CRUSTAL STRESS FIELD IN THE ACTIVE SEISMIC ZONES IN AND AROUND VRANCEA AREA, ROMANIA*

ANDREI BĂLĂ[1], MIRCEA RADULIAN[1,2], DRAGOȘ TOMA-DĂNILĂ[1]

[1] *National Institute for Earth Physics, 12, Calugăreni St., Măgurele, Ilfov, Romania*
[2] *Academy of Romanian Scientists, 54, Splaiul Independenței, Bucharest, Romania*

The mechanisms involved in the geodynamic evolution and the links with present day seismicity in and around an active orogenic area such as Vrancea area, located at the arc bend of the South-Eastern Carpathians in Romania, are of fundamental importance for studies concerning the seismic hazard assessment in Romania. The task is attempted through the partitioning of seismic events and corresponding stress at crustal level in and around the Vrancea zone. We start in this respect with the configuration of seismogenic zones as defined in previous investigations and then we use all the available and reliable earthquake focal mechanisms to study present-day deformation and stress. The goal of the present paper is to investigate the stress field characteristics in relation to the specific geotectonic and seismogenic zones in Vrancea and neighboring areas. The principal stress components are computed by inverting the fault plane solutions provided by a completed and updated catalogue for the crustal earthquakes recorded from 1952 up to 2012. Our investigation is justified to the extent that the basic hypothesis of adequately representing the seismic area partitioning by individual clusters of events is relevant at the scale of each earthquake-prone area and from statistical point of view (minimum 25 – 30 events/active zone). The results obtained through the inversion procedure show that the focal mechanisms are kinematically compatible with the selected clusters (earthquake-prone areas) despite an apparent scattering of the fault plane solutions. For example, the specific thrust faulting regime (compression) in the seismogenic zones in the Vrancea area and extensional stress regime as we go away from the Vrancea area. Note also the general lack of strike-slip faulting, except the seismogenic area located along the Peceneaga–Camena fault, which separates the Scythian platform to the north-east from the Moesian platform to the southwest. All the relevant information obtained in the process of inversion is further used in order to analyze the geodynamic evolution of the active seismic zones around Vrancea area and to try to improve the understanding of some geophysical observations that still do not have a satisfactory explanation in the light of existing models. The assessment of the stress field configuration based on improved and updated focal mechanism data led to a real improvement of the shape of the regional field as computed in the last version of the World Stress Map (WSM 2016).

Key words: stress field, crustal model, Moho discontinuity, tectonic structure, geodynamic behavior.

INTRODUCTION

The main feature of the seismic activity in Romania is the intense concentration at the Carpathians Arc bend, at intermediate depths (60–180 km) in the Vrancea region (zone VNI in Fig. 1). Here, an isolated lithospheric slab downgoing in the mantle is permanently releasing seismic energy in a narrow volume (40 × 70 km at surface and from 60 to 180 km depth). On average, three earthquakes with magnitude above 7 were reported each century for a time span of six centuries.

Seismicity in the crust is developed especially along the South Carpathians, Carpathians foreland (between the Intramoesian and Vaslui faults), and in the Banat region (BA):

– An extended area of diffused seismicity is considered to characterize the seismic activity in the eastern side of the Moesian platform, situated from the Intramoesian fault (in fact from a parallel line situated westward from the Intramoesian fault, along the Argeş river) to the Peceneaga–Camena fault (the border between the Moesian platform to the southwest and Scythian platform to the north-east). The Moesian (MO) zone also covers part of the Carpathians Arc Bend, including earthquakes that occur in the crust above VNI.

* Paper presented at the 5th GEOSCIENCE Symposium of the Romanian Society of Applied Geophysics, November 20–22, 2020, Bucharest, Romania.

- Seismic activity in the North Dobrogean orogen and Bârlad depression (ND–BD) zone concentrates along main faults: Peceneaga–Camena (north branch), Trotuş fault and Vaslui fault.
- A new active segment of seismicity (CSC) is introduced in the central part of the Southern Carpathians (following Radulian *et al.*, 2019) which has almost the same activity as Făgăraș–Câmpulung zone (FC).

The **North Dobrogean orogen** is an alpine folded zone, delimited by the Peceneaga–Camena fault to the south and by the Trotuş fault and Sf. Gheorghe fault to the north and north-east (Săndulescu, 1984; Hippolyte, 2002). The North Dobrogean orogen can be considered as a separate seismic zone – NDO, due to its tectonic origin, however in agreement with other papers (Hippolyte, 2002), we prefer to merge NDO with BD seismic zones because they belong to the same tectonic unit (Scythian Platform) and the seismic regimes have many features in common.

The **Peceneaga–Camena fault** represents the contact between the Scythian Platform and Moesian Platform. Some of the events located in its vicinity in the NDO zone and in the MO zone are probably generated along this PC fault so that they were previously artificially attributed to two different earthquake-prone areas (Radulian *et al.*, 2018). In the present paper we have considered the limit between MO and NDO zone as being some distance to the south from Peceneaga–Camena fault. In this way all the events located along this fault are attributed to the NDO zone, as in the same zone there is a dense system of faults having the same general direction, roughly parallel to the northern part of Peceneaga–Camena fault (Fig. 1).

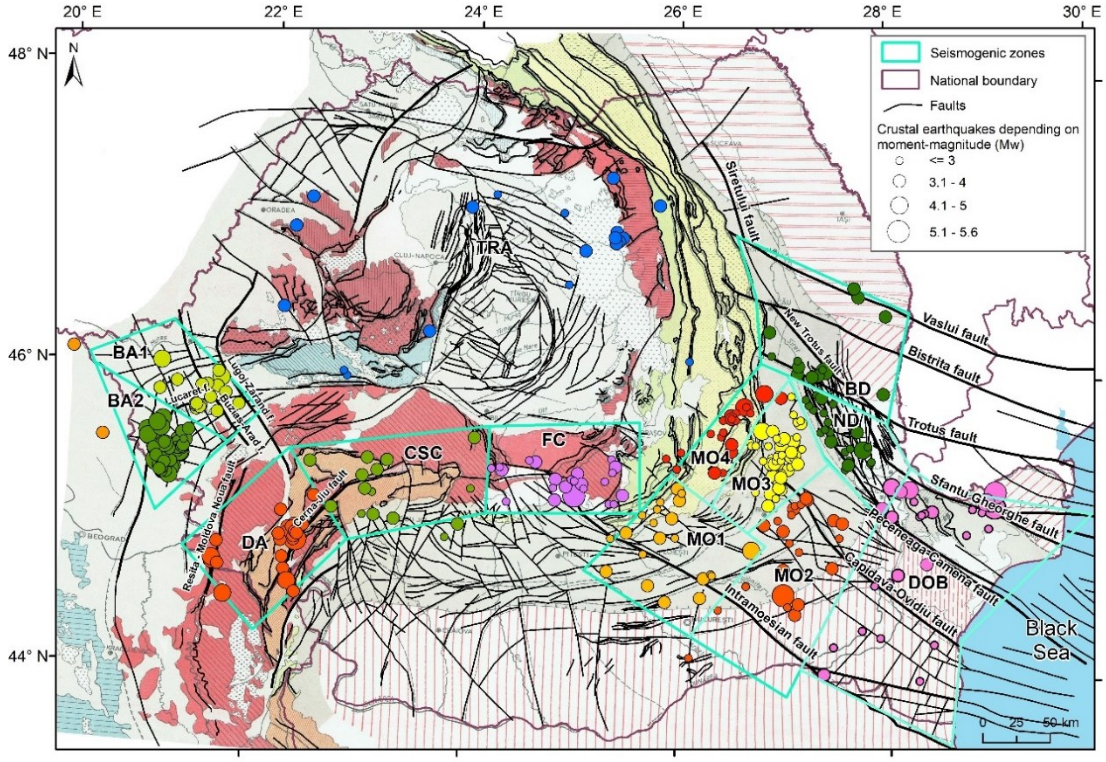

Fig. 1 – Seismogenic zones defined as polygons in the frame of tectonic settings (Săndulescu, 1984). The epicenters belonging to a seismogenic zone are specified by a particular color.

The seismicity along the **Southern Carpathians** is enhanced in the eastern sector, in FC, and in the western sector, in the Danubian zone (DA). More recent data suggest that the sector between them has earthquake generating potential (Radulian *et al.*, 2019), so that we insert a new seismogenic area in the central part of the Southern Carpathians (CSC). The crustal earthquakes with available fault plane solutions are plotted in Fig. 1 with different colors.

1. DISTRIBUTION OF EARTHQUAKE MECHANISMS IN SEISMOGENIC ZONES OF ROMANIA

A catalogue of fault plane solutions for earthquakes recorded in Romania between 1929 and 2012 is analyzed to outline the statistical features of the mechanism solutions in correlation with the earthquake-prone areas and tectonics in Romania. The catalogue contains both groups: crustal earthquakes (h < 50 km) and intermediate-depth earthquakes (h ≥50 km), but only the crustal earthquakes are analyzed here. The data for the 1929–2000 time interval are published in "Revised Catalog of Earthquake Mechanisms for the events occurred in Romania until the end of XX century – REFMC" (Radulian *et al.*, 2019). For the 2000–2012 time interval the catalog is completed with data from: "Earthquake mechanism and characterization of seismogenic zones in the south-eastern part of Romania" (Radulian *et al.*, 2018).

Because in Dobrogea region (DOB) the seismic activity is scarce, we added the data published by Maliţa and Rădulescu (2010), including solutions with a small number of polarities. The epicenters of all the crustal events with focal mechanisms considered in our study are plotted in Fig. 1 and their characteristics are summarized in Table 1.

Table 1

Number of earthquakes recorded between 1929 and 2012, with reliable fault plane solutions, selected in the present paper; N_{pol} means number of mechanisms with a specific number of polarities.

Seismic region	**No. of events**	$\mathbf{M_w}$	**Depth interval** (km)	**No. of polarities**
Crustal sources in the depth interval 0 < h ≤ 50 km	**354**	**2.3–5.6**	**1–49**	**8–185**
Moesian platform (MO)	122	2.3–5.4	2–49	10–73
North Dobrogean Orogen (NDO)– Barlad depression NDO-BD	38	2.4–5.1	3–33	10–81
Dobrogea (DOB)	30	2.3–4.5	2–37	10–25
Fagaras-Campulung (FC-CSC)	41	2.5–5.2	1–48	10–38
Transylvanian basin (TRA)	20	2.6–3.8	1–28	10–37
Banat (BA) – BA1+BA2	78	2.5–5.6	1–33	8–104
BA1	19	2.5–5	1–25	8–20
BA2	59	2.5–5.6	1–33	8–104
Danubian zone (DA)	25	2.6–5.3	1–20	8–185

2. METHODS TO OBTAIN RELIABLE HORIZONTAL STRESS VECTORS USING EARTHQUAKE MECHANISMS

2.1. COMPUTING METHOD AND ALGORITHMS

If we know focal mechanisms for a set of earthquakes that occurred in a specific focal zone, we can invert them to determine the tectonic stress (*e.g.*, Michael, 1984; Zoback, 1992). The stress inversion is based on several assumptions (Vavryčuk, 2015): (1) the stress is uniform in the region, (2) the earthquakes occur on faults with varying orientations, (3) the slip vector points in the direction of the shear traction on the fault (the so-called Wallace–Bott hypothesis; see Bott, 1959) and (4) the earthquakes do not interact with each other and do not disturb the background tectonic stress. Under these conditions the stress inversion allows us to estimate the orientation of the principal stress axes and the shape (stress) ratio.

$$R = (\sigma_1 - \sigma_2)/(\sigma_1 - \sigma_3) \quad (1)$$

The assumptions of the stress inversion look very restrictive, but analysis of real observations proves that they are well-satisfied in most cases, in particular, for local seismicity formed by weak or moderate earthquakes (Fojtíková, Vavryčuk, 2018).

A common difficulty of stress inversions of focal mechanisms is the ambiguous choice of a fault plane from the two nodal planes. Since incorrectly selected fault planes in focal mechanisms may bias the retrieved stress ratio Vavryčuk (2015), the inversion can be improved by incorporating an algorithm for identifying the fault plane based on evaluating the fault instability. As proposed by Vavryčuk (2014), the joint inversion for stress and fault orientations utilizing the instability concept is carried out in several iterations.

The program STRESSINVERSE is used here, in which the inversion is based on Michael's method (1984) and an instability criterion proposed by Lund, Slunga (1999) is incorporated. Details about the method and its accuracy are published in Vavryčuk (2015).

The partition of the earthquake epicenters is made using the seismic zonation employed by Radulian *et al.* (2018 and 2019), which is divided in 4 clusters (MO1 – MO4, see Fig. 1). Due to the spreading of the events in the Banat zone, this zone is divided into subzones: Banat 1 (BA1) in north and Banat 2 (BA2) in south. Although the seismic zones are not extended, we have enough events mechanisms in each seismic zone and the quality of our results validate our choice for the clustering.

The open-access code STRESSINVERSE has a particular feature. One can use in the input a random selection of the principal fault planes of computed mechanisms, and the code can compute in the output a list of the real fault planes that are matching the mean stress computed in the area. We have tested this possibility on a selection of 12 events with computed source mechanisms, occurred in southern Dobrogea. We have tried the code first with the computed planes A and then with the planes B. The program offered in the output a selection of the true fault planes and also the mean orientation of the event mechanisms in the area for both cases. The difference between the values of the mean mechanism computed in the two cases is in the order of 2–3%.

2.2. HORIZONTAL STRESS AXES AND PRECISION OBTAINED

In Fig. 2 stereograms of principal stress axes in all studied regions are presented on the tectonic map of Săndulescu (1984). The confidence limits of the principal stress directions σ1, σ2, σ3 are plotted as well. For the areas with less intense and more spread seismic activity, Dobrogea, MO2, MO3, FC, and CSC, we include in the inversion all the mechanisms available for these areas, even though different tectonic units are acting (this is evident for Dobrogea, for example). In this way, we process a greater number of mechanisms and a better resolution of the results is obtained. The results show that the crustal tectonic stresses seem to behave in a similar way over these large areas.

The estimation of errors is provided by a repeated stress inversion of focal mechanisms contaminated by artificial noise. We use 100 realizations of random noise in the inversion. The level of noise of $10–12^0$ corresponds to the estimated accuracy of input focal mechanisms. The inversion process is stopped after several iterations.

The fault-slip data are inverted to obtain the parameters of the reduced stress tensor. These parameters are the principal stress axes σ1, σ2 and σ3, where σ1> σ2> σ3.

According to Delvaux *et al.* (1997), the stress regime is a function of the orientation of the principal stress axes and the shape of the stress ellipsoid (R): extensional when σ1 is vertical, strike-slip when σ2 is vertical, and compressional when σ3 is vertical. So we can introduce the stress regime index R', and the relations between R and R' are:

R' = R when σ1 is vertical (extensional stress regime); R' = 2-R when σ2 is vertical (strike-slip regime); R' = 2+R when σ3 is vertical (compressional regime).

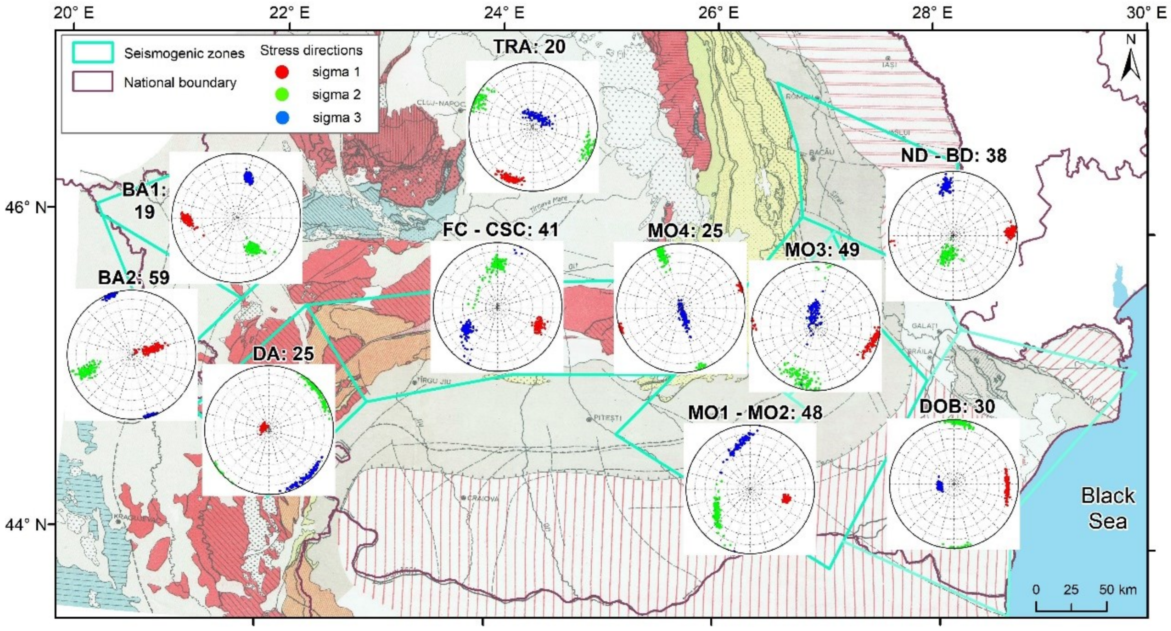

Fig. 2 – Stereograms of principal stress axes in all studied areas resulted from the inversion of mechanisms of the crustal earthquakes.

In Table 2, we have all the output data obtained with the code STRESSINVERSE for the seismic zones in Romania at crustal level. According to the value of R and the value of the plunge of σ1, σ2, σ3, which is closest to vertical, we established the value R' and the tectonic regime of the zone according to the inversion of the selected mechanisms.

Table 2

Rezults obtained for the inversion of horizontal stress with the code STRESSINVERSE for mechanisms of crustal earthquakes.

Seismic zone	No. of events	σ1	σ2	σ3	R	R'	Fault-ing type	Tectonic regime
		Strike/pl.	Strike/pl.	Strike/pl.				
FC-CSC	41	164/**63**	260/3	351/27	0.74+/-0.15	0.74	NF	extensional
DA	25	296/**81**	44/3	134/8	0.76+/-0.08	0.76	NF	Extensional
BA1	19	269/24	153/43	19/37	0.63+/-0.16	1.37	-	Inconclusive
BA2	59	74/**62**	251/28	342/1	0.33+/-0.17	0.33	NF	Extensional
MO1	23	119/39	306/51	212/3	0.75+/-0.10	1.25	SS?	Inconclusive
MO2	25	80/38	189/23	302/43	0.81+/-0.10	2.81	-	Inconclusive
MO1-MO2	48	108/42	220/23	330/39	0.87+/-0.10	0.87	-	Inconclusive
MO3	49	103/7	195/14	348/**74**	0.80+/-0.14	2.80	TF	Radial compression
MO4	25	71/0	341/4	163/**86**	0.81+/-0.10	2.81	TF	Radial compression
MO3-MO4	74	84/1	354/19	177/**71**	0.78+/-0.10	2.78	TF	Radial compression
DOB	30	94/20	184/0	274/**70**	0.38+/-0.12	2.38	TF	compression
ND-BD	38	85/7	194/**69**	352/20	0.66+/-0.12	1.34	SS	Strike-slip
GAL	18	278/**59**	90/31	182/4	0.83+/-0.09	0.83	NF	Extensional
TRA	20	203/13	112/6	357/**76**	0.67+/-0.13	2.67	TF	Radial compression

The value of plunge in bold means it is the closest value to 90^0 and that is the factor that indicates the faulting type and tectonic regime in the seismic zone.

For some regions, the stress regime is inconclusive as two of the plunge values are close to 45°, so that we can not establish the tectonic regime on the data we have, for example in MO1 and MO2. Even if we put together all the data in MO1 and MO2, the tectonic regime remains inconclusive (Table 2). The situation is different in MO3 and MO4, where we have a definite thrust faulting regime and even if we combine the data the result is very similar. The value of the stress ratio is between 0.33 +- 0.17 (BA2) to 0.87 = -0.1 (MO1-MO2). The confidence limits are wide-spread because the shape ratio is sensitive to the number of focal mechanisms inverted and their accuracy. The low value of the shape ratio physically means that the stresses are of similar magnitudes and thus the axes cannot be easily distinguished.

3. SHORT INTERPRETATION OF THE RESULTS

Initially we have divided the Moesian seismic zone into four subzones, but the results show that MO1 and MO2 in the northern part of MO have a similar thrust faulting regime, while MO1 and MO2 have an inconclusive tectonic regime, probably because almost all events in the area are spread on secondary faults which are intersecting each other. Also the σ2 and σ3 are spread on the stereograms, which means that they are in a relatively wide domain.

If we consider together the data from the entire Dobrogea region, except the North Dobrogea orogen, coherent results are obtained showing a thrust-faulting regime. In the zone of North Dobrogea orogen and Bârlad depression a strike-slip regime is present which might be linked with the position of the seismic events which are either on the Peceneaga – Camena fault (northern part) and with some satellites which are very close and have the same orientation (Fig. 1). This is the single region in which a definite strike-slip regime is observed.

FC–CSC zone shows a prevailing normal faulting regime, although some different directions of the stress axes are present (Fig. 2). In the Banat area the focal mechanisms are spread in two distinct zones, so we have introduced the BA1 and BA2 zones. In BA2 zone a normal faulting regime is present (59 events), while in BA1 an inconclusive stress regime can be seen. Danubian area (DA) is characterized by a good normal faulting regime and stress axes are almost in the same direction as in the BA2 area.

4. CONCLUSIONS

The diversity of S_{hmax} orientations and the changes in the tectonic regime in the crust from one seismic zone to the other lead us to the conclusion that the contribution from regional stress (like plate boundary forces acting on large scale SS faults) on the magnitude of tectonic stresses is almost inexistent. This implies that local stress sources have a large influence on both the S_{hmax} orientation and the tectonic regime in the SE Carpathians Bend as well as in Southern Carpathians. Possible local stress sources in the crust are: lateral density and strength contrasts (Focșani Basin with 15 km depth, foreland, Moesian platform, or most likely, basin subsidence due to slab pull remain from a former subduction in the Vrancea zone).

Superposition of these multiple secondary stress sources leads to a complex stress field and short-scale changes of the tectonic regime, as we have seen in MO and ND-BD zones and above Vrancea seismogenic zone. The moderate and strong Vrancea earthquakes are followed by swarms of earthquakes in the crust, which are placed mainly on some secondary fault system, parallel with Carpathians and not on the main crustal faults in the area. Our conclusions are very similar to those in World Stress Map, Scientific Technical Report 2016, on the data of WSM recorded for Romania.

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Received: November 25, 2020
Accepted for publication: December 10, 2020