The Seismogenic Sources from the West and South-West of Romania

E. Oros, M. Popa and M. Diaconescu

Abstract The study region is the most important seismic region of Romania when we refer to the crustal seismicity as a source of seismic hazard. So far there have been recorded 91 seismic events that produced significant effect in buildings (Io $\geq$ 6 EMS), some of them resulting in severe damage and even casualties (Io $\geq$ 7 EMS). In this paper we modelled the seismogenic sources in the region using a new seismotectonic model constructed on new earthquakes and focal mechanisms catalogues basis. This model was elaborated starting from the relationship between geology and historical and instrumental seismicity and then it was better constrained by geophysical, neotectonic, geodetic data and particularly by active stress field features. The stress tensor parameters and the stress regime have been determined by formal inversion of the focal mechanisms solutions. Our study provides evidence of at least seven different deformation domains with different tectonic regimes as a realistic support for assessing the seismogenic potential of the geological structures. Each seismogenic source is characterized by completeness magnitude (Mcomp), maximum probable magnitude (Mmax) and magnitude—recurrence parameters. The probabilistic hazard maps produced in terms of PGA using the new seismic sources highlights the importance of their configuration on the hazard parameter values and their spatial distribution.

Keywords Seismogenic sources · Seismotectonics · Seismicity
Mmax · Stress field

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1 Introduction

The seismic hazard analyses, probabilistic or deterministic, use as the key input data the earthquake source models which describe the seismicity of the location of interest and reflect the architecture of active fault systems. These models, so-called *seismic source*, are associated with a geological structure and are defined in different configurations depending on the quality and resolution of geological, seismological, tectonic, geophysical and geodetic available data. The seismic sources are usually characterized by their potential to produce strong earthquakes (Mmax) and their ability to produce such earthquakes repeatedly (recurrence parameters). These characteristics are estimated using earthquakes catalogues that cover most of the time only a very short period of a seismic cycle. Thus, if there are no data about the seismic activity some geological structures can be neglected in the process of modelling of seismic sources even if their geometry is favourable to be reactivated in a particular stress field. Therefore the seismic sources models require detailed geological and geophysical constraints to ensure realism and reliability to the final hazard models. The seismic hazard analysts use different types of seismic sources the most common being faults, localizing structures and seismotectonic units (Reiter 1991). Recently have been defined Individual Seismogenic Sources (ISS), Composite Seismogenic Sources (CSS), Seismogenic Areas (SA) and Debated Seismogenic Sources (DSS) (e.g. Basili et al. 2008).

Radulian et al. (2000) defined the Seismogenic Zones in Romania using seismicity and tectonics data and their correlation with morpho-structural units. They described two seismogenic zones in the study region, *Banat Seismogenic Zone* (*BSZ*) in the North and *Danube Seismogenic Zone* (*DSZ*) in the South, respectively. This seismic zoning was used in many seismic hazard studies, (e.g. Ardeleanu et al. 2005; Moldovan et al. 2008; Oros 2011; Simeonova et al. 2006).

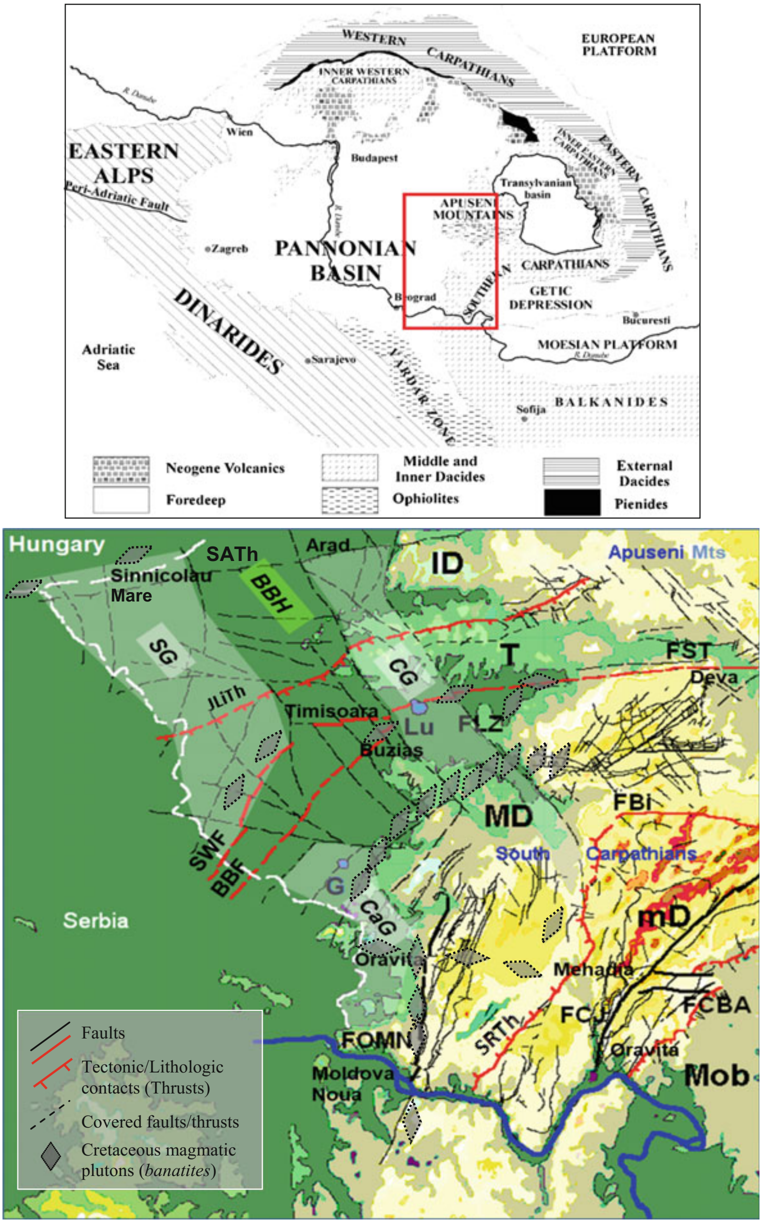
The study region can be considered the most important region of Romania if we refer to the seismic hazard associated with crustal seismicity. The last earthquakes catalogues (e.g. Oncescu el al. 1999; Oros 2011; Stucchi et al. 2013) contain a lot of earthquakes which produced significant engineering effects (Io $\geq$ VI EMS, *EMS is European Macroseismic Scale*) and even heavy damages and casualties (Io $\geq$ VII EMS). Generally the seismicity is diffuse but there is a clear clustering trend for both historical and instrumental periods (Oros and Diaconescu 2015). The region is located at the contact between the Carpathians and Pannonian Depression where three geodynamic units develop and control the seismic activity (Zugravescu and Plolonic 1997). Several crustal blocks characterize the basement tectonics. These are covered by sedimentary formations and fragmented by neo-structures (Polonic 1985; Sandulescu 1984). All structural units are bounded by faults systems of different ages that were reactivated or blocked in a variable stress field controlled by NE Adria Microplate pushing and the basin inversion processes (e.g. Bada et al. 2007; Bala et al. 2015).

In this paper we present a new seismic zoning of the study region. The definition of seismogenic source as a geological structure reactivated or with reactivation potential in a particular stress field, with or without associated seismicity is the basic concept of the applied methodology. The seismogenic sources were identified and defined using a new seismotectonic model. This model has been constructed at different scales on the relationship between geology, seismicity and active stress field basis. Geophysical, geodetic and neotectonic data constrained the final version of the model. Thus, identifying, defining and characterization the earthquake sources rely (1) on knowing the geology and tectonics of the region and (2) then the understanding of their relationship to active stress field and seismicity. Each seismogenic source is characterized by completeness magnitude of the catalogue, magnitude—recurrence parameters and *Mmax*.

2 Geology and Geotectonic Setting

The study region is located on the south-eastern border of the Pannonian Basin at the contact between Carpathians and Pannonian Depression (Fig. 1, top). The Pannonian Basin sensu stricto, is a Miocene-Quaternary back-arc extensional basin formed after pre-Neogene orogeny. The present structure of the region consists of (1) *basement pre-Neogene units* (nappes, suture zones, close rifts, magmatic bodies, sedimentary formations, etc.) bordered by faults systems (thrusts) that were successively reactivated during Alpine history under different stress regimes and (2) *neo-structures* (deep basins, grabens, horsts, depressions) having different structural positions controlled by normal/listric faults (Fig. 1, bottom) (Polonic 1985). Several geotectonic units compose the basement and are described by Sandulescu (1984) as *Inner Dacides* (*ID*), *Median Dacides* (*MD*), *Marginal Dacides* (*mD*) *and Transylvanides* (*T*). These units are structural components of the Pannonian, Geto-Danubian and Moesian Geodynamic Blocks (Zugravescu and Polonic 1997). Dacides and Transilvanides structures are segmented by faults and neo-structures that intersect them more or less orthogonal. Two main faults systems can be defined in the region. One, called here as *Carpathian system*, is NE–SW to EW oriented and characterizes the basement and orogenic structures bordering the major geotectonic and geodynamic units (Fig. 1, bottom). These are either thrusts that delineate SSE—verging nappes within Inner Dacides (e.g. Sinnicolau Mare-Arad and Jimbolia-Lipova Thrusts) and WNW—verging nappes within Median and Marginal Dacides (e.g. Sichevita-Retezat Thrust) either vertical trans-crustal faults (e.g. Oravita-Moldova Noua Fault system). The other one (*Pannonian system*) controlled the neotectonic activity in the region and have predominant NW–SE to NS and NNE–SSW directions being generally normal and low angle faults (Sandulescu 1984; Polonic 1985).

Magmatic plutons (Cretaceous *banatites*) and volcanic intrusions (e.g. Lucaret and Gataia Neogene basalts) are distributed through the basement of the study region being associated with continental subduction zones and deep faults systems.


WESTERN
CARPATHIANS
INNER WESTERN CARPATHIANS
EUROPEAN PLATFORM
R. Danube
Wien
EASTERN ALPS
Peri-Adriatic Fault
Budapest
INNER EASTERN CARPATHIANS
EASTERN CARPATHIANS
Transylvanian basin
APUSENI MOUNTAINS
Zagreb
PANNONIAN BASIN
SOUTHERN CARPATHIANS
GETIC DEPRESSION
Beograd
Bucuresti
DINARIDES
MOESIAN PLATFORM
Adriatic Sea
Sarajevo
VARDAR ZONE
Sofija
BALKANIDES
Neogene Volcanics
Foredeep
Middle and Inner Dacides
Ophiolites
External Dacides
Pienides
Hungary
SATh
Arad
Sinnicolau Mare
BBH
ID
Apuseni Mts
SG
CG
T
FST
Deva
JLiTh
Timisoara
Lu
FLZ
Buzias
FBi
MD
South Carpathians
SWF
BBF
G
CaG
mD
Serbia
Oravita
Mehadia
FCBA
FCJ
SRTh
FOMN
Oravita
Moldova Noua
Mob
Faults
Tectonic/Lithologic contacts (Thrusts)
Covered faults/thrusts
Cretaceous magmatic plutons (banatites)

◂**Fig. 1** Upper Carpatho-Pannonian system and the location of the study area (red polygon). Bottom map Syntetic map of geotectonic units and major faults sytems (topografic background). ID Inner Dacides, T Transilvanides, MD Median Dacides, mD Marginal Dacides, Mob Moesian Bazin, SG Sinnicolau Mare-Szeged Grabens system, CG Caransebes Graben, CaG Caras Graben, BBH Battonya-Buzias High, Lu/G Lucaret and Gataia Quaternary basalts, SATh Sinnicolau Mare-Arad Thrust, JliTh Jimbolia–Lipova Thrust, SRTh Sichevita-Retezat Thrust, FST South Transilvanian Fault system, BBF Banloc-Buzias Fault system, SWF SW Timisoara Fault system, FLZ Lugoj-Zarand Fault system, FBi Bistra Fault (segment of South Carpathian Fault system), FOMN Oravita-Moldova Nouă Fault system, FCJ Cerna-Jiu Fault system, FCBA Closani-Baia de Arama Fault system. Some of symbols for magmatic plutons only localize the structures without defining their limits (top map reproduced after Ciulavu et al. 2000, bottom map compilation after Ciobanu et al. 2002; Polonic 1985; Sandulescu 1984; Institutul Geologic Roman 1968)

3 Seismicity

The seismicity map of the region is presented in Fig. 2a, b. These maps are constructed using a compilation of the revised catalogues elaborated by Oros et al. (2008a, b) and Oros (2011) that was completed with data from the catalogues of Oncescu et al. (1999) (updated version on www.infp.ro), Stucchi et al. (2013) and Grunthal et al. (2013). This compilation contains over 8500 earthquakes with Mw = 0.4 − 5.6 that occurred between 1443 and 2016. A number of *91* earthquakes with Io $\geq$ VI EMS (Mw $\geq$ 4.0) have been catalogued. 32 of them had Io $\geq$ VII EMS (Mw $\geq$ 4.7) producing heavy damages and even casualties. In the known seismic history of the study region there are *2 major seismic crisis* well documented by Oros (2011). The first was recorded between 1879 and 1880 and is characterized by two sequences located in two areas: (1) one in DSZ at Moldova Noua (10.10.1879, Io = VIII EMS/Mw = 5.8 and 11.10.1879, Io = VII EMS/Mw = 5.3) and (2) the second in BSZ at

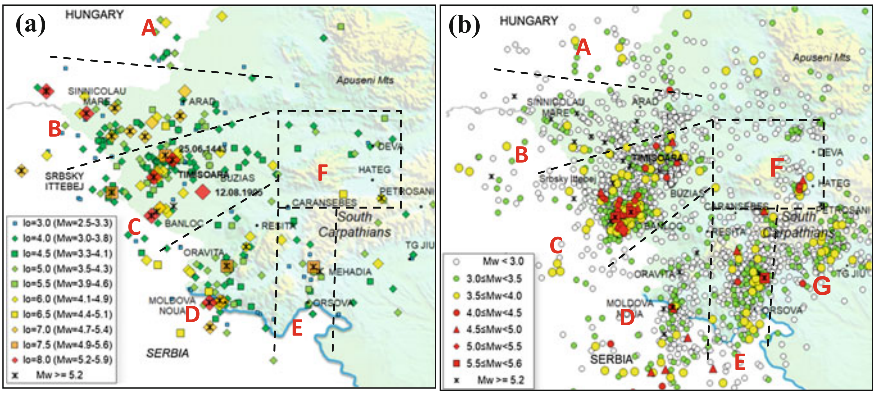


Fig. 2 Seismicity maps of the study region. **a** Macroseismic epicentres (1443–1979), conversion relationship Mw = 0.53*Io* + 1.2 log *h* + 0.11 for h = 5–20 km from Oros (2011); **b** instrumental epicentres (1980–2015). The events with Mw $\geq$ 5.2 (I = VIII EMS) recoded from the whole period are displayed on both maps. Black dashed lines delineate the zones with particular grouped seismicity (A–G)

Tomnatic (16.04.1879, Io = VI − VII/Mw = 5.2), Sinnicolau Mare (31.10. 1879, Io = VII EMS/Mw = 5.3) and Sacalaz-Timisoara (19.11.1879, Io = VII EMS/Mw = 5.2). The second crisis occurred in 1991 and lasted several years. It also had two different sequences and started at Banloc in BSZ (12.07.1991, Io = VIII EMS/Mw = 5.6). It was followed on 18.07.1991 by a strong earthquake (Io = VII EMS/Mw = 5.6) located at Mehadia in DSZ. On 2nd December 1991 other strong event occurred at Voiteg (Io = VIII EMS/Mw = 5.5).

Two main groups of epicentres can be defined, one in North (BSZ) and the other in South (DSZ), respectively (Fig. 2). Inside the two zones there is a clear tendency of grouping the historical epicentres in several groups, called from North to South (Fig. 1a): *A*, Bekes (at the Romanian border with Hungary), *B*, Sinnicolau Mare-Arad with two almost EW—orientated alignments, parallel with Inner Dacides structures; *C*, Timisoara-Banloc, with clusters at Timisoara, Banloc, Sirbsky Ittebej at the Romanian border with Serbia and at North of Buzias; *D*, Moldova Noua-Resita with groups at Moldova Noua, Oravita, Oravita-Resita; *E*, Orsova-Caransebes, *F*, Hateg-Deva-Mures Valley. The zone *G*, South Petrosani is outlined only on the instrumental seismicity map (Fig. 2b). These areas have been defined so that they can be characterized by at least one major earthquake with Mw $\geq$ 5.2, except G zone located outside the study region. The instrumental seismicity displays a roughly identical model. However some differences can be noted: (1) the boundaries between A, B and C zones are more poorly defined by Mw $\leq$ 3.0 earthquakes the distribution; (2) the distribution of smaller events (Mw $\leq$ 3.5) defines more clearly small clusters and alignments (e.g. between Arad and Timisoara, Oravita, Moldova Noua, Hateg, Deva and South Petrosani). The depth distribution shows a layering model with three levels (Oros 2011): h_1 = 2–10 km ($h_{average}$ = 8.0 ± 1.6 km), h_2 = 10–15 km ($h_{average}$ = 12.5 ± 1.6 km) and h_3 = 15–20 km ($h_{average}$ = 17.2 ± 1.3 km). There are also a few deeper hypocentres (Oros and Oros 2009).

Seismicity is usually described by the Gutenberg–Richter relationship which coefficients, *a* and *b*, quantify the seismic activity rate and the ratio between small and large magnitudes, respectively. The space distribution of b-value is useful to mapping the state of stress and its heterogeneities within seismic active areas (Scholz 2015). The values of b vary significantly if the stress changes are large and there are some structural conditions (e.g. geometric heterogeneities) that may affect the seismogenic potential of fault zones and fractured structures. Thus *b-value variations* can constrain the limits of areas where particular correlations between seismicity, tectonics and stress field are defined. We present in Fig. 3 the 2D the distribution of *b*-values along with several parameters that shows their statistical quality and support the reliability of the analyses that rely on them, e.g. goodness of fit to power law, R as the percentage of the distribution frequency—magnitude which can be modelled by power law type; the data set can be considered reliable if R = 80–90%, (Wiemer 2001), standard deviation of b-value and completeness magnitude, Mcomp. The maps were constructed using the Zmap code by Wiemer (2001), samples with N = 250 events (Nmin = 50) and a grid with cells of 0.1 × 0.1 degree (Oros 2011).

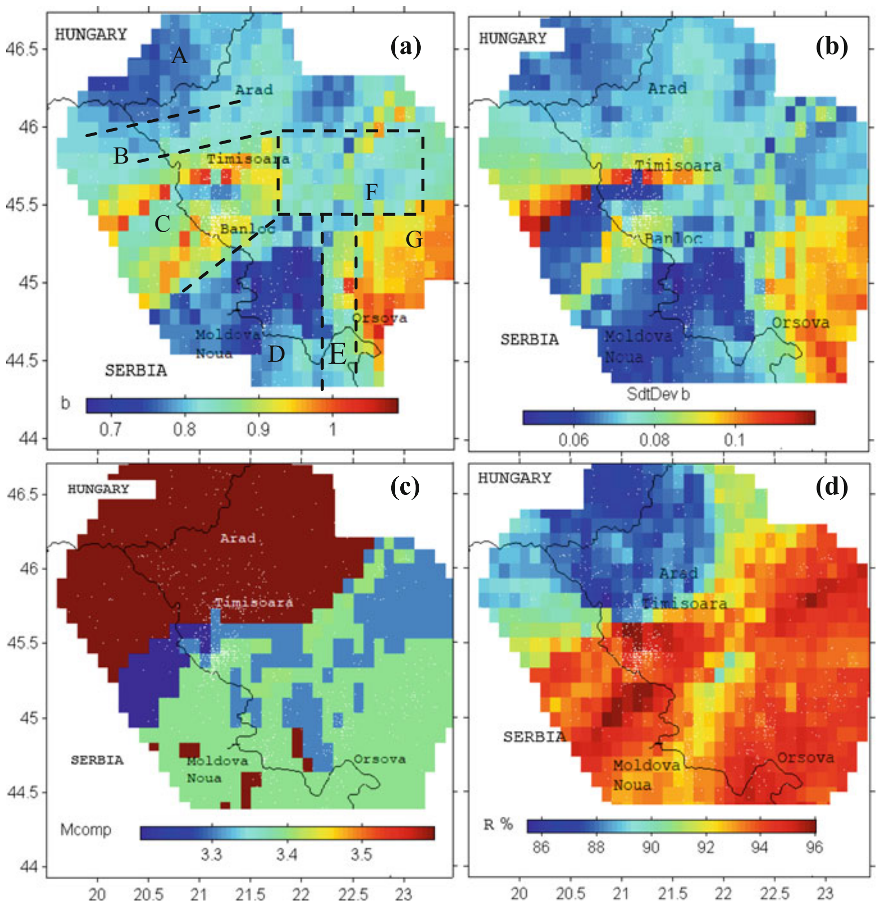


Fig. 3 **a** 2D distribution of b-value, **b** Standard deviations of b-value, **c** Completeness magnitude Mcomp, **d** Goodness of fit to power law (R), (reproduced from Oros 2011). *Black dashed lines* delineate the zones with particular grouped seismicity and nearly uniform b-values (A–G)

The b-values indicate wide variation ($0.65 < b < 1.05$) well correlated with geotectonic structures in the study region. Their distribution suggests a high heterogeneous state of stress highlighted through an alternation between: (1) *low b values* ($b \leq 0.8$) within A, B, and D zones and partly C, E and F zones from Fig. 2 what does it means that high stress concentration associated with strain accumulation exists in the region and (2) *higher b-value* ($b > 1.0$) within small areas where very active faults are descried (e.g. Bala et al 2015; Oros 2011). These variations suggest a high level of stress heterogeneity or high stress drop associated with high seismic activity. Strong earthquakes ($Mw \geq 5.2$) occurred recently in these zones, e.g. Timisoara (27.05.1959, Mw = 5.3), Banloc (07.12.1991, Mw = 5.6) and Mehadia (18.07.1991, Mw = 5.7). All areas from A to G, defined in Fig. 2, can be

Fig. 4 **a** Modelled principal stress direction (black bars) with inversion variance constructed ▶ using Zmap code (Wiemmer 2001); dashed white lines delineate the zones A–G from Fig. 1, **b** Seismotectonic sketch. *Inset* (right upper corner): regional stress tensor; *1* Inner Dacides, *2* Transilvanides *3* Median Dacides *4* Marginal Dacides *5* Outer Dacides (rift structures) *6* Moesian Paleozoic Platform *7* faults (black/dashed thin lines are faults/thrusts; red thick lines, neotectonic structures) *8* Late Quaternary basalts, 9 Cretaceous plutons ("Banatite") *10* trajectories of recent stress *11* earthquakes with Io $\geq$ VI EMS (Mw $\geq$ 5.0); *12* vertical recent movements; *13* stress symbols (black/white bars are Shmax/Shmin, small coloured circles symbolizes stress regime and strain style: N, SS, T are normal, strike slip and thrust faulting) (Inset and stress tensors—large symbols reproduced from Oros et al. 2016; tectonics and stress model reproduced from Sandulescu 1984 and Bada et al. 2007; vertical movement from Horvath et al. 2006)

characterized by nearly uniform b-values. However there are some differences regarding their limits, dimensions and shapes that better correlate with geology, e.g. (1) *A* zone can be extended towards South including the Sinnicolau Mare epicentral area from B zone that is well correlated with SATh in the SG graben; (2) *F* zone with generally low b-value is divided by a N–S oriented narrow area of higher b-value resulting two sub-zones, Hateg in East and Caransebes in West, respectively. Analysed at smaller scale almost every seismic zone may be divided on the basis of sharply variations in the values of b. Thus, within C zone there are three areas with b = 1.05 (Timisoara), b = 0.92 (Banloc) and b = 0.75 (South Timisoara), respectively. Moldova Noua-Oravita zone can be also divided in two sub-zones, one in South having b = 0.8 − 0.85 and the other in North where b = 0.65 − 0.75.

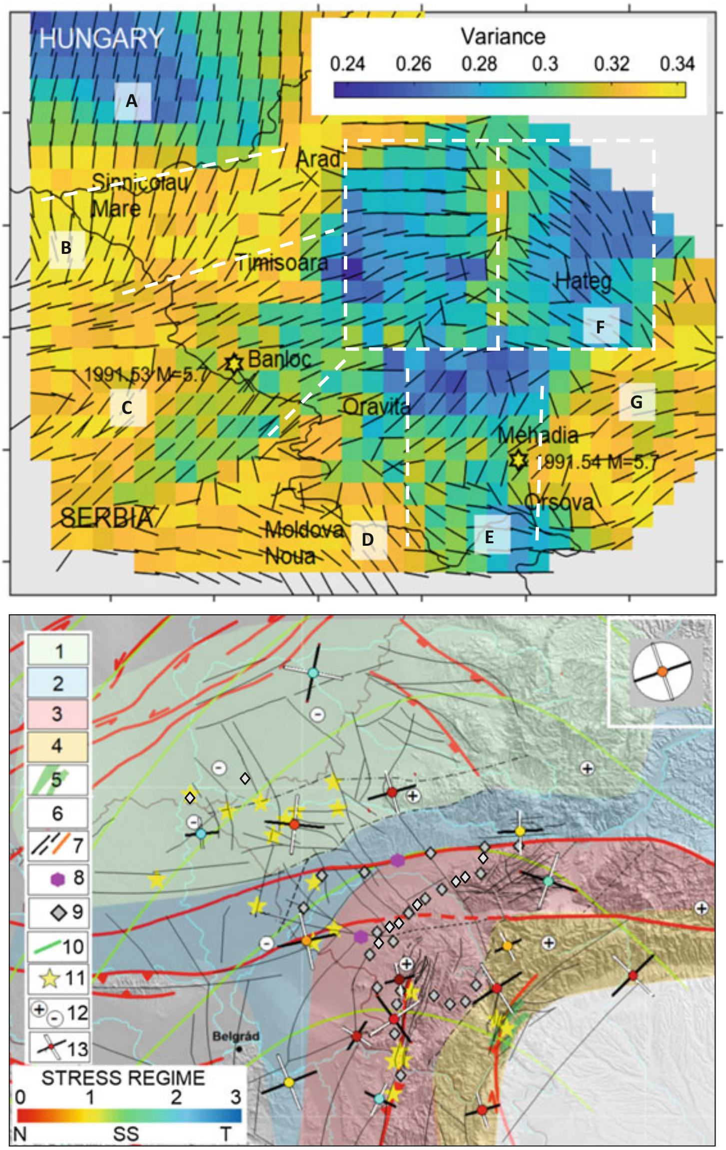
The low b-values areas overlap with zones with positive velocity anomalies of P waves (Vp) computed by Zaharia et al. (2010, 2017).

4 Active Stress Field and Seismotectonic Model

Stress field pattern helps to identify deformation zones and tectonically active structures at different scales both in space and time. Usually, the stress inversion using earthquake focal mechanisms allows estimating the orientation of the principal stress axes (S1 > S2 > S3), the stress ratio [R = (S2 − S3)/(S1 − S3)] and the derived stress regime index R′ (R′ = 0–1 for normal faulting, R′ = 1–2 for strike-slip faulting and R′ = 2–3 for reverse faulting) (Delvaux and Sperner 2003). We used 438 focal mechanisms solutions determined by Oros et al. (2008b, 2016) to compute the reduced stress tensor. Two analyses were conducted to obtain reliable data to a realistic constraint of seismogenic sources defined on seismicity basis. First, to identify characteristics of stress field in relation to local tectonics and seismicity we computed and mapped the 2D distribution of the principal stress orientation (S1) and the variance of inversion using the Zmap code (Wiemer 2001) (Fig. 4a). Second, we investigate the horizontal stresses (SHmax and Shmin) and

(a)

(b)



tectonic regime for every seismic zone defined previously in order to identify the structures with seismogenic potential (Fig. 4b). For this purpose we analysed the preliminary stress field modelled by Oros et al. (2016) and we used Win-Tensor program of Delvaux and Sperner (2003) to compute reduced stress tensors for different smaller data sets selected in areas with large variations of seismicity, S1 directions and homogeneity and with particular tectonics (small symbols in Fig. 4b).

The regional stress field was investigated by Oros et al. (2016, 2017) using 1132 focal mechanisms from Intra-Carpathian region of Romania. They obtained the following data that are comparable with the first order stress field described by Bada et al. (2007): S1 (azimuth/plunge) = 234°/45°, S2 = 72°/44°, S3 = 333°/9°, R = 0.48, SHmax = N60°E and Shmin = N15°E. The tectonic regime is oblique extensive (R′ = 0.48). The misfit is 56° meaning that the stress field in the region is spatially very heterogeneous. Oros (2011) used for the stress tensor inversion in West Romania 140 focal mechanisms and obtained similar parameters: SHmax = N71°E, Shmin = 161°E and R = 0.40 (SHmax = N67°E, R = 71 and extensional strike slip regime in BSZ and N52°E, R = 77, extensional regime in DSZ). Radulian et al. (2000) computed SHmax = N87°E in BSZ and SHmax = N70°E in DSZ.

Generally, S1 directions mapped in Fig. 4a are comparable to the regional stress trajectories modelled by Bada et al. (2007) (Fig. 4b). However, the stress field is heterogen ($\sigma \geq 0.2$—threshold after Wiemer et al. 2002) throughout the region. The pattern displays a short—scale variations of these parameters suggesting strong disturbance of the regional stress field by local sources of stress, like active faults, contrast density, rheology, etc. It resembles the seismicity zones presented in Figs. 2 and 3 but with some differences in shape and limits and also correlate with tectonic features.

The stress regime and SHmax orientations disclose two different major trends in the active stress field and crustal deformation (Fig. 4b): (1) SHmax is parallel with SHmax regional modelled by Bada et al. (2007) and there is a strike slip faulting, with a large extensional component at the limit between the Transilvanides (ophiolites) and the Median Dacides (South Transilvanian Fault) and (2) SHmax is oblique up to perpendicular to the direction of the SHmax regional and transtensive to pure extensional faulting are defined (Sinnicolau Mare-Arad, Moldova Noua Oravita si South Petrosani). The stress field heterogeneity is also noted by stress regime and strain style changes both at regional and local scale, e.g. there are significant differences between BSZ (uppermost extensional strike slip) and DSZ (extensional) and between small areas within B and D zones. The most heterogeneous area is located between Resita and Moldova Noua prolonged in Serbia where the average SHmax is almost NS-oriented, in opposite sense towards the DSZ general direction. This is most likely due to the influence of the focal mechanism form the South of the Danube located in a different tectonic setting. In this area as well as throughout the study region the stress field features and seismicity can be associated with magmatic intrusions of different sizes and shapes distributed on alignments with different orientations (e.g. Sinnicolau Mare, Caras and Caransebes grabens Moldova Noua-Oravita seismic area). Interesting to the N–NW, close to these magmatic and volcanic structures located in DSZ, an area with low seismic activity develops between BSZ and DSZ as transition zone.

The geodetic model of crustal deformations described in the NATO report (2011) is characterized by a large variation of horizontal velocity vectors, both in direction and size suggesting a very complex geodynamic ongoing context and actives tectonic setting. Thus in the North of region they have opposite directions, towards North in the Pannonian Basin area and towards South on the western border of Apuseni Mountains, respectively. This model could displays a share zone between Carpathian and Pannonian Basin structures that overlap an area with high horizontal gradient of recent vertical movements. In the southern region horizontal velocity vectors are also oriented towards South between roughly 21°E and 22°E but they converged on directions around the East and West borders. Thus, they show crustal movements towards East in the Pannonian Basin area and towards West in the Moesian Basin.

A seismotectonic sketch is presented in Fig. 4b. We highlight several features of the stress-tectonic-seismic activity relationship that support the seismogenic potential of the known geological structures: (1) there is a strong correlation between major earthquakes (Mw $\geq$ 5.0) and the faults intersections; (2) the largest number of these significant events appear in the North of the study region (Sinnicolau Mare-Arad area, BSZ) where a high contrast between negative and positive vertical movements can be observed and opposite horizontal GPS velocity was recorded (NATO report, 2011); (3) the stress field parameters seem to be controlled by major structural peculiarities (e.g. South Transylvania, Oravita-Moldova Noua, Cerna-Jiu faults systems and thrusts) with strong local influences (e.g. magmatic plutons, faults geometry and fault populations, thermal and rheological anomalies); (4) faults systems in the seismic active zones have favourable geometries to be reactivated within particular stress field through normal, strike slip and thrust faulting, e.g. Shmin, as the characteristic axis for the extensional stress regime, is perpendicular or oblique to the thrusts and major faults in the region, suggesting a high probability of their reactivation as low angle normal faults; SHmax is parallel to almost EW-oriented faults systems from the western borders of the region meaning favourable relationship to their reactivation as strike slip faults, (5) geodetic model of recent crustal deformations is generally non-conforming to that of stress suggesting possible decupling between different layers of the crust what may substantially alter the seismogenic model of the region.

5 Seismogenic Sources Models. Results and Discussions

To identify, locate and define the seismogenic sources within the study region we started from their definition that we adopted here according to which any geological structure can be reactivated if there is a favourable relation between its geometry and the active stress field. We defined only seismogenic source of type area since missing the essential data necessary for a well-documented investigation of the active faults systems. Thus, there is not available a geological database of faults and faults systems and the seismicity data cannot yet assure an acceptable quality level of correlation seismicity—tectonics throughout the region.

The process of defining the seismogenic sources consists of 3 stages. Every stage is characterized by different criteria and constraints used for the identification and delimitation of seismogenic sources. The process started with a simple model, defined on the basis of the regional structure (blocks geodynamic process) correlated with seismicity (Mw $\geq$ 5.0). This model was further improved by applying successive some additional constraints. We obtained at each stage different sources models characterized by particular recurrence parameters. Any of these models can be used to seismic hazard assessment depending of the final products of the end users. The recurrence parameters were computed on a declustered catalogue basis (Table 1).

Stage1/Model 1. Starting with the geodynamic and structural models constructed at basement level (geotectonic units, trans-crustal faults) and the seismicity model (Mw $\geq$ 5.0) we delineated three main areas with reactivated structures under different stress conditions: extensive strike slip in North (BSZ), pure strike slip in ENE (Hateg—Caransebes Seismogenic Zone, HCSZ) and pure extensive in South (DSZ) (Fig. 5a). The earthquakes are located along Carpathian faults system (tectonic contacts between the geotectonic units), especially at their intersections with Pannonian faults systems. BSZ and DSZ are similar with the models defined by Radulian et al. (2000). HCSZ is located in Hateg—Caransebes area where a significant earthquake (M = 5.2) occurred in 1912 and it is characterized by relative homogeneous stress field and strike slip stress regime.

Stage 2/Model 2. We divided BSZ and DSZ in several sub-zones using some geological and geophysical constraints described on smaller scale such as the tectonic limits between the geotectonic units (Dacides and Transilvanides) as well as the 2D distribution of b-value, stress regime and SHmax/Shmin orientation and seismicity pattern (Mw $\geq$ 4.0). Finally we obtained a more detailed earthquake model with 5 Seismogenic Sources having dimensions of order of dacidic structures segmented by neo-structures: Sinnicolau Mare-Arad (SASZ) and Timisoara-Banloc (TBSZ) within BSZ (extensive strike slip stress regime), Moldova Noua-Oravita

Table 1 Recurrence parameters for the seismogenic sources

Source	Mwcomp	a (yearly)	b
BSZ	4.0	2.64 ± 0.277	0.74 ± 0.057
DSZ	3.0	2.12 ± 0.077	0.68 ± 0.018
HCSZ	3.9	1.99 ± 0.171	0.75 ± 0.038
SASZ	4.0	2.67 ± 0.443	0.82 ± 0.094
TBSZ	3.2	2.66 ± 0.064	0.77 ± 0.015
MNOSZ	4.0	2.35 ± 0.302	0.80 ± 0.064
OCSZ	3.5	1.88 ± 0.141	0.72 ± 0.032
TSZ	3.5	2.49 ± 0.122	0.79 ± 0.028
BVSZ	3.6	1.82 ± 0.142	0.66 ± 0.031
OSZ	4.3	2.37 ± 0.562	0.83 ± 0.122
MNSZ	4.0	1.56 ± 0.286	0.60 ± 0.060
OCSZss	3.9	1.42 ± 0.218	0.63 ± 0.046
BASZ	3.8	2.33 ± 0.304	0.86 ± 0.071
HCSZss	3.0	1.26 ± 0.073	0.59 ± 0.018
DMVSZ	3.1	2.32 ± 0.540	1.04 ± 0.147
SPSZ	3.8	2.60 ± 0.398	0.97 ± 0.117

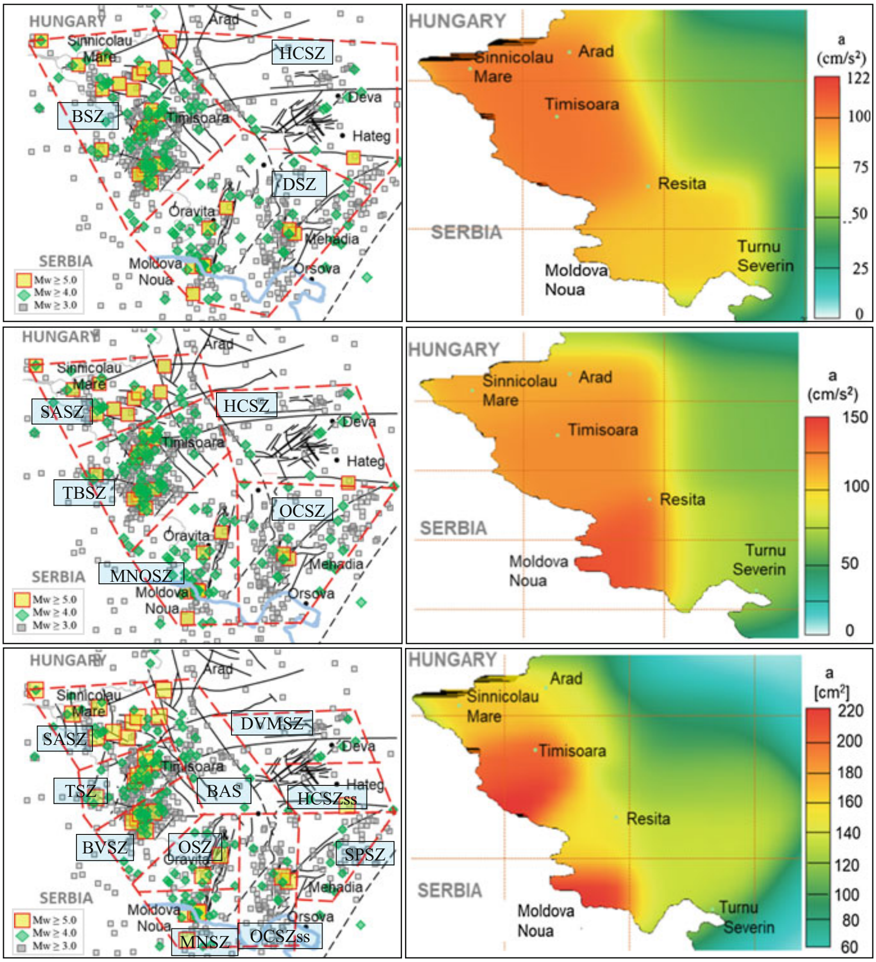


Fig. 5 *Left* Maps of the seismogenic sources defined within the study region (details in text). *Right* Probabilistic Seismic Hazard (PGA) maps corresponding to each seismogenic source model obtained using Crisis 2007 software (Ordaz et al 2007)

(MNOSZ) and Orsova-Caransebes (OCSZ) in DSZ (pure extensive stress regime) and HCSZ as it was before defined. SASZ is characterized by two different stress regimes and a geodetic pattern of crustal deformations that could describe as local sharing area. Thus, there is a strike slip stress regime in West where the velocity vectors are oriented towards the North and an extensive strike slip stress regime in the East where the crustal movements are oriented towards South (NATO report 2011).

Stage 3/Model 3. We improved the previous seismogenic sources model by applying additional constraints. Thus we introduced data about neo-structures and the relationship between their geometry (strike and dip) and SHmax/Shmin direction, 2D principal stress axis orientation and stress regime as well as $M \geq 3.0$ seismicity patterns. The new earthquake model contains 9 small seismogenic zones that correlate better with the details of local scale tectonics and having dimensions comparable with those of the active structures and faults systems: Sinnicolau Mare-Arad (SASZ), Timisoara (TSZ), Banloc-Voiteg (BVSZ), Moldova Noua (MNSZ), Oravita (OSZ), Orsova-Caransebes sensu stricto (OCSZss), Buzias-Arad (BASZ), Hateg-Caransebes sensu stricto (HCSZss), Deva-Mures Valley (DMVSZ) and South Petrosani (SPSZ). HCSZ was divided in two sub-zone on SHmax direction and stress regime basis. Thus HCSZss has a pure strike slip stress regime with SHmax oriented towards NW–SE and DMVSZ is characterized by strike slip stress regime with a large extensive component and SHmax oriented on EW direction. This model appears to be more realistic and should be used for estimation of seismic hazard in the study region.

Each model described above present a lot of particular characteristics, e.g. structural details, stress parameters and tectonic regime, possible local stress sources, tectonics, segmentation with locked structures under particular stress conditions, seismogenic potential of each dominant structure.

Mmax, defined simply as the maximum magnitude that may occur under specific geological conditions (the greatest possible magnitude), was computed for the study region using Kijko-Sellevol parametric estimator (Kijko 2004):

$$\Delta = \frac{E1(n2) - E1(n1)}{\beta \exp(-n2)} + m\text{min} \exp(-n) \quad (1)$$

where $n1 = n/\{1 - \exp[-\beta(\text{mmax} - \text{mmin})]\}$, $n2 = n1 \exp[-\beta(\text{mmax} - \text{mmin})]$, and E1 can be estimated as follows:

$$E1(z) = \frac{z^2 + a1z + a2}{z(z^2 + b1z + b2)} \exp(-z) \quad (2)$$

with a1 = 2.334733, a2 = 0.250621, b1 = 3.330657, b2 = 1.681534. Then solve the equation: Mmax = mmaxObs + Δ.

Appling these relationships we calculated Mmax = 6.1 ± 0.3. This value is similar to that computed from Mmaxobs (5.7 + 0.5 = 6.2). Oros (2011) computed the thickness of the seismogenic layer obtaining h = 11.6 ± 4.4 km. Using the relationship between magnitude and the rupture width (Wells and Coppersmith 1994) he obtained Mw = 6.5 for h = 11.6 km.

We computed Probabilistic Seismic Hazard in terms of PGA (cm/s^2) to investigate the effects of the three Seismogenic Sources Models on the space hazard distribution and its values (Fig. 5, right). All hazard models display a distribution of PGS values concentrated in the proximity of seismogenic sources. However the first two models have a high level of smoothing of hazard distribution with overestimating of the PGA values in areas with low seismic activity or with structures without seismogenic potential. It appears in the context that the seismic hazard computed using the “model 3” of seismogenic sources is the most reliable, both as PGA values and their space distribution.

6 Conclusions

We elaborated three models of seismogenic sources as input for the seismic hazard assessment of the western and southwestern region of Romania. They are constructed on new seismotectonic features basis resulted from detailed analysis of the relationship between geology, active/recent stress field and seismicity. We used new earthquakes and focal mechanisms catalogues, stress field computed through formal inversion of the focal mechanisms. The seismogenic sources have been defined by a successive division of regional geological structures at different scales (seismogenic structures) and applying realistic constraints (e.g. stress field properties, 2D distribution of $a - b$ coefficients of Gutemberg Richter relationship, geophysical anomalies, geodetic model of crustal deformations). The detailed seismic zoning of the study region with many smaller seismogenic sources avoid excessive smoothing of seismic hazard that happen in the case of greater seismogenic zones. Each source was characterized by magnitude—recurrence parameters and a unic, regional, maximum magnitude computed by an analytical method and validated using observational (Mmax observed) and seismo-geological (thickness of seismogenic layer) data.

Some seismotectonic peculiarities pointed out by our study may be useful in tectonic, geodynamic, neotectonic studies or deterministic assessment of seismic hazard and risk. Thus, we noted (1) the strongest earthquakes recorded in the study region occurred preferentially at the intersections of almost orthogonal faults systems; (2) there are several local sources of stress that can significantly influence the seismotectonics of the region with direct impact on hazards and seismic risk.

New high quality and resolution data about geological faults, 3D models of seismicity, local stress features are required to realistically model the seismogenic sources as faults.

The methodology used in this study will be applied to all crustal seismic zones from Intra- Carpathian region of Romania.

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