth events recorded in the twentieth century starting from 1929. On the basis of the new catalogue data and seismotectonic investigation, we propose a reconfiguration of the seismogenic zones located along Southern Carpathians toward the western side of Romania.

**Keywords** Earthquake mechanism · Seismogenic zones · Crustal seismicity · Romanian earthquakes

## 1 Introduction

The purpose of this paper is to present the research which lead to the compilation of the most comprehensive catalogue of focal mechanisms for all the earthquakes recorded in Romania until 2000 for which information within acceptable accuracy could be acquired. The earthquake mechanism catalogue was assembled on the basis of four main sources: (1) the catalogue published by (Radulian et al. 2002) for the earthquakes occurred before 1997; (2) the catalogue of (Oros et al. 2008) focused on Banat and Danubian areas; (3) the fault plane solutions computed for the last part of the catalogue (1998–2000), recently

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published in (Radulian et al. 2018); (4) the mechanisms of several low-magnitude earthquakes of Vrancea region and surroundings, determined by high-frequency waveform inversion in Ardeleanu (2012, 2018) and Ardeleanu and Raileanu (2011).

Available fault plane solutions from different published papers and internal reports were reconsidered for each event in the catalogue and finally a single mechanism was selected and attributed to that event. Whenever fault-plane solutions provided by different sources were available, all the sources were mentioned in the reference column. In some cases, necessary corrections to the previous solutions were carried out.

As a rule, the magnitude in the source document (paper, report, etc.) was adopted. In order to provide a unique magnitude scale for the entire catalogue, we adopted the moment magnitude ( $M_w$ ), in concordance with the Romanian earthquake catalogue—ROMPLUS (Oncescu et al. 1999). Whenever other magnitude scales were available ( $M_L$ ,  $M_D$ ,  $M_S$ ), we applied the conversion formulas proposed by Oncescu et al. (1999) in order to obtain associated  $M_w$  value. If  $M_w$  obtained by conversion formula is different from the  $M_w$  value in the ROMPLUS catalogue, the latter is also noted in parenthesis.

In its final form, the compiled catalogue is presented in Annex 1 and is made accessible online at [www.infp.ro](http://www.infp.ro). A comprehensive list of all the sources and abbreviations used is also provided in Annex 2. The paper is elaborated in two parts: (1) catalogue description and related statistics and (2) discussion on possible implications on configuring the earthquake-prone areas in Romania.

Seismicity in Romania takes place in two characteristic and distinct depth intervals: crust ( $h < 50$  km) and upper mantle ( $h \geq 50$  km). 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 crustal and subcrustal seismic activities appear to be largely decoupled by a transition layer (around 50 km depth) with poor seismicity. The density of the seismic energy release is extremely high in the subcrustal part 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 crustal seismicity, which is much more dispersed and significantly smaller as rate of seismic energy release (Radulian et al. 2018). Areas with increased seismicity are located along the Carpathian orogen, in front of the Carpathians Arc bend and at the contact between the Apuseni Mts. and the eastern part of Pannonian Basin.

The crustal structure in Romania reflects different tectonic zones as shown by Răileanu et al. (2012a, b), Bălă et al. (2017) and Bălă and Toma-Dănilă (2018). The crustal thickness is large in the platform areas located in front of the Carpathians, reaches a maximum thickness of 42–45 km beneath the Carpathians Arc bend area (Hauser et al. 2007), and continuously decreases in the inner side of the Carpathians toward 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 focal mechanism (e.g., Radulian et al. 2000b). Updating the fault-plane solution database will contribute to better define and constrain the input parameters for seismic hazard assessment (no matter the probabilistic or deterministic approach), stress field evaluation and active fault system mapping.

The present paper reconsiders the catalogue of fault plane solutions of Radulian et al. (2002) in order to investigate the specific features of the focal mechanism in correlation with the earthquake-prone areas in Romania. The solutions obtained by Oros et al. (2008) 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. (2000a) and adjusted to some extent in this work. While the peculiarities previously noticed for the earthquakes in the Vrancea intermediate-depth source (clustered beneath Eastern Carpathians Arc bend) are still present in our analysis, reinterpretation of data for crustal earthquakes allowed us to advance new features in the configuration of the seismogenic areas. This will be discussed together with several considerations on local tectonic and geologic features in the second part of the paper.

## 2 Catalogue description

### 2.1 Earthquake mechanism revision

The catalogue of Romanian Earthquakes Focal Mechanisms—REFMC (see Annex 1) contains 258 events which occurred in the crust (at depths  $-h \leq 50$  km) and 428 events which occurred at intermediate depths ( $50 < h \leq 201$  km). Most of the fault plane solutions were computed using the first P-wave polarities as recorded by the seismic stations in Romania, supplemented sometimes with polarities recorded at stations in the neighbouring countries. All valuable information was taken out from published papers or internal reports of the National Institute for Earth Physics and was integrated in the resulted catalogue.

Several catalogues covering partially or completely the area of interest and the time interval considered are available: RAD02 (Radulian et al. 2012), TOT02 (Tóth et al. 2002), OR08 (Oros et al. 2008), SAZ08 (Sandu and Zaicenco 2008), and RAD18 (Radulian et al. 2018). We provide in Table 1 outlines of these catalogues. To reach the original catalogue data, the references mentioned in these papers should be investigated. Sometimes, a branching quotation should be followed to get to the source information (for example, citation of Gerner (1995) in RAD02, who in turn quoted the original works that actually performed the focal mechanism computation).

In parallel with the catalogues above, we consider the global catalogues providing moment tensor solutions compiled by different agencies: the International Seismological Center (ISC 2015), the Harvard group (Dziewonski et al. 2001), see also references therein), the USGS (Sipkin 1986, 2002 and references therein), the Swiss Seismological Service (ZUR-RMT), and the Med-Net Regional Centroid Moment Tensor project (MED-RCMT), the last two for Europe. In all these cases, the moment tensor inversions

**Table 1** The sources of catalogue data

Catalogue	Time interval	No. events in the original catalogue	No. of selected events in REFMC	
			$h \leq 50$ km	$h > 50$ km
RAD02 (Radulian et al. 2012)	1929–1997	526	130	387
TOT02 Tóth et al. (2002)	1928–1998	190	7	2
OR08 Oros et al. (2008)	1959–2006	140	94	0
SAZ08 (Sandu and Zaicenco 2008)	1967–2006	282	0	6
RAD18 (Radulian et al. 2018)	1998–2012	349	15	29
ISC (International Seismological Center 2015)	1964–2000	106	6	11

are compiled using teleseismic waveforms and hence reliable solutions can be obtained only for larger earthquakes ( $M_w \geq 5$ ). Since the ISC catalogue (International Seismological Center 2015) includes the information from all the other catalogues, we adopted it as reference in Table 1.

For the largest events ( $M_w \geq 4.8$ ) for which there are solutions computed by inversion of teleseismic waveforms in global catalogues we complete a separate catalogue presented in Annex 3 This catalogue contains 11 solutions for intermediate-depth earthquakes and 6 solutions for crustal earthquakes which were selected for Romania and the time interval 1964–2000. The parameters of the fault-plane solutions differ in some cases significantly in comparison with the solutions obtained from polarities of local data and this is an argument to keep two separate catalogues for these events. Another argument is the importance of these events in any approach of seismic hazard assessment.

The REFMC catalogue is following closely the catalogue RAD02 for the time interval 1929–1997, supplemented with data from the catalogue TOT02, OR08 and SAZ08. The catalogue TOT02 consists of 190 events recorded between 1928 and 1998 in the entire Pannonian region (44.0°–50.0°N; 13.0°–28.0°E). The authors acquired the data from Gerner (1995) for the time interval 1928–1979 as Radulian et al. (2012) did, from Gerner et al. (1999) for the time interval 1980–1993 and from Tóth et al. (1999) for the time interval 1995–1998. TOT02 overlaps RAD02, except two events occurred in the north-western part of Romania (Maramureş) in 1979 (on 8 and 30 March). The other earthquakes belonging to the Romanian territory have similar fault plane solutions, as expected since they have the same source Gerner (1995). For 8 events with higher errors in RAD02, we adopted the solutions from TOT02.

SAZ08 catalogue was computed for the time interval 1967–2006 for the geographical area delimited by lat. 44°–50°N and lon. 24°–30°E. Since the authors used the polarities of the P waves reported in ISC bulletin as primary data, the fault plane solutions are available only for larger events (i.e.,  $M_w > 3.6$ ). For the time interval 1929–1997, only five events with focal mechanism (all of them from the Vrancea intermediate-depth source) differ in SAZ08 as compared with RAD02. For the other common events we preferred the fault plane solutions with the minimum proportion of inconsistent polarities.

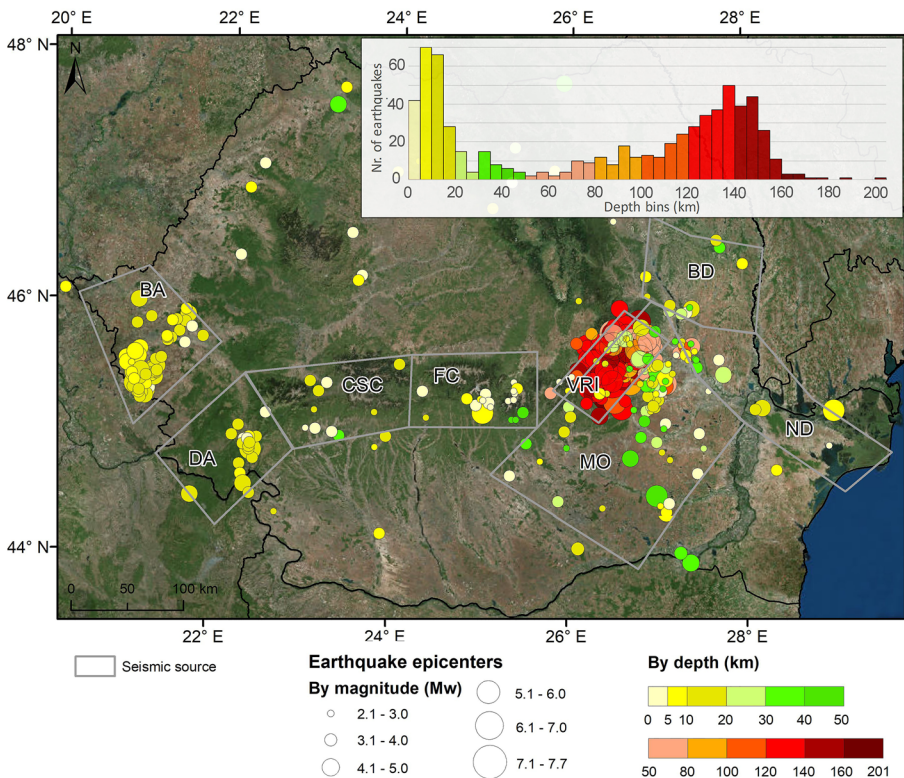
OR08 catalogue is focused on the Banat and Danubian regions (south-western side of Romania). The authors carried out a careful and critical analysis on the available data for this area and collected extra data from neighbouring countries. As a consequence, for this region their fault plane solutions were mostly preferred: 93 focal mechanisms for the time interval 1929–1997. However, the events outside the border which do not fit the seismic zones defined in the present paper were not included in our catalogue.

In addition, the works of Ardeleanu et al. (2005), Ardeleanu and Raileanu (2011), Ardeleanu (2012, 2018) provide the fault plane solutions for 21 small-size ( $M_w \leq 3$ ) earthquakes located in Vrancea region and in front of the Carpathians Arc bend (Moesian Platform). These mechanisms are determined by modelling the short-period good-quality records (high signal-to-noise ratio) from 5-to-7 local seismic stations, using the two-step algorithm INPAR (INDirect PARAMetrization) developed by Šílený et al. (1992). The Green's functions were generated by multimodal summation (Panza 1985; Panza and Suhadolc, 1987), using specific 1-D structures along the individual source-to-station paths. A bootstrapping procedure was applied to reduce the distortion of the reconstructed mechanisms, due to the oversimplification of the medium structure by the adopted 1-D models, and to estimate the uncertainty of the retrieved fault plane solutions.

Whenever several focal mechanisms were available for the same event we mentioned in the catalogue all the corresponding references, but we preferred to stick to a single

solution per earthquake. Exceptions are the events with solutions obtained in global catalogues, available for larger earthquakes occurred after 1977. For these events a separate fault plane solutions catalogue is presented, as mentioned above (Annex 3). Generally, we had no access to the raw data, so that we had no way to check the accuracy of the resulting solutions, except the number of stations used in the computation of focal mechanism which is presented in the last column of the catalogue. We selected as the fault plane solution the most recently computed solution or the one with the higher number of polarity data. The same procedure was adopted by Radulian et al. (2012), which provides the greatest part of the earthquake mechanisms. In the few cases, when the mechanisms determined from first arrival signs and by local waveform modelling were both available, the choice was made by taking into consideration the number of polarities used, on one hand, and the assessed errors of the solution calculated by full waveform inversion, on the other hand.

We adopted in all cases a single magnitude scale ( $M_w$ ). Events magnitude comprises a wide range from 2.6 to 7.7. The location of the events in the catalogue is represented in Fig. 1. The figure shows also the distribution of the events as a function of magnitude. The magnitude of the events in the crust ( $h < 50$  km) spans the interval 2.6–5.6. The event number is maximum for earthquakes with magnitude around  $M_w$  3.1. Nine earthquakes have magnitude at least equal to 5.0: three in the Banat zone (BA), one in



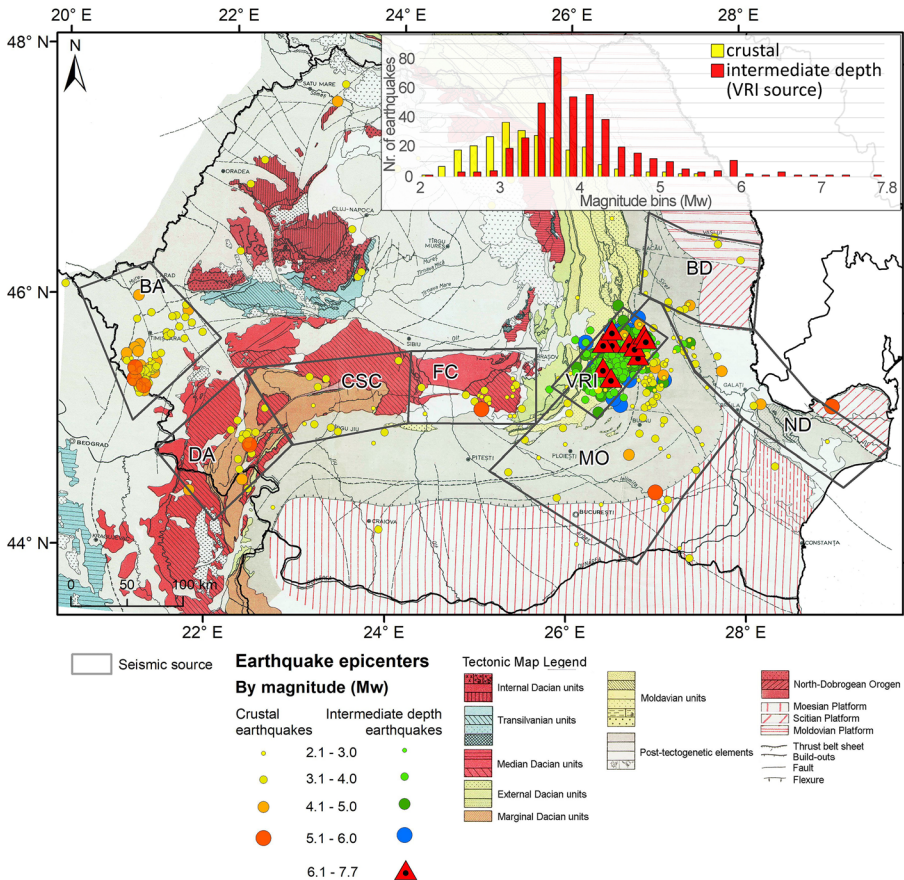
**Fig. 1** Epicentral distribution of earthquakes in the catalogue as a function of magnitude and depth, and histogram depending on depth interval. The configuration and nomination of the seismogenic zones (solid-line polygons) follows that defined in Radulian et al. (2000a) with some modifications (see below)



the Danubian zone (DA), two in the Moesian zone (MO), one in the Făgăraș–Câmpulung zone (FC) and one in the North Dobrogea zone (ND). The largest event in the crustal domain was recorded on 12 July 1991 in the BA area ( $M_w = 5.6$ ).

The size of the intermediate-depth events of the Vrancea source are shifted toward higher magnitude (Fig. 2) for two reasons: first, the greater attenuation which makes impossible detection of too small earthquakes (note the tremendous decrease of events below magnitude 2.5) and second, the capability of the intermediate-depth source to generate frequently events above magnitude 7. The maximum number of intermediate-depth events is obtained around magnitude 3.7. The catalogue includes the largest instrumentally recorded event generated by the Vrancea intermediate-depth source on 10 November 1940 ( $M_w = 7.7$ ) and other two Vrancea major events recorded on 4 March 1977 ( $M_w = 7.4$ ) and 30 August 1986 ( $M_w = 7.1$ ). Eleven earthquakes with magnitude in the 6–7 interval are included in the catalogue, belonging to the Vrancea intermediate-depth source as well.

The representation of catalogue epicentres as a function of magnitude and depth, along with tectonic background is given in Fig. 2. The subcrustal depths concentrate



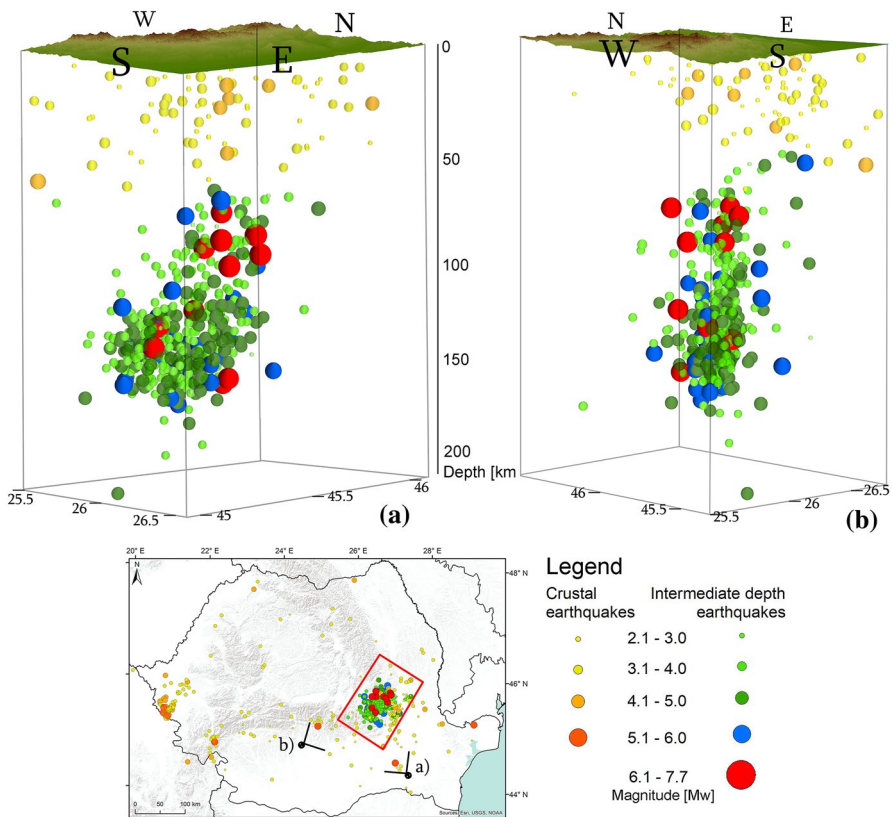
**Fig. 2** Epicentral distribution of earthquakes in the catalogue as a function of magnitude and depth, and histogram depending on magnitude. The base map is the tectonic map of Săndulescu (1984)

at the Carpathians Arc bend, in the Vrancea region. The hypocentres in the lower crust (30–50 km) tend to appear in the proximity of the Vrancea region, while hypocentres in the upper crust (0–30) predominate in all the other seismogenic zones.

In Fig. 3 the distribution of the hypocentres is given in a 3D projection for the Vrancea zone and neighbouring areas. Some decoupling between the seismicity in the crust ( $h < 50$  km) and beneath the crust is visible. We also note the clustering of the intermediate-depth foci in a quasi-cylindrical body almost vertically descending in the mantle with a strong density of seismic energy release. Down to 200 km depth this active seismic body is resembling the body put into evidence by Martin et al. (2006), which is characterized by an increased  $V_p$  velocity in comparison with the mantle around it.

## 2.2 Completion of the catalogue database

Focal mechanism solutions are provided in various forms in different studies. Often the nodal planes are reported without the associated principal tension or compression axes or, in other cases, only one nodal plane and two principal axes are reported. In some cases, slip parameter is used instead of rake parameter.



**Fig. 3** 3D representations of the events with earthquake mechanism in Vrancea zone, at crustal and intermediate depth level as seen from: **a** South-east; **b** South-west

In order to make the catalogue consistent we selected some of the solutions which lack the complete solution and filled-in the missing parameters, using classic matrix orthogonalizations. The final complete catalogue is given in Annex 1.

To calculate the slip (**l**) and normal (**n**) vectors from strike, dip, and rake of the given fault plane we use equations from Jarosch and Aboodi (1970) and Smith (2006). In our preferred coordinate system, **l** and **n** are:

$$l = \begin{pmatrix} l_E \\ l_N \\ l_U \end{pmatrix} = \begin{pmatrix} \sin \theta \cos \lambda - \cos \theta \cos \delta \sin \lambda \\ \cos \theta \cos \lambda + \sin \theta \cos \delta \sin \lambda \\ \sin \delta \sin \lambda \end{pmatrix}, \tag{1}$$

$$n = \begin{pmatrix} n_E \\ n_N \\ n_U \end{pmatrix} = \begin{pmatrix} \cos \theta \sin \delta \\ -\sin \theta \sin \delta \\ \cos \delta \end{pmatrix}. \tag{2}$$

The definition of the pressure (**P**), tension (**T**) and null (**B**) axes of the focal mechanism are:

$$P = \frac{1}{\sqrt{2}}(n - l), \tag{3}$$

$$T = \frac{1}{\sqrt{2}}(n + l), \tag{4}$$

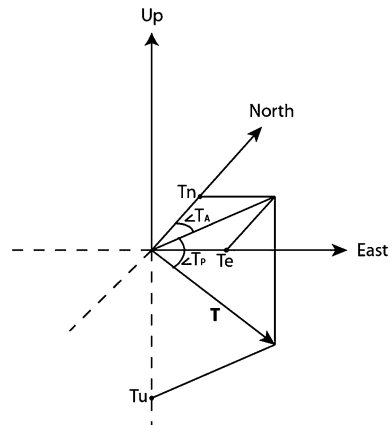
$$B = n \times l. \tag{5}$$

The principal axes can thus be defined in terms of the strike, dip and rake as follows:

$$P = \begin{pmatrix} P_E \\ P_N \\ P_U \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \cos \theta \sin \delta - \sin \theta \cos \lambda + \cos \theta \cos \delta \sin \lambda \\ -\sin \theta \sin \delta - \cos \theta \cos \lambda - \sin \theta \cos \delta \sin \lambda \\ \cos \delta - \sin \delta \sin \lambda \end{pmatrix}, \tag{6}$$

$$T = \begin{pmatrix} T_E \\ T_N \\ T_U \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \cos \theta \sin \delta + \sin \theta \cos \lambda - \cos \theta \cos \delta \sin \lambda \\ -\sin \theta \sin \delta + \cos \theta \cos \lambda + \sin \theta \cos \delta \sin \lambda \\ \cos \delta + \sin \delta \sin \lambda \end{pmatrix}, \tag{7}$$

**Fig. 4** Graphic representation of the chosen geographical coordinates (Up, East, North) and an example of a possible orientation of the T axis, its geographical components ( $T_E, T_N, T_U$ ) and the azimuth ( $\angle T_A$ ) and plunge ( $\angle T_P$ ), respectively





$$B = \begin{pmatrix} B_E \\ B_N \\ B_U \end{pmatrix} = \begin{pmatrix} -\sin \lambda \cos \theta + \cos \lambda \cos \delta \sin \theta \\ -\sin \lambda \sin \theta - \cos \lambda \cos \delta \cos \theta \\ \cos \lambda \sin \delta \end{pmatrix}. \tag{8}$$

The spherical coordinates of the  $P$ ,  $T$  and  $B$  axes, consisting of unit value, plunge and azimuth, respectively, are then derived geometrically from their geographical coordinates. The plunge is the angle down from the horizontal plane and the azimuth is the angle measured clockwise from North (Fig. 4).

For example, the plunge and azimuth of the  $T$  axis are:

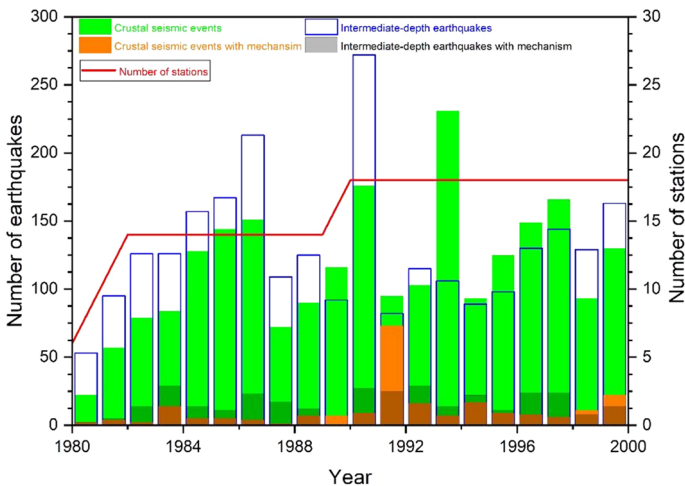
$$\angle T_P = a \tan \frac{|T_U|}{\sqrt{T_E^2 + T_N^2}}, \tag{9}$$

$$\angle T_A = a \tan \frac{T_E}{T_N} \pm 2\pi. \tag{10}$$

Similarly, the plunge and azimuth of the  $P$  and  $B$  axes, respectively, can be calculated using the standard transformations of geographical coordinates to spherical coordinates.

### 3 Evaluation of catalogue data

A diagram showing the number of earthquakes per year as recorded in the ROMPLUS catalogue from 1980 to 2000 in correlation with the evolution of the Romanian seismic network capability is plotted in Fig. 5. The rate of detected and located earthquakes has reached a stationary level after 1980 when the seismic network has been significantly



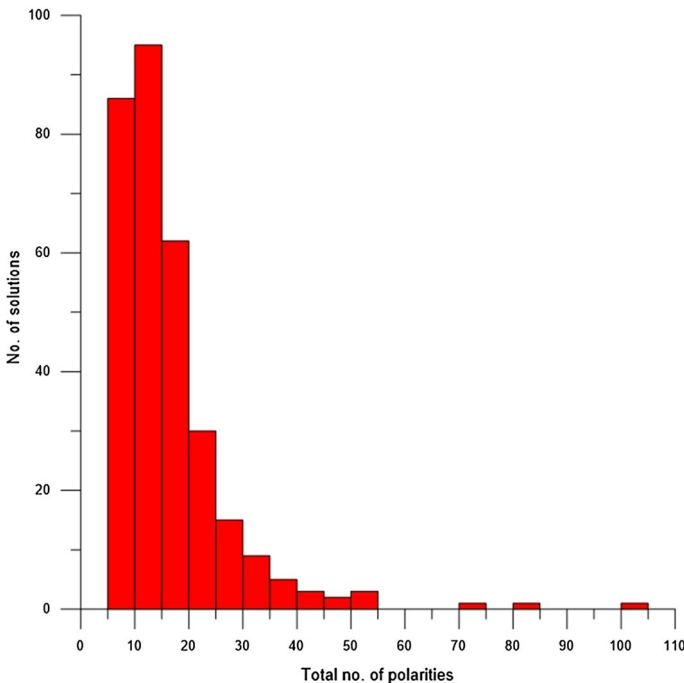
**Fig. 5** Evolution of seismicity as recorded in the ROMPLUS catalogue from 1980 to 2000 in correlation with the number of events with mechanism, separate for crustal and intermediate-depth events after Grecu et al. (2017)

improved from 6 stations with local recording to 14 stations telemetered in real time to the data centre in the National Institute for Earth Physics (Măgurele–Bucharest). Fluctuations in intermediate-depth seismicity (such as in 1986 and 1990) are explained by the after-shock activities associated to the Vrancea major shocks of 30 August 1986 and 30–31 May 1990, and in the crustal seismicity (such as in 1993) by a multiple and extended sequence recorded in the south-eastern part of the FC region.

In general, focal mechanisms are better constrained for the Vrancea intermediate-depth earthquakes due to the better stations coverage (the network was designed to monitor firstly these events) and the size of the events, which is systematically larger than the shallow events. One exception is 1991 when 60 fault-plane solutions could be determined for the earthquake sequence that occurred in the BA and DA regions (4 shocks with magnitude above 5 and more than 20 with magnitude above 4, see Oros et al. 2008).

As a rule, we selected in the catalogue the location and magnitude parameters as computed in the original sources. Thus, the magnitude values are often quoted in other scales such as  $M_S$ ,  $M_L$  or  $M_w$ . We converted all the magnitudes to  $M_w$  scale in order to set a uniform scale for the entire catalogue and to harmonize the information. The conversion was made using the formulas proposed by Oncescu et al. (1999) from  $M_S$  or  $M_L$  to  $M_w$  scale.

The number of seismic stations in the Romanian network was low before 1980 and even after starting to build a modern network the number of stations reached only 18 stations in 2000 (Fig. 5). Due to this situation the majority of the mechanism solutions were determined with less than 20 polarities (Fig. 6). Before 1980 it was customary to use stations from abroad in order to obtain focal mechanism solutions. For each event the number of



**Fig. 6** The distribution of the number of polarities used to obtain the solutions; 80% of solutions are computed using 20 polarities or less

polarities used is presented in the last part of our catalogue, while inconsistent polarities are noted only after 1996.

## 4 Seismogenic zones and their characterization in Romania

Tectonics of Romania comprises both pre-alpine platforms and alpine orogen units: western margin of the East European (Moldavian) platform, Scythian and Moesian platforms, Eastern, Southern and Western (Apuseni Mountains), North Dobrogea orogeny, foredeep of Eastern and Southern Carpathians, Transylvanian depression and western margin of Pannonian depression (Săndulescu 1984). The contacts between the major tectonic units are marked by crustal-scale faults, some of them still seismogenic.

In platforms a sedimentary cover with a variable thickness from a few hundred meters up to 10 km or more overlies the crystalline basement. The platform areas are overridden by the external units of Carpathians resulting in sinking of platform basement underneath the orogen along some faults parallel to the Carpathians. Other crustal fractures obliquely transverse to the Carpathians have created an unlevelled block structure. Many of the secondary crustal fractures that are marking the relatively small blocks have proven to generate a low to moderate seismicity (Săndulescu 1984).

Seismogenic zones are represented as polygon areas with potential to generate earthquakes of a characteristic size and with a specific frequency in time. For Romania several configurations of seismogenic zones have been proposed, starting basically from two approaches: geographical distribution (Radu et al. 1980; Constantinescu and Marza 1980) and seismo-geotectonic distribution (Radulian et al. 2000a, 2002) and successive updates, such as Pavel et al. (2016).

### 4.1 Vrancea intermediate-depth zone (VRI)

The **Vrancea intermediate-depth zone (VRI)** is a cluster of seismicity beneath the crust, with a narrow epicentral area and a significant vertical extension (see Figs. 1 and 3). It is partly overlapped by a seismic activity in the crustal layer of the Moesian Platform (**MO** in Fig. 1), but this one is more dispersed and less energetic. The fault plane solutions indicate a predominant compressive regime with the maximum compressive horizontal axis oriented either NW-SE or NE-SW.

### 4.2 The eastern sector of the Moesian platform (MO)

The entire eastern sector of the Moesian Platform, from the east of Intramoesian Fault to the west, until the contact with the North Dobrogea Orogeny and Barlad depression (Peceneaga-Camena fault), is generating small-to-moderate earthquakes (a single event of magnitude above 5 was reported during the twentieth century). The northern part of MO zone is partially overlapping at surface the Eastern Carpathians arc bend and the VRI intermediate zone (Figs. 1 and 2).

The seismicity in the *eastern* Moesian Platform is significantly more intense than in the western sector. Crustal earthquakes with  $M_w \leq 5.4$  were reported here. Several weak and moderate events located around Bucharest were well felt in the city. The most significant

earthquakes occurred NE and E of Bucharest in 1967 ( $M_w=5.0$  at Cazanesti) and 1960 ( $M_w=5.4$  at Radulesti) on basement faults of the Moesian platform. From west of the Intramoesian fault to the Olt river very few weaker earthquakes ( $3.0 < M_w < 3.9$ ) occurred on several basement faults of the Moesian platform (Bălă et al. 2015).

In the northern part of MO zone a crustal seismicity was reported with  $M_w < 5.0$  and relatively rare events. Enhancement of seismicity is noticed in the **Focsani Basin**, where more frequent small to moderate magnitude earthquakes ( $M_w \leq 5.6$ ) occur usually grouped in swarms and clusters. Here 20 earthquake sequences were recorded during the last five decades, some of them lasting for several weeks, the main shock being followed by tens of aftershocks. Recorded sequences indicate a systematic alignment of the breaking directions parallel to the Carpathians on a NE–SW direction. Hypocenters are in two depth intervals: 5–20 km and over 30 km. The NE–SW basement fault system at the bottom of Focsani Basin accounts for the seismicity of the two above mentioned areas. To the NE and E of Focsani Basin the **Braila-Galati-Marasesti** seismogenic area is known by a rather large number of weak to moderate events, sometimes with  $M_w > 4.0$  (Bălă et al. 2015).

Normal and strike-slip faulting is characteristic with random orientation of the principal axes.

#### 4.3 North Dobrogea Orogeny (ND) and Bârlad Depression (BD)

**North Dobrogea** (ND) and **Bârlad Depression** (BD) are represented originally as separated seismogenic zones (Radulian et al. 2000a). However, from tectonic point of view, they belong to the same unit (Scythian Platform), so they can be eventually combined in a single zone (Radulian et al. 2018). In BD some moderate earthquakes with  $M_w \leq 5.6$  occurred. Trotus fault and its satellites play a main role in the seismicity of the area.

Towards SE another seismogenic zone is located at the border of **Predobrogean Depression** with **North Dobrogea Orogen** (ND). Seismicity and focal mechanism solutions are quite similar with those in the Bârlad Depression: an extensional faulting regime and moderate magnitude events ( $M_w \leq 5.3$ ). Most of events are grouped along the Sfântu Gheorghe fault (Bălă et al. 2015).

#### 4.4 Făgăraș-Câmpulung zone (FC), Danubian zone (DA) and Banat (BA)

The Southern Carpathians, in contrast with the northern part of Eastern Carpathians, appears to be seismically active over the entire length of the mountain chain, from the vicinity with Vrancea zone to the east (FC) and to the Danube river to the south east.

The strongest Romanian crustal earthquakes occurred in the **Făgăraș-Câmpulung** zone (FC). The maximum estimated magnitude is 6.5  $M_w$ . The last major event occurred in January 26, 1916 with  $M_w$  6.4. A more recent event on April 12, 1969 had  $M_w$  5.2 and was followed by about 500 aftershocks.

The earthquakes occurred in the southern area could be generated on NE deep old Hercynian fractures and on NE younger alpine fractures (Cornea and Lăzărescu 1980), while the seismicity in the northern area could be connected to the fault systems which separate the northern flank of the Southern Carpathians from the Transylvania depression.

Unlike previous studies, in which only the Eastern (FC) and Western (DA) sectors were considered as earthquake-prone areas, we added the middle segment (Central segment of the Southern Carpathians—CSC) as seismogenic zone (Fig. 1). Rather conventionally, this segment fills the gap between FC and DA, between the Olt river and the area of sudden

bending toward SW of the Carpathians belt. The seismic activity after 2000 (Radulian et al. 2014; Plăcintă et al. 2016) confirms the capability of this segment to generate significant earthquakes. Another new relevant element come out from our investigation is the insertion of a strip (of ~ 50 km width) of low seismicity between **DA** and **BA**. Typical for Carpathians are normal and strike-slip faultings with some reverse faulting in the **FC** zone and at the contact of Getic Depression with the orogen.

A relatively well-defined and well documented seismogenic area is delimited to the western extremity of Romania (Banat zone—BA). This part was described at length in Oros et al. (2008) and more recently in Oros et al. (2016). It should be noted that this zone is considered the second earthquake endangered zone in Romania since moderate events with magnitudes of 5–5.5 occurring at shallow depths (5–15 km) are producing occasionally damage at surface. An extensional regime trend (normal and strike-slip) is noticed in the fault plane solutions.

As simple test to check if seismicity patterns related to the configuration of seismogenic zones as defined above, keep similar features for two separate time intervals, we compare in Table 2 the repartition of earthquakes among different seismogenic zones for two catalogues: the present catalogue (1929–2000) and the catalogue of Radulian et al. (2018) (1998–2012).

It should be noted that the ratio between number of earthquakes in Vrancea intermediate zone (VRI) and the crustal earthquakes in the zones above (MO, BD–ND and FC zones) is rather constant, being around 3.3–3.5 in both catalogues. Also, the ratio between the number of crustal events in the two catalogues, and the ratio between the number of intermediate depth earthquakes are similar (around 1.6–1.7), implying that the seismic activity regime keeps the same distribution among seismogenic areas and depth ranges with no notable changes for the two time intervals considered.

## 5 Conclusions

The catalogue of earthquakes recorded in Romania in the twentieth century is compiled from all the data available in the previously published studies and reports for the events occurred before 1994, and from the computations carried out mostly by the authors for the events which occurred after 1994, until the end of 2000.

**Table 2** Number of earthquakes with computed focal mechanism in 1929–2000 (1) compared to a selection from a recent catalogue in Radulian et al. (2018) [focal mechanisms in 1998–2012 (2)]

Seismogenic zone	No. events 1929–2000	Range of $M_w$ (1)	No. events 2001–2012	Range of $M_w$ (2)
Moesian platform zone MO	88	2.6–5.4	49	2.3–3.3
Bârlad depression and Pre-Dobrogean depression BD–ND	23	3–5.1	19	2.3–4.9
Făgăraș-Câmpulung area FC	16	3–5.2	7	2.3–3.3
Central Southern Carpathians—CSC	12	3–3.7	–	–
Danubian zone—DA	19	3.1–5.3	–	–
Banat zone—BA	80	3–5	–	–
Vrancea intermediate depth zone—VRI	416	2.6–7.7	261	2.7–6.0



Although not recent, the period revised here is of important reference for Romania's seismicity, including the largest instrumentally recorded Vrancea earthquakes. In order to produce a close-to definitive version compatible with more recent and less uncertain focal mechanisms we revised multiple sets of data, recalculated and corrected some of the parameters and reached a consensus. For the mentioned period, the catalogue comprises 226 crustal events and 406 intermediate-depth events starting from 1929.

A preliminary interpretation of the catalogue data confirmed the peculiarities of the Vrancea intermediate-depth nest of earthquakes and allowed us on the other hand to advance new features related to the configuration and properties of the seismogenic zones in the crustal domain. Thus, we introduce a new seismogenic zone in the central segment of the South Carpathians (**CSC** zone) and separate the Danubian zone (**DA**) from the Banat zone (**BA**) by a strip of reduced seismicity. We will dedicate to a future work the detailed analysis of the focal mechanism and related stress field as it results from the new catalogue and their implication on seismogenic zones characterization.

The present catalogue is a first step in creating a centralized and continuous database of earthquake mechanisms in Romania, which is added to ROMPLUS catalogue of earthquakes, computed and updated by the National Institute for Earth Physics. Updating the catalogue for the earthquakes occurred after 2000 has already begun with the catalogue of the mechanism solutions for the period 1998–2012, published and analysed by Radulian et al. (2018). These solutions have an increased accuracy since the original data and the computing software are treated in a uniform approach carried out directly by the authors.

The REFMC catalogue is built as a solid database for a number of future applications such as: (1) modelling the main stress field features and correlating with revised tectonic and geodynamic investigations in Romania; (2) modelling the seismic hazard according to the stress field at crustal and subcrustal levels; (3) contributing to a complete geodynamic model of the Vrancea region able to satisfy all the geologic/tectonic and geophysical/seismological observations.

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