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EARTHQUAKE PRONE AREAS IN ROMANIA

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Abstract. *The paper brings together all existing data related to seismic monitoring in order to characterize the earthquake-prone areas in Romania. A review of previous works on this subject is also carried out. The impetuous development of the Romanian seismic network in the recent years as number and quality of instruments makes it possible today to identify with a high degree of confidence the geometrical configuration of seismicity patterns able to generate strong earthquakes. At the same time, we are now able to separate the tectonic active zones from those contaminated by human activity and to define with higher accuracy the earthquake-prone areas. By increasing the range of magnitude completeness and by assessing specific variations in time and space of seismicity, the paper brings a significant contribution to improve our ability to evaluate seismic hazard in Romania.*

Keywords: seismicity pattern, earthquake-prone area, earthquake catalogue, seismic hazard

1. Introduction

Generally speaking, seismic activity can be regarded as being directly related to relatively well-defined areas of particular geometrical configuration (that we call earthquake-prone areas) or dispersed over undefined areas (that we call background seismicity). In specific cases, the earthquake-prone areas can be restrained to the projections of active faults on the Earth surface, if we have arguments to assume that these particular faults are only capable to successively generate significant earthquakes in a region.

Definition of the seismogenic zones is the starting point for any approach of seismic hazard assessment. The seismic sources are associated with a specific potential to generate earthquakes (for example, the maximum magnitude that can be expected and the frequency of generating strong earthquakes). According to [12], there are two basic ways to introduce seismogenic zones in hazard studies: line (fault) sources and area sources. Earthquakes generation is naturally connected to pre-existence of faults and from this point of view, the best definition of a seismic source would be the active fault itself.

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Nevertheless, in reality the things are much more complicated. The stress action which controls the deformation in a given area can trigger slip on well-defined pre-existing faults, but equally it can activate secondary faults or hidden faults. This situation is all the more valid if we refer to areas of continental seismicity. Less commonly, earthquakes are triggered by the new fracturing of the rocks.

For the regions of continental seismicity where frequently the fault trace is covered by thick sedimentary layers and we cannot have access to the buried fault, we have to choose the less accurate version of modelling the seismic source: a seismic homogenous area where the probability of exceedance of future earthquakes at every point inside the source is assumed to be same. This implies that seismicity is uniformly distributed within the seismic source and future earthquake epicentres would be placed anywhere in the zone. This is the typical case for Romania [43].

There is also a third situation for the so-called background earthquakes which cannot be associated with any well-defined source, either fault or area. A background source is a special case of an area source, where the seismicity is scarce and dispersed and no characteristic major earthquake/tectonic feature is observed.

The seismicity characterization of the particular area is commonly expressed by source parameters of representative earthquakes occurring in that area. Understanding of earthquake source physics requires knowledge of fault properties such as the stress on the fault, the material strength, and the fault geometry. The challenge is to combine the data for particular events - earthquake source parameters (e.g., source time function, stress drop, radiated energy, moment tensor, and magnitude) with earthquake statistical properties (e.g., a and b values of the Gutenberg-Richter relation, recurrence rate, maximum estimated magnitude) observed from natural or lab-induced earthquakes.

The seismic activity in Romania follows generally the line of Carpathians orogen with a sharp concentration at the SE Carpathians Arc bend in the Vrancea region. Here, a cluster of earthquakes is continuously recorded inside a lithospheric high-velocity body descending almost vertically in the mantle. Several events of magnitude above 7 have been recorded each century since about a millennium [24]. The seismicity in the overriding crust in the Vrancea region and around is discussed separately from the activity in the mantle. It is relatively dispersed and significantly reduced as intensity. Apparently, the two activities are decoupled, however, there are sufficient arguments in favour of a certain interdependence between them [5, 22]. Some seismicity clusters are recorded in the extra-Carpathian area as well, especially in front of the Carpathians Arc bend (foredeep region) and in the western part of the country (see [42], for more details).

In the following, we will characterize the earthquake-prone areas in Romania, separately on geographic areas, considering the configuration of the seismogenic zones as defined for the first time by [42]. The significant development of the Romanian seismic network from 2000 to the present led to changes in the seismicity patterns, especially for low to moderate magnitudes, to an increase of location accuracy and inevitably to a considerable alteration of seismicity image due to the substantial growth of artificial events in the catalogue. The main purpose of the present study is to reconsider the definition and characterization of the earthquake-prone areas in Romania and to identify and characterize the areas generating non-tectonic events (essentially quarry blasts events). Our results will be an extremely useful database for filtering catalogue data and for improving input data for seismic hazard assessment in Romania.

In order to inspect systematically all the country surface and to include all the potential sources, either tectonic or non-tectonic, we prefer to discuss and characterize the catalogue data separately on a set of geographical regions following roughly the Romanian administrative districts. These regions are defined somewhat conventionally so that they combine perfectly and cover the Romania territory like in a puzzle (see Figure 1). In total, 12 geographic regions are considered: Vrancea (intermediate-depth earthquakes), Vrancea (shallow earthquakes), Bucovina-Moldova, Dobrogea, Muntenia, Oltenia, Făgăraş-Câmpulung, Banat, Transilvania, Crişana, Maramureş and Transilvania.

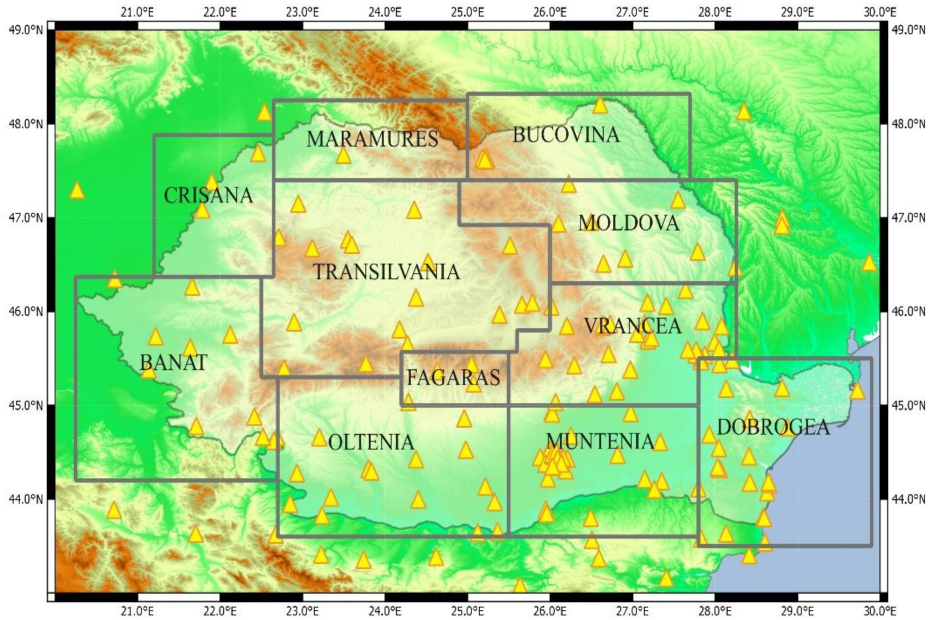


Fig. 1. Division of Romania territory into conventional areas roughly following the administrative regions.

Obviously, this approach has the advantage of including all events recorded in the catalogues, but also the disadvantage of neglecting the specific tectonic and geomorphologic features related to earthquake-prone areas. After describing separately each administrative region, in the final section of the paper we will summarize and integrate the results in correlation with tectonics and geomorphologic features.

Similar approaches were carried out by [3, 6, 41, 42]. In the present paper we limit ourselves to a descriptive approach on the basis of updated catalogue data. In a subsequent paper we will define completely the specific parameters for each source separately, as they are required by seismic hazard assessment.

2.1 Vrancea – intermediate-depth earthquakes

Vrancea, located at the South-Eastern Carpathians arc bend, is the main earthquake-prone area in Romania. At the same time is the more complex and concentrated area of seismicity in the entire Pannonian-Carpathian-Dinaric system [20]. It represents the junction of three tectonic units: East-European plate, Intra-Alpine subplate and Moesian subplate.

Earthquakes are continuously generated in two depth domains, relatively well-separated: in the mantle ($60 \leq h < 180$ km) and in the crust ($h < 60$ km). To some extent, the two activities can be considered either decoupled or coupled.

For example, a deficit of seismicity is noticed in the transition zone between mantle and crustal seismicity.

On the other hand, much of the activity observed in the Vrancea fore-deep crust seems to be like a reaction to the deep earthquakes [5, 22]. The intermediate-depth source is confined in a seismically active volume of high-velocity lithosphere descending in the upper mantle. It produces in average five shocks/century with magnitude $M_w > 6.5$, as shown by a catalogue recorded for an interval of 6 centuries [24]. The maximum recorded magnitude is attributed to the event of 1802 ($M_w = 7.9$). In the last century, four shocks with magnitude above 7 were recorded, characterized by large damage over extended and dense-populated areas.

All the major earthquakes are characterized by similar focal mechanism of reverse faulting with the rupture plane NE-SW oriented, parallel to the Carpathians Arc bend. The stress pattern consists of horizontal compression and vertical extension over the entire depth range (60-200 km). Hypocenters of the mantle earthquakes in the Vrancea zone are focused in a small seismogenic volume about 70 km × 30 km × 110 km extending to a depth of about 180 km. This volume fits well within a high seismic wave speed body, evidenced by several tomographic studies.

The atypical geometrical configuration of the hypocenters, elongated along NE-SW direction and close to a planar distribution, the persistence of the earthquake generation in time (around 15 events/month with M greater than 3 and around 3 events/century with M greater than 7), the predominance of the focal mechanism, rise a lot of questions and debates in connection with the origin of the Vrancea earthquakes.

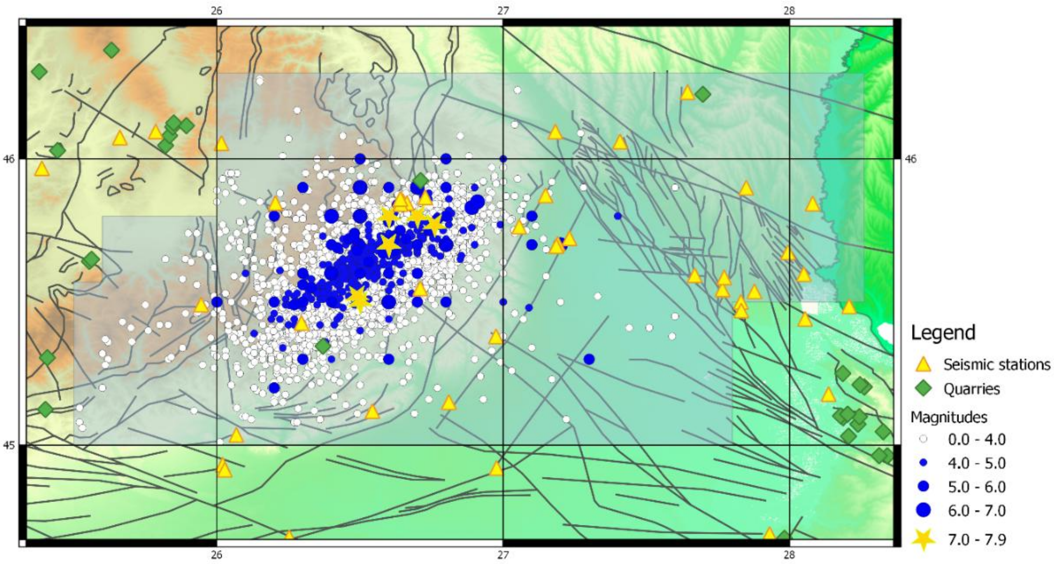
The data collected for the Vrancea intermediate-depth earthquakes (h ≥60 km) comprises 7341 events reported between 1900 and 2017 in the ROMPLUS catalogue [24 – updated at www.infp.ro] and 69 historical events occurred before 1900 as they are registered in the SHEEC catalogue [49].

The epicentral distribution of the Vrancea intermediate-depth earthquakes recorded after 1900 (see top of Figure 2) shows the NE-SW alignment, while the distribution on depth (seebottom of Figure 2) suggests the existence of at least two active segments releasing the major seismic energy, one around 90 km depth, the other around 130 km depth.

We can assume that two planes of weakness have been developed within the two segments which control both the small-to-moderate seismicity as the rupture of the major shocks [13]. The stress transfer and triggering effects among the active segments remain still a poorly known issue.

A possible extra active segment at the bottom edge (around 160 km depth) may play also a significant role in the tectonics of the Vrancea source.

According to [19], the next Vrancea major earthquake will be generated in this segment.



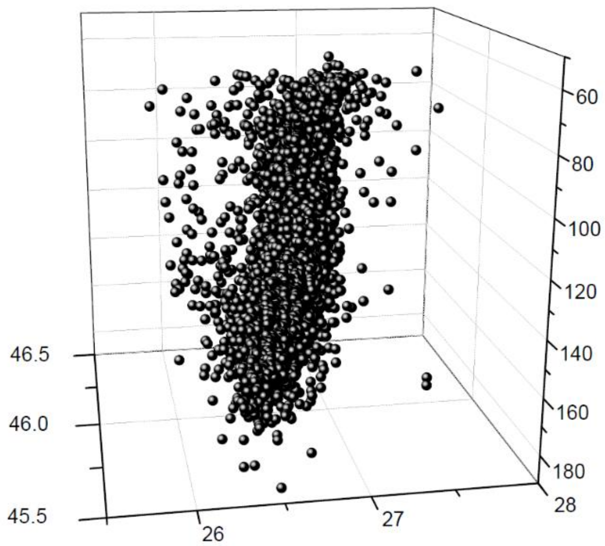
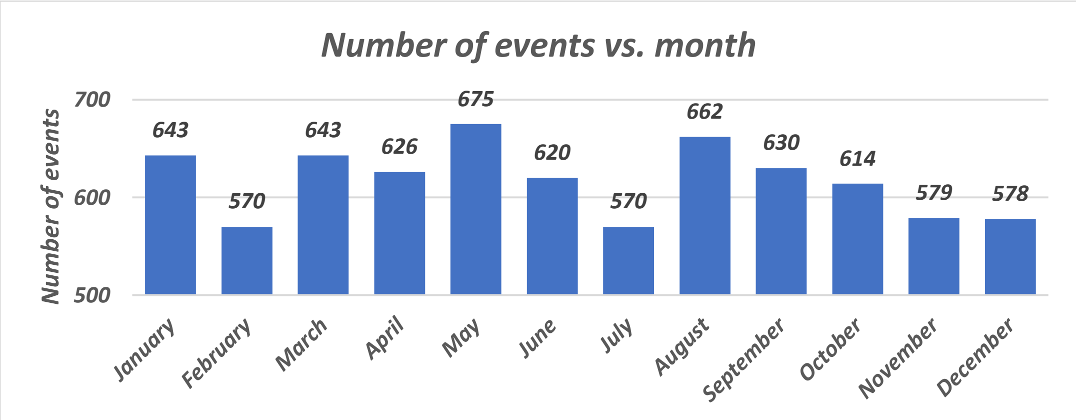


Fig. 2. Top: Epicenters of the earthquakes recorded after 1900 in the Vrancea intermediate-depth source. Seismic stations (yellow triangles) and quarries (green diamonds) situated inside the area (shaded polygon) and in its vicinity are plotted as well. Fault traces are extracted from [47]; Bottom: Distribution on depth of the Vrancea intermediate-depth earthquakes.

The fluctuations in the distributions of events per month, weekday and hour (see Figure 3) fall within statistically expected limits.

The largest values in May, August and March correspond with the months when the most recent large events occurred (30 and 31 May 1990, 30 August 1986 and 4 March 1977).

Also, the slight increase in Sundays and during night reflect a slight improvement in the S/N ratio during the non-working time.



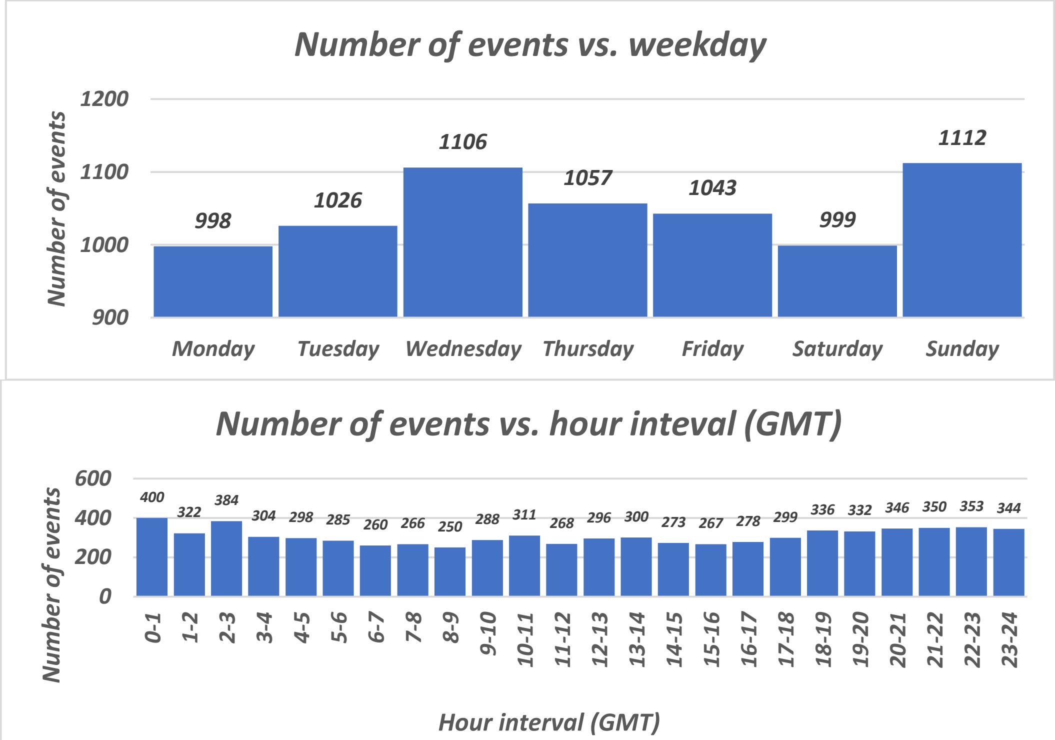
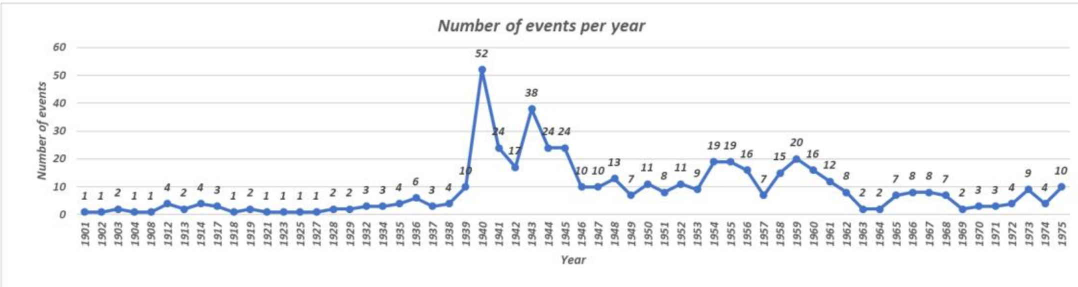


Fig. 3. Distributions of number of events as a function of month (top), weekday (middle) and hour (bottom).

The time history of the seismic activity represented since 1900 in the Fig. 4 (up: between 1901 and 1975 and down between 1976 and 2017) shows the peaks related to the aftershock activities associated with the major shocks of 1940, 1977, 1986 and 1990 amid three levels of constant seismic regime: before 1980, between 1980 and 2006 and after 2006.



The big jumps in the number of recorded events from one regime to the other correspond to significant improvements in the quality of the seismic survey.

In 1980 a new seismic network with transmission in real time was installed in Romania, whereas the number and quality of the seismic sensors of the Romanian seismic network has increased substantially after 2006 [23, 32] which has led practically to a doubling of the number of the earthquakes per year.

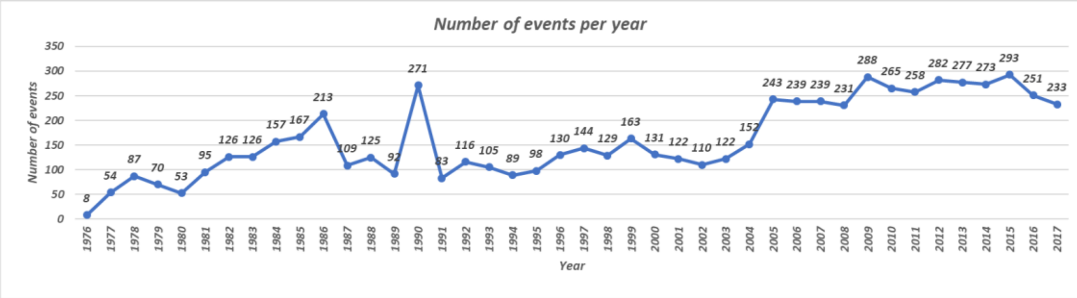


Fig. 4. Time evolution of the number of events/year: between 1901 and 1975 (top) and between 1976 and 2017 (bottom).

The distribution on magnitude (see Figure 5) reveals at magnitude of completeness around $M_w = 2.9$ and a relative deficit of earthquakes in the interval 6.5 – 7.0 in comparison with a linear Gutenberg-Richter distribution.

This is favour of a process of seismic release by characteristic shocks and percolation [51].

The characteristic and well-defined dimension of the Vrancea major events could be ascribed either to the presence of specific major asperities, or to specific active segments.

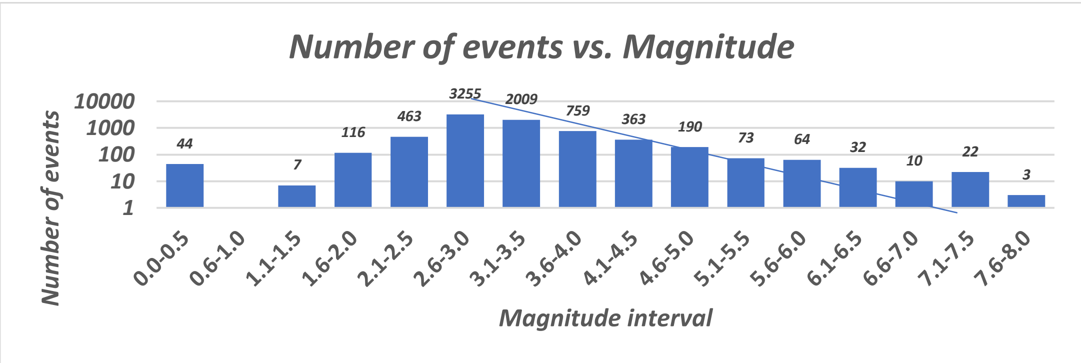


Fig. 5. Number of events versus moment magnitude. The slope of the linear decrease is b~0.6.

The distribution on depth (see Figure 6) shows two characteristic segments of activity: 70 – 100 km and 120 – 150 km. The major shocks recorded in the last 80 years (with instrumental recordings available) were generated in one or other of the segments.

In the areas with lower seismic regime (100 – 110 km and 150 – 170 km) only events with magnitude below 6 have been recorded during 80-year time interval.

It is difficult to say in this moment if these areas are able to generate future major events (in line with „seismic gap" models) or if their specific rheology prevent large seismic energy release (e.g., due to infiltration of fluids or melt materials).

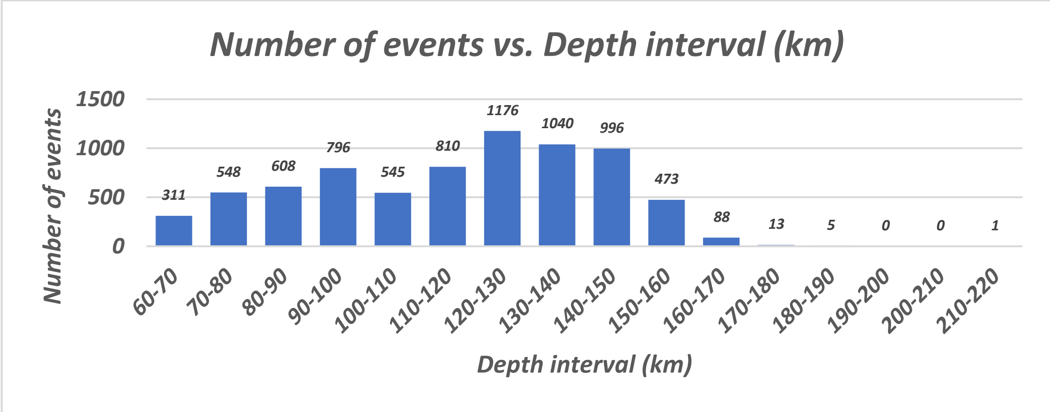


Fig. 6. Number of events versus focal depth

2.2 Vrancea – crustal earthquakes

The seismicity in the crust overriding the Vrancea intermediate-depth source shows an asymmetric pattern (see Figure 7): it overlaps the epicentral area of the Vrancea subcrustal earthquakes, but it is more developed and extended toward SE (fore arc) than toward NW (back arc). The seismic activity developed in the crust in front of the South-Eastern Carpathians Arc bend, between the Trotuş Fault and the Intramoesian Fault, reflects the complex post-collisional processes driven by the slab-pull beneath Vrancea and intraplate folding in the foredeep area. They are partly explained by the collision between the East European Plate and Moesian Plate with the intruding of the North Dobrogea Promontory belonging to Scythian Plate between them, along a SE-NW direction.

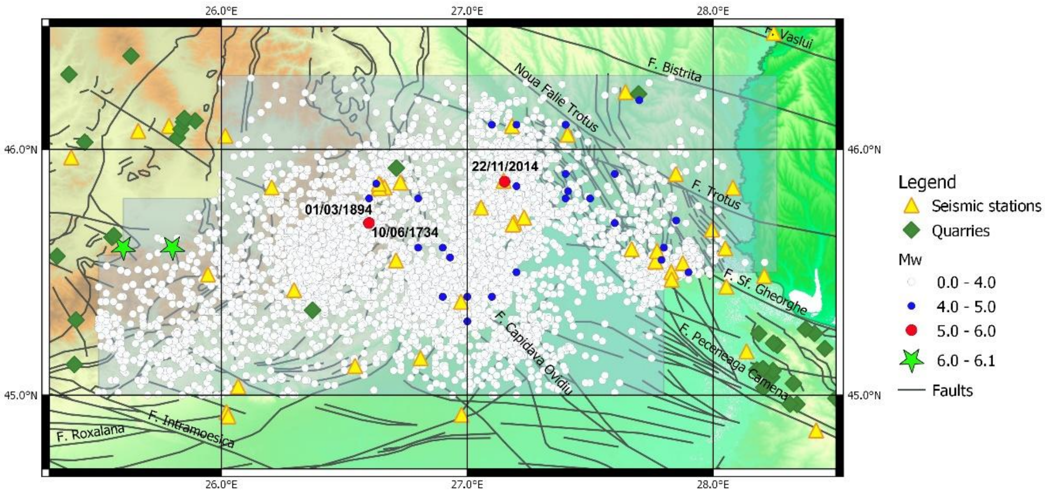


Fig. 7. Epicenters of the events located in the Vrancea crustal region. Seismic stations and quarries situated inside the area (shaded polygon) and in its vicinity are plotted as well. Fault traces are extracted from [47].

Only three earthquakes with magnitude above 5 are reported: 10.06.1734 (M_w = 5.2), 01.03.1894 (M_w = 5.9) and 22.11.2014 (M_w = 5.4). The two historical events have identical epicentral coordinates and their epicenters are overlapped in Figure 7. The event of 2014 occurred close to the Peceneaga-Camena Fault (in the proximity of Mărăşeşti city) and triggered an enhanced seismicity during three months over an extended area in front of the Carpathians Arc bend.

An overall view of the crustal seismicity in the Carpathians foredeep shows a few persistent active clusters which distinguish on a scattered and sporadic background seismicity.

These clusters, identified and defined as subzones (Râmnicu Sărat, Vrincioaia and Mărăşeşti-Brăila-Galaţi), follow specific lineaments [e.g., 36, 46]. They are activated from time to time especially as earthquake sequences. There are numerous papers investigating different particular sequences produced in the Carpathians foredeep area [e.g., 35, 36, 37, 38, 39].

An important group of earthquakes are generated along a SE-NW stripe bounded by the Trotuş Fault to the north and Peceneaga-Camena Fault to the south, where a complex branching system of active secondary faults has been developed. Note the tremendous decrease of seismicity immediately north of Trotuş Fault and south of Peceneaga-Camena Fault.

Another important group of earthquakes is located along a perpendicular direction, in parallel to the Carpathians Arc bend, following an alignment passing through Adjud – Mărăşeşti – Focşani – Râmnicu-Sărat. A system of NE-SW oriented faults buried beneath the Focşani Basin apparently control the seismicity developed in front of the Carpathians Arc, adjacent to the epicentral area of the Vrancea subcrustal earthquakes [47]. The configuration of these faults mimics the predominant rupture alignments in the Vrancea subcrustal source [5] and this can be an indication of a possible coupling between the seismic activity in the mantle with that in the overlying crust [22].

The seismic activity in the inner side of the Carpathians Arc, in the proximity of the Vrancea epicentral area, is apparently inhibited. Note only a few small patches with both shallow and intermediate-depth foci, like remnant fragments of the main active lithospheric body descending beneath the Vrancea region. Only weak and sporadic earthquakes are recorded here.

Two strong earthquakes with M_w = 6.1 are included in the SHEEC catalogue as historical events (9 June 1523 and 9 July 1545). They are located in the western extremity of the region in an area with low seismicity at present. We assume that they are more likely earthquakes belonging to neighboring areas (Făgăraş-Câmpulung or Transylvania regions).

The exploitation activities in the Vrancea are irrelevant and for this reason the distributions of events per month, weekday and hour (see Figure 8) are uniform showing only typically statistical fluctuations. Some difference between the events detected during night vs. events detected during day-time is simply explained by the relative increase of the S/N ratio during the night hours. The same explanation for the slight increase of the events number in the weekend relative to working days.

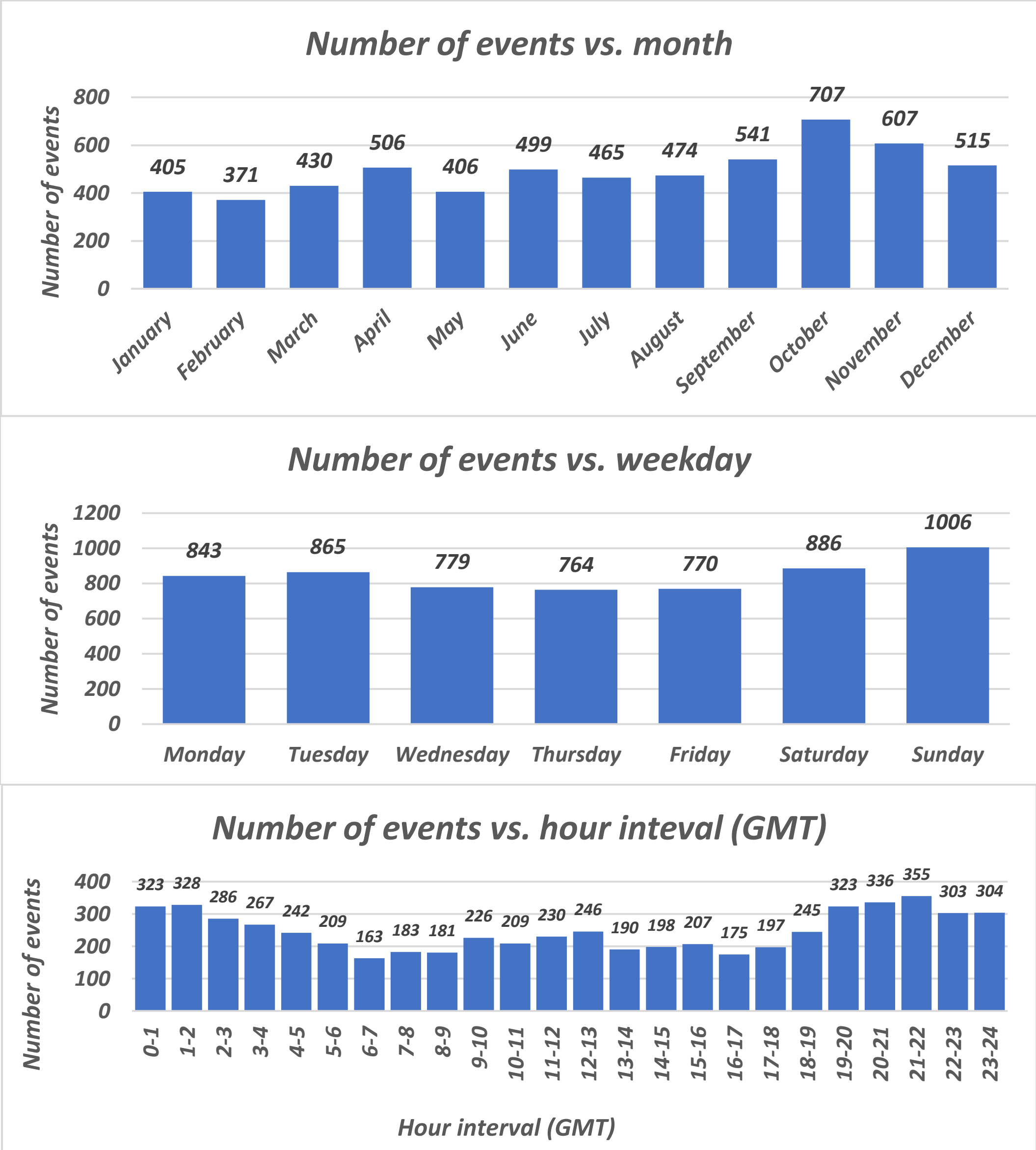


Fig. 8. Distributions of number of events as a function of month (top), weekday (middle) and hour (bottom).

The fluctuations observed in the time history distribution of the seismic activity represented since 1900 in the Figure 9 reflect on one side the major change in the seismic network capability to detect and locate Vrancea earthquakes after 1980, and on the other side the bursts of seismic activity related to generation of sequences.

Thus, we note the increase of seismicity in 1977 in response to the strong Vrancea earthquake (a swarm of shallow earthquakes in the vicinity of Vrincioaia station), the swarms of 1989, 1991, 1993, 1997 and 2008 in the same region, the sequences of June 1979, February 1983, August 1984, April 1986, August – September 1991, December 1997, April 2004, September 2005, November – December 2007, December 2009 in the Râmnicu Sărat area, the seismic swarm recorded between September and December 2013 in the Galaţi area and the sequence of Mărăşeşti started on November 2014 and followed for several months by a significant enhancement of seismic activity in the entire area situated in front of the Carpathians Arc [33].

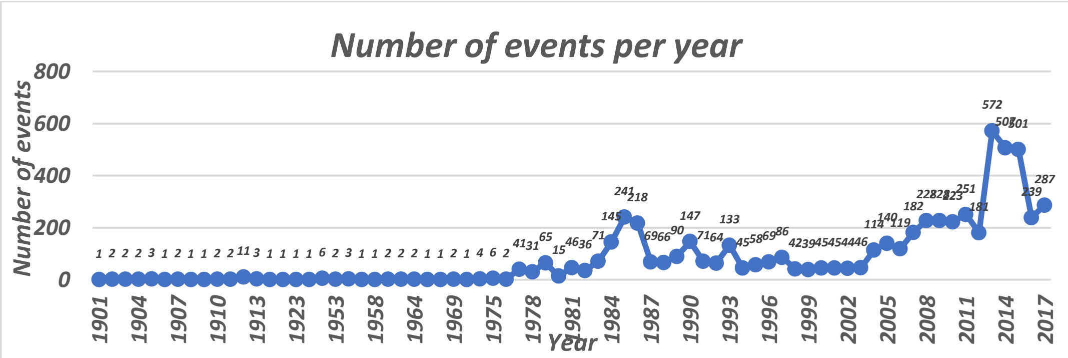


Fig. 9. Time evolution of the number of events/year since 1900.

The distribution on magnitude (see Figure 10) reveals the magnitude threshold of completeness around $M_w = 2.2 – 2.3$. The largest event ($M_w = 5.9$) was recorded in historical time (March 1st, 1894). The largest instrumentally recorded event was recorded in 2014 close to Mărăşeşti ($M_w = 5.4$).

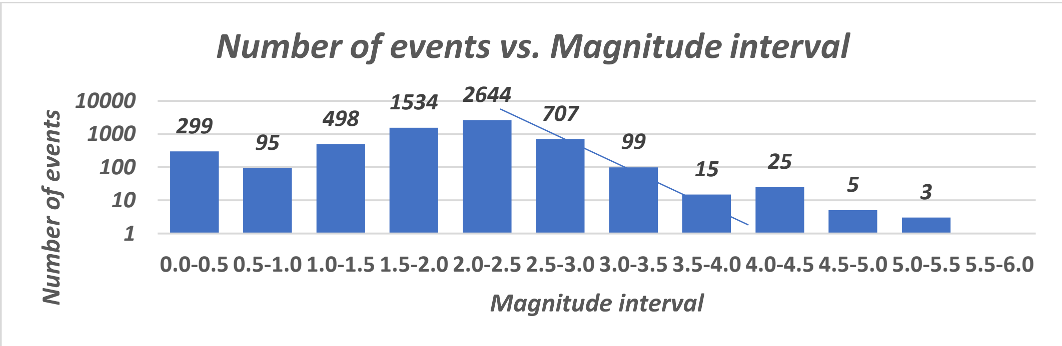


Fig. 10. Number of events versus moment magnitude. The slope of the linear distribution is b ~1.

Most of the earthquakes are located within first 20 km depth (upper crust) as shown in the Figure 11. However, there is a significant number of earthquakes located in the lower crust as well. We can assume that the presence of events at the bottom of the crust is to some extent related to a kind of response to the geodynamic processes progressing in the mantle beneath Vrancea.

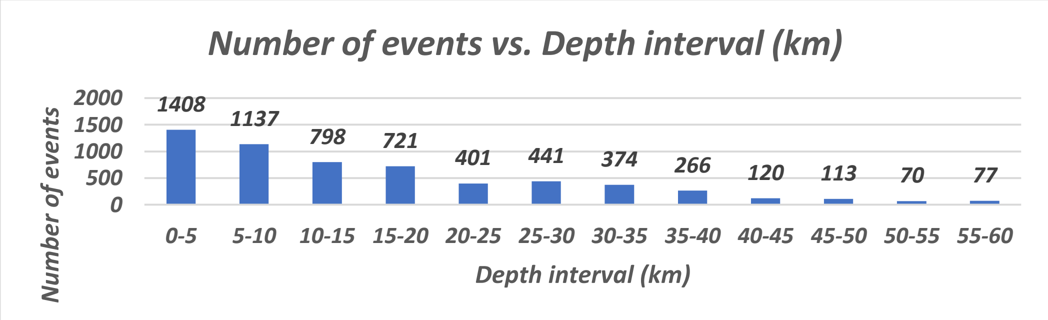


Fig. 11. Number of events versus focal depth

2.3 Bucovina - Moldova

Bucovina region is located in the north-eastern extremity of Romania. As conventionally defined in this paper, the Moldova region contains mainly the Moldavian Platform and the northern segment of the Eastern Carpathians. Since the seismicity in these areas is weak and dispersed, we prefer to analyse the two regions together. In Bucovina only 3 historical earthquakes are reported in the SHEEC catalogue:

- 9 May 1822, $M_w = 3.5$, h = 5 km, at the border with Ukraine
- 1 May 1895 03:35, $M_w = 3.2$, h = 9 km
- 28 December 1898 09:38, $M_w = 3.2$, h = 9 km

while in Moldova reported historical events are:

- 1 January 1800, $M_w = 4.5$, h = 9 km, south of Iasi city
- 4 November 1896, $M_w = 3.8$, h = 9 km, on Trotus Fault
- 11 December 1897, $M_w = 3.5$, h = 9 km, on Trotus Fault

The events with magnitude greater than 4 are presented in the Table 1.

Table 1. The largest events recorded in the Bucovina and Moldova regions since 1900

year	*month*	*day*	*hour*	*Lat. (^{0}N)*	*Lon. (^{0}E)*	*h (km)*	*M_w*
1900	01	31	09:00	46.50	27.30	9	5.5
1903	1	20	03:04	47.80	26.60	9	4.1
1906	10	17	23:15	46.60	27.30	30	4.9
1950	5	10	02:08	48.10	25.60	7	4.1
1962	7	28	00:00	47.10	25.60	9	4.5
1970	7	10	14:18	47.70	25.60	33	4.7
1978	10	13	01:02	46.65	26.61	30	4.3
2011	6	24	13:08	47.43	25.84	6	4.3

The events recorded in Moldova are of tectonic origin related to the major faults crossing from SE to NW the south-eastern sector (Bistriţa and Vaslui Faults) or to the thrusting faults lying along the Eastern Carpathians orogen. We note as representative events: 31.01.1900 (M_w = 5.5), 17.10.1906 (M_w = 4.9), 06.11.1997 (M_w = 3.1) - along the Bistriţa Fault, 08.11.1905 (M_w = 4.2), 05.051981 (M_w = 3.2) – along Vaslui Fault and 20.01.1903 (M_w = 4.1), 20.10.1979 (M_w = 3.7), 24.06.2011 (M_w = 3.8) - along the Avrămeşti-Suceava Fault.

The mapping of the epicenters represented separated in Figure 12 for two magnitude ranges: lower-magnitude (LM) events (M_w < 2.5) and higher-magnitude (HM) events (M_w > 2.5), looks mostly uniformly scattered in space both for smaller (white dots) and for larger events (black dots). Two small earthquake sequences are recorded in June 2011 and December 2013, both located in the Bucovina region. The associated parameters for the 2011 sequence are taken from [40], while for the 2013 sequence we use the coordinates and magnitude from ROMPLUS catalogue. The first sequence has a main shock of magnitude 3.8, one preshock (3.1) and seven aftershocks (2.5 – 3.1). The second sequence is an earthquake swarm of ten events in 22-27 December 2013 with magnitudes between 0.7 and 1.5.

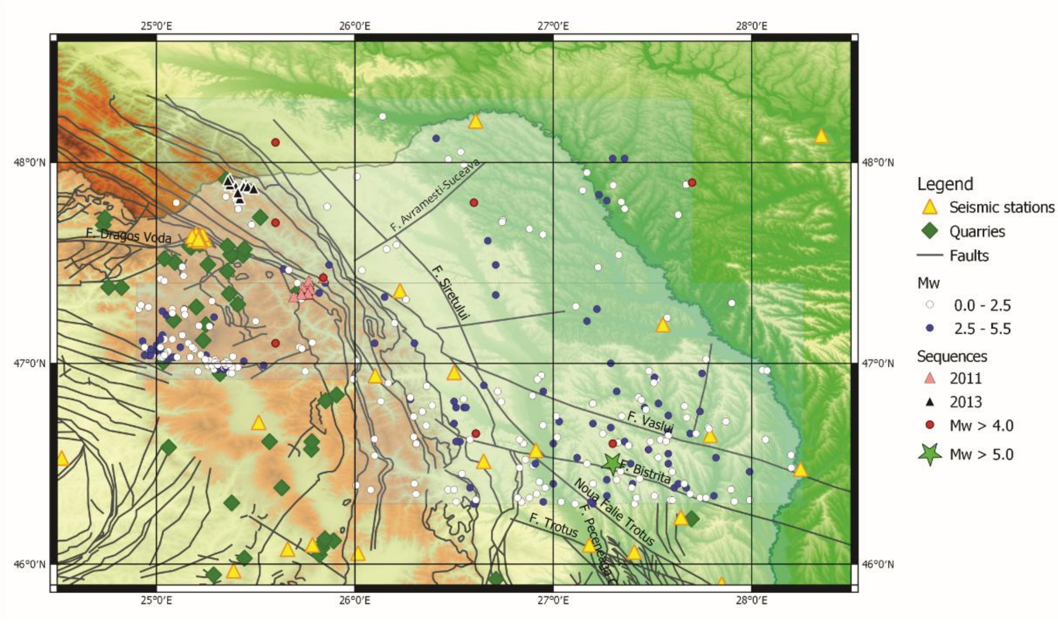


Fig. 12. Epicenters of the events located in the Moldova and Bucovina regions. Seismic stations and quarries situated inside the area are plotted as well. Fault traces are extracted from [47].

The time evolution of the yearly rate of earthquakes (see Figure 13) shows the impact of improving the seismic network capability to detect events below 2.5 magnitude.

Nearly all the events recorded before 2013 are in the higher magnitude range ($M_w \geq 2.5$), while the events recorded after 2013 are in the lower magnitude range ($M_w < 2.5$).

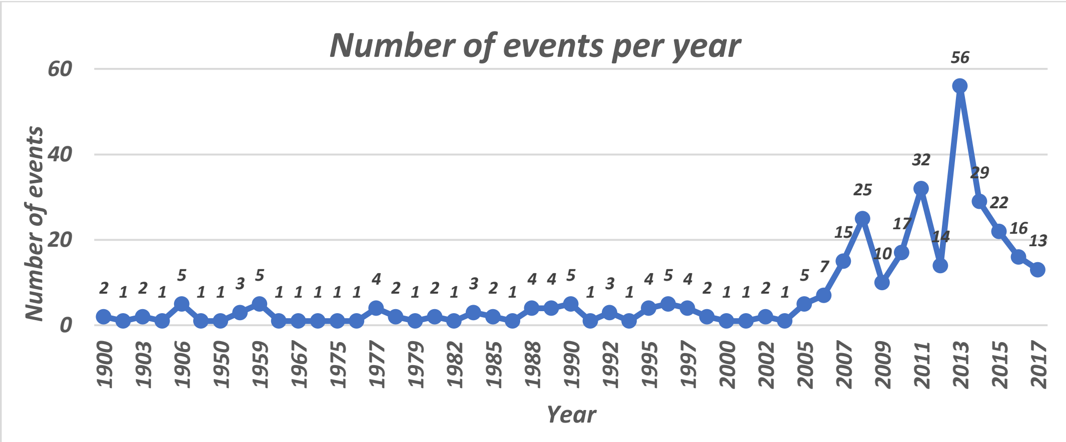
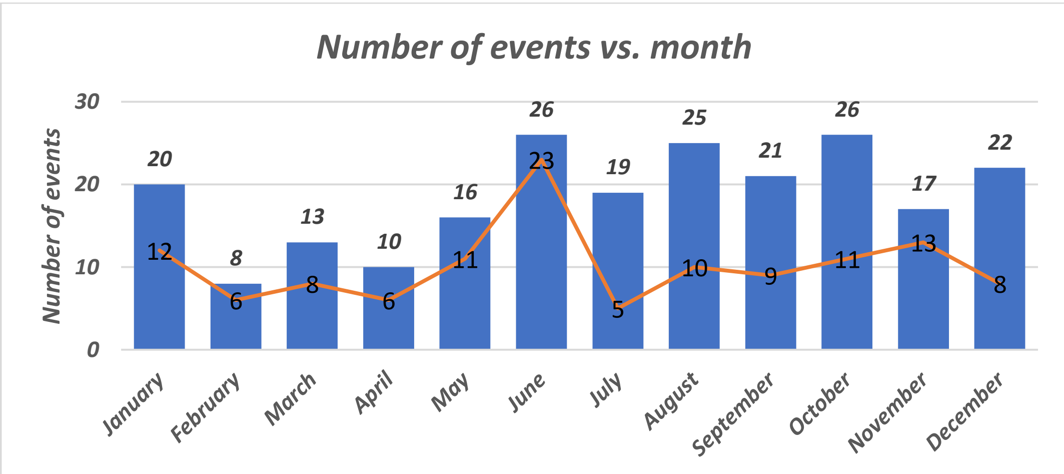


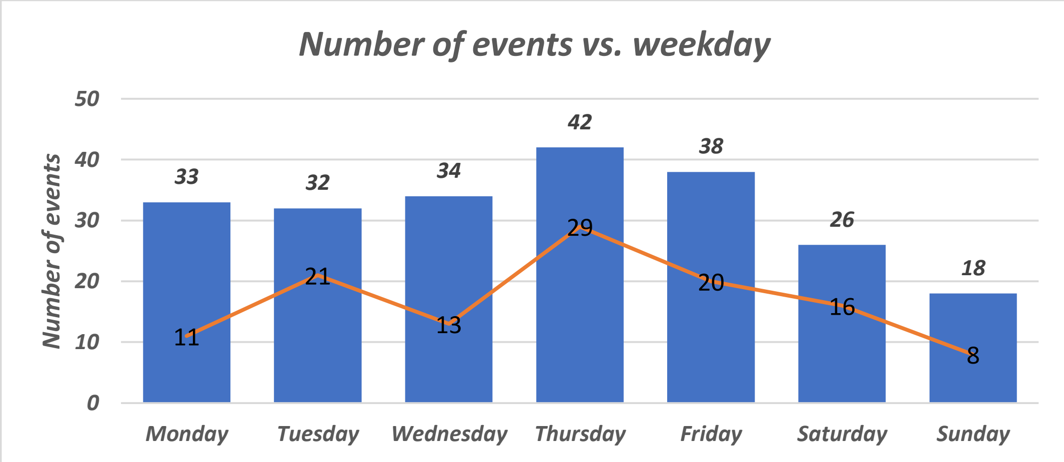
Fig.13. Time evolution of the number of events/year since 1900 for Bucovina and Moldova regions.

The peaks of activity in 2011 and 2013 are explained by the presence of two sequences: the main shock of 24 June 2011 and three associated events (one preshock and seven aftershocks) and an earthquake swarm of ten events in 22-27 December 2013 with magnitudes between 0.7 and 1.5.

The fluctuations in the distributions of events per month, weekday and hour (see Figure 14) fall within statistically expected limits.

However, the slight enhancement for the daily hours reflects the quarry activity in the western side, while the peak of activity in December is clearly related to the sequence of 22 – 27 December 2013.





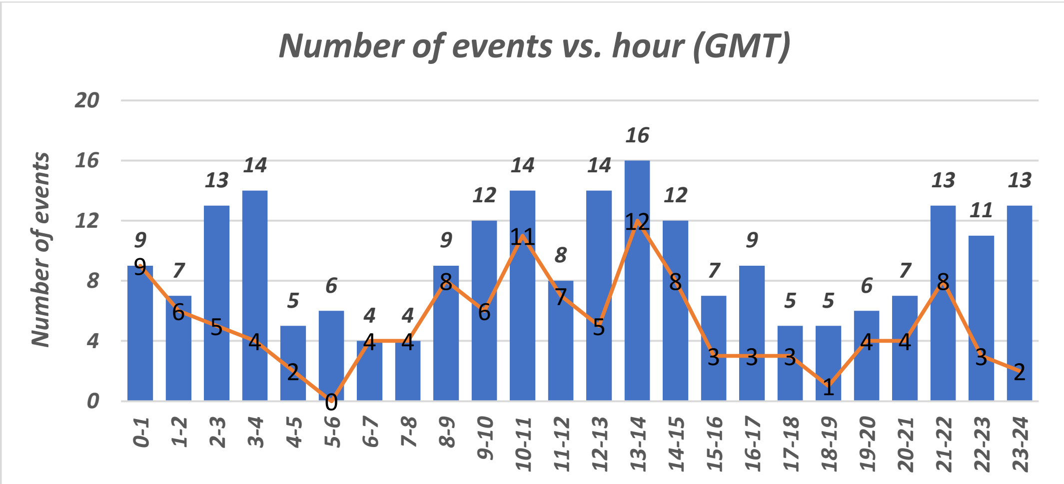


Fig. 14. Distributions of number of events as a function of month (top), weekday (middle) and hour (bottom) for Bucovina and Moldova regions.
Number on top of bars – number of LM events ($M_w < 2.5$);
number on orange curve – number of HM events ($M_w \geq 2.5$).

The analysis of the events located in the south-western corner shows that these events are largely related to the presence of the quarries running here (more than 50% of them occurred between 9 and 15-hour interval).

The distribution of events on magnitude (Figure 15) can be approximated by a linear decay for a magnitude of completeness around 2.5.

The focal depth concentrates in the upper crust (h < 15 km).

Two eccentric depths around 80 and 160 km are probably caused by poor hypocenter determination (Figure 16).

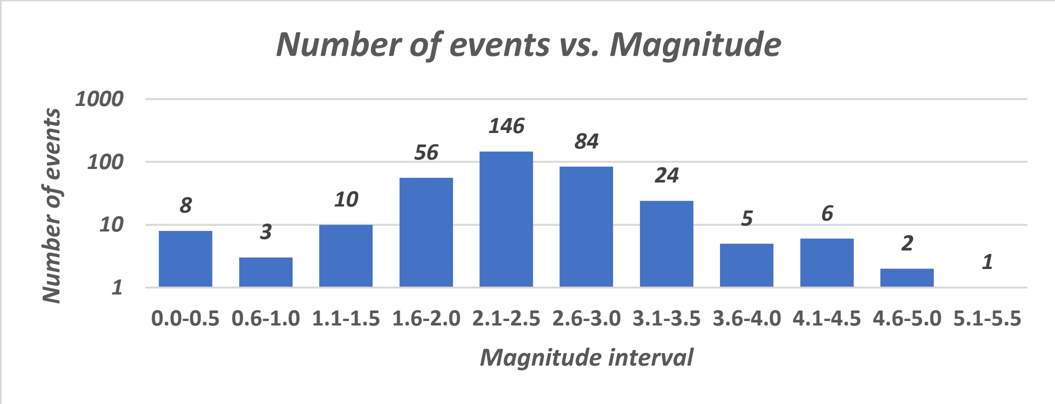


Fig.15. Number of events recorded since 1900 versus moment magnitude.

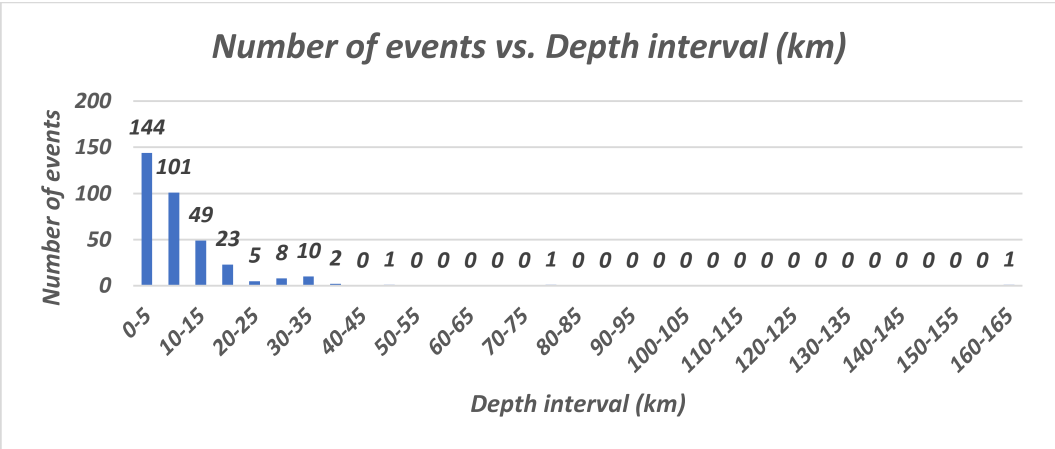


Fig.16. Number of events versus focal depth.

2.4 Dobrogea

Dobrogea region is located in the eastern side of Romania between the Black Sea and Danube river. From tectonic point of view, Dobrogea is composed of three distinct compartments: the Scythian Platform, the North Dobrogea orogen and Moesian Platform. The three tectonic compartments have distinct lithological and structural features and they are separated by well-defined crustal faults. The Scythian Platform is located north of the Sf. Gheorghe or North Dobrogea Fault and includes the Danube Delta and southern Ukraine. The North Dobrogea orogen is situated between the Peceneaga-Camena Fault to south and the Sf. Gheorghe Fault to north. The Moesian Platform is developed south of the Peceneaga-Camena Fault.

The three units are extended to the east, to the shelf of the Black Sea, as well as to the west of Danube, in Muntenia and southern Moldova.

To analyze the seismicity (see Figure 17), we divide the region into three segments: South Dobrogea (up to Capidava-Ovidiu Fault), Central Dobrogea (between Capidava-Ovidiu Fault and Peceneaga-Camena Fault) and North Dobrogea (north of Peceneaga-Camena Fault).

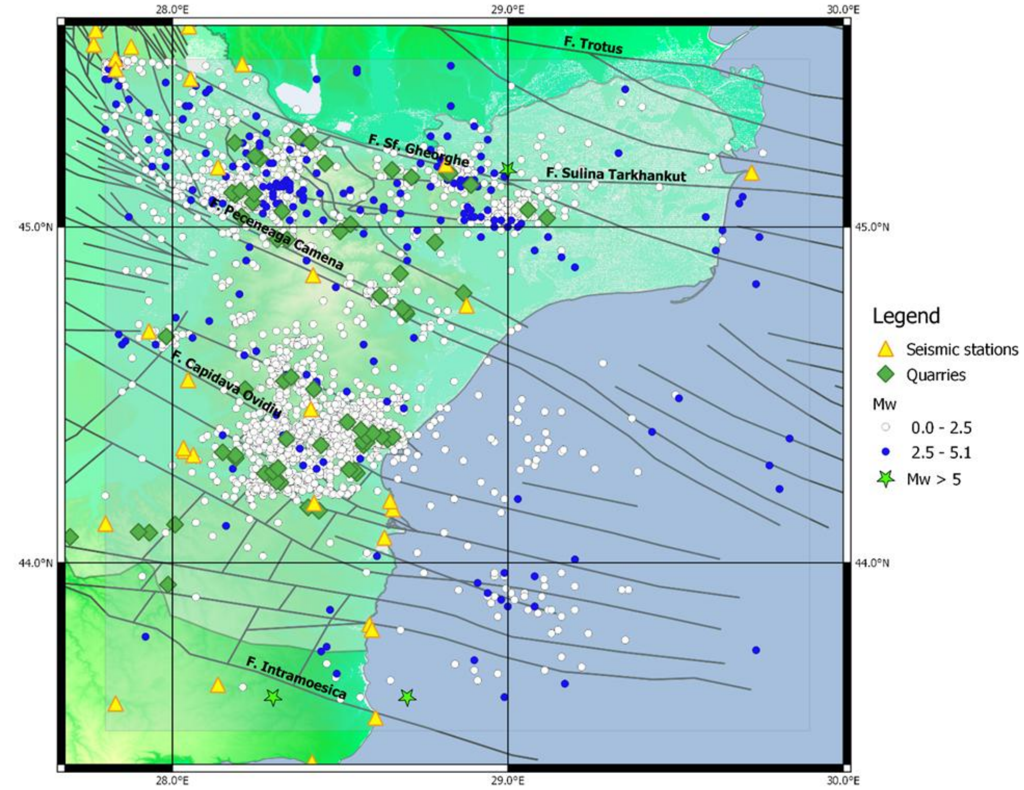


Fig. 17. Epicentres of the events located in the Dobrogea region. Seismic stations and quarries situated inside the area (shaded polygon) and in its vicinity are plotted as well. Fault traces are extracted from [47].

The seismic activity in the South Dobrogea segment is generally weak and scattered, except the source located in the Shabla-Cavarna region (Black Sea offshore in the NE of Bulgaria). The earthquakes generated here were nominated by [1] as „Pontic earthquakes".

They are generated along a NE-SW fault line (Shabla fault) which lies parallel to the Black Sea coast line. The activity on this fault line can be linked to the presence of the NE-SW right lateral strike-slip rupture characteristic for this area. The strongest earthquakes in the past were recorded in 1832 (M_w= 6.5) and in 1901 (M_w= 7.2). The strongest event produced in the last 100 years was recorded in 1956 (M_w= 5.5). The foci are located mainly in the upper 10-20 km, with few events located down around 30 km depth.

The mainshock of 31 March 1901 (07:10) was followed by an intense aftershock activity that lasted for three years, until 1904. A few villages along the Black Sea shore were largely destroyed. Intensity III-IV was reported over an area of about 250.000 km^2, to the foot of Carpathians and southern edge of the Moldavian plateau to the north, to the Portile-de-Fier to the west and to the Balkan mountain range to the south.

A first significant aftershock (M_w= 5.0) generated after three hours (11:30) was felt up to Giurgiu. We mention other two moderate earthquakes produced in the Shabla source during 20th and 21st centuries, one in 25 January 1915 07:55 (M_w= 5.0) with intensity VII-VIII in epicenter and weakly felt in Bucharest, the other in 5 August 2009 07:49 (M_w = 5.0) felt in Dobrogea (intensity IV in Constanta) and in the eastern part of Muntenia (intensity III in Bucharest).

Another group of earthquakes, localized in northern Bulgaria (Kemanlar – Ruslar region) are nominated by [1] as „Pre-Balkan earthquakes". Several faults in the basement are located here according to the tectonic map of Bulgaria [21].

Significant events are reported in 14 October 1892 (M_w= 6.6) which was felt with intensity VIII-IX in epicenter, intensity VII along Danube river and intensity V in Bucharest, 15 November 1892 (M_w= 4.5), 14 January 1900 (M_w= 5.9), 1915 (M_w= 5.0) and 1942 (M_w= 5.1). The seismicity is shallow, down to about 30 km, with highest density of foci between 10 and 20 km.

Besides these tectonic sources, the activity in the South Dobrogea segment is dominated by the man-made activities: quarry blasts routinely detected and located as small seismic events by the Romanian Seismic Network. A complex of mines activates at the northern limit of the South Dobrogea segment, south of Capidava-Ovidiu Fault (see Figure 17).

Commonly, the quarry sources release characteristic energies for surface explosions of about 1 ton of TNT [4] which correspond to moment magnitudes below 2.5.

Clearly the magnitude distribution (see Figure 18), monthly, weekly and hourly distributions (see Figure 19) show a strong contamination of the ROMPLUS catalogue with artificial events.

The activity in the Central Dobrogea segment is mostly controlled by the man-made activity related to the group of mines located in the central part of Dobrogea. The percentage of assumed tectonic events in this area is apparently below 10%. The largest events located here in the Romplus catalogue have magnitudes below 3. From this point of view, we can characterize the Central Dobrogea as aseismic in strong contrast with the North Dobrogea segment (northern side vs southern side of the Peceneaga-Camena Fault).

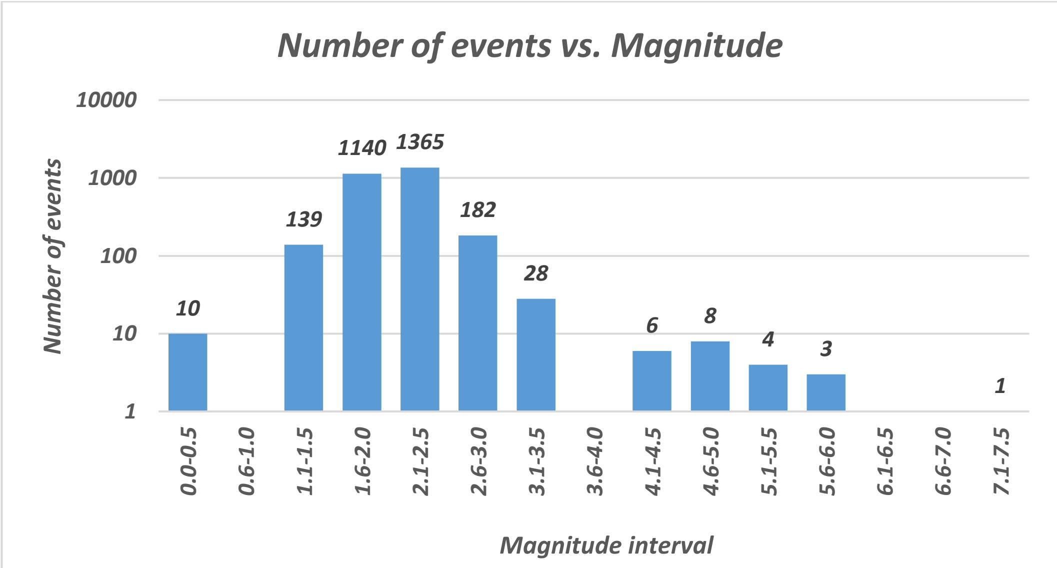
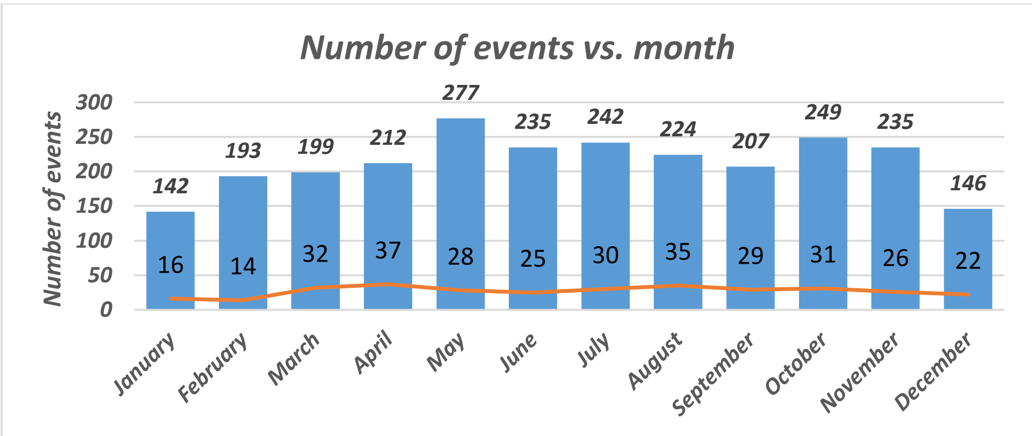
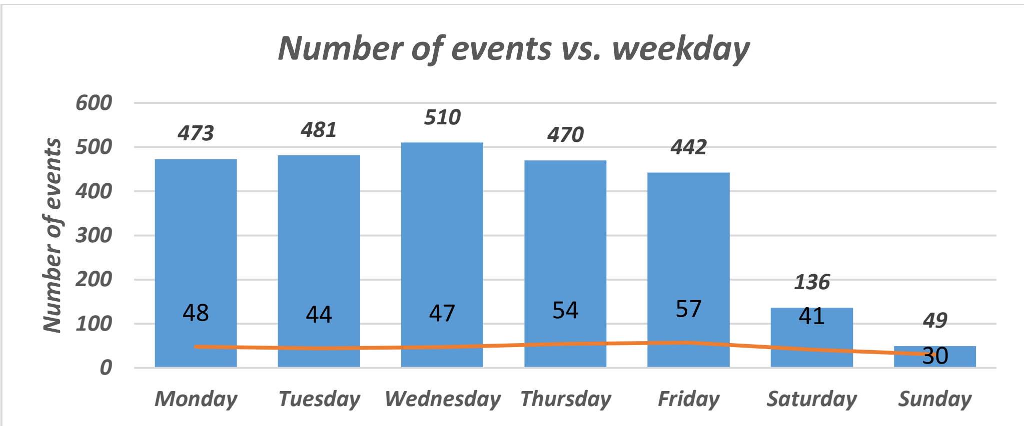


Fig. 18. Number of events versus moment magnitude.





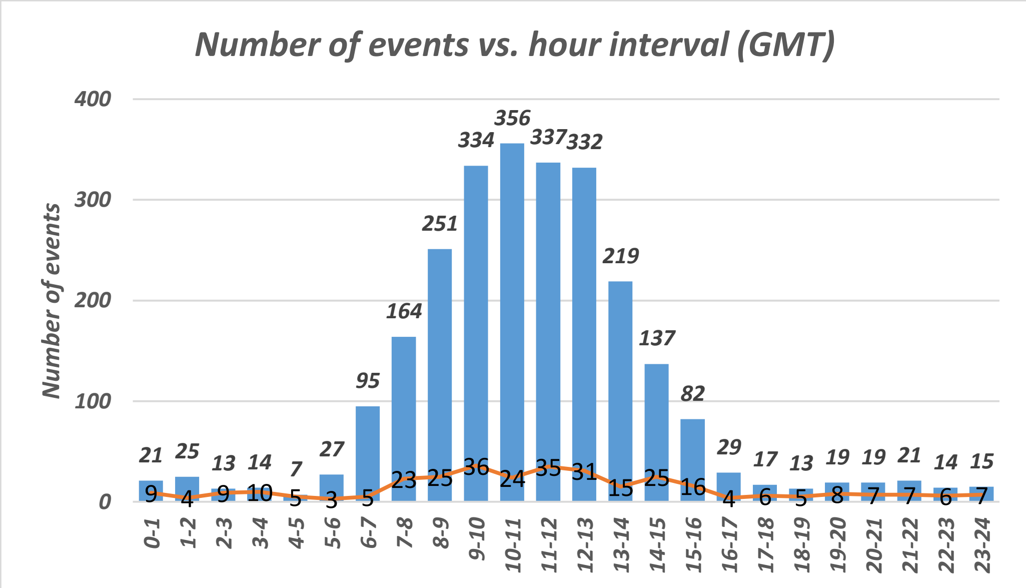
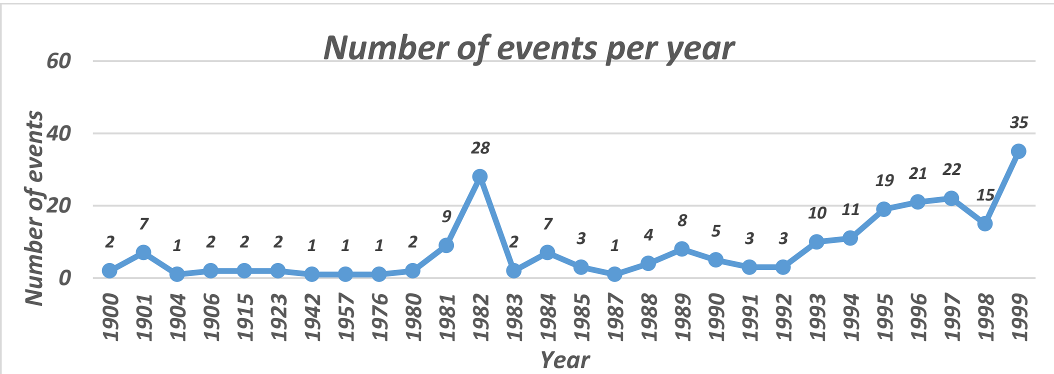


Fig. 19. Distributions of number of events as a function of month (top), weekday (middle) and hour (bottom).

The activity in the North Dobrogea segment concentrates between the Peceneaga-Camena Fault and Sf. Gheorghe Fault and is related, on the one hand, to the tectonic activity along these faults, and, on the other hand, to the presence of numerous quarries spread throughout the region. All the events with magnitude above 3.5 occurred in this segment (except for events in Bulgaria). The largest earthquake occurred 13 November 1981 (M_w= 5.1), located close to Tulcea city.

The time history of the events detected and located in the catalogue is represented in the Figure 20. The oldest earthquake mentioned in the ROMPLUS catalogue (but not in SHEEC) occurred on 26 January 1872 in the North Dobrogea segment (M_w= 3.2). In the northern part of Bulgaria the oldest event was reported in 1864 (M_w= 6.0).



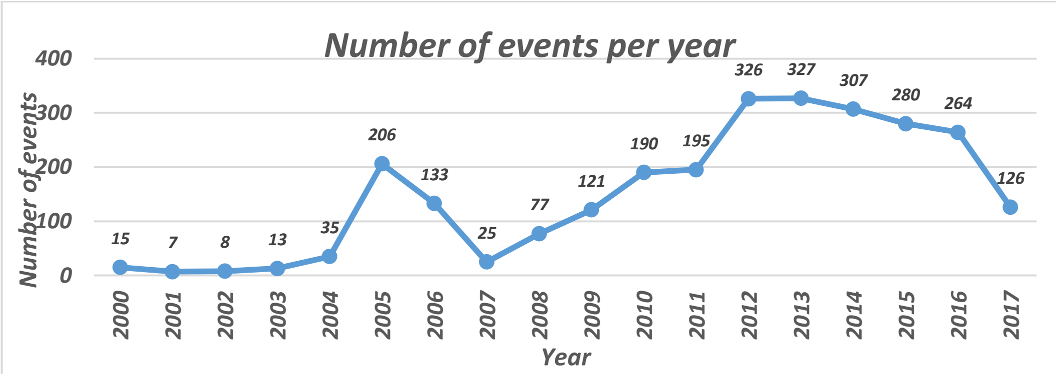


Fig. 20. Time evolution of the number of events/year in Dobrogea region for 1900 – 1999 (top) and 2000 – 2017 (bottom) time intervals.

A refined analysis of the magnitude distribution of Figure 18 (smaller magnitude intervals) shows two maxima, around M_w 1.7 and M_w 2.1-2.2. Only ~1.5% of the events have magnitudes 3 or more. The first cluster of events is associated with the group of quarries in the North Dobrogea (Măcin area), while the second cluster is associated with the group of quarries in the Central Dobrogea (Medgidia area). The difference in magnitude range can be explained by differences in specific energy releases and/or by different detection capability of the seismic network for the two local groups of events.

The monthly distribution of the events (see Figure 19-top) shows some seasonal variation due to man-made activities, with minimum activity in the winter time (nearly half of the number of events per month in the summer time). Similarly, the number of events per weekday (see Figure 19-middle) is strongly diminished on Sunday and Saturday and the number of events per hour is increasing more than 10 times in the middle of the day (see Figure 19-bottom). A rough estimation using these diagrams indicates about 80% of the events as being artificially generated.

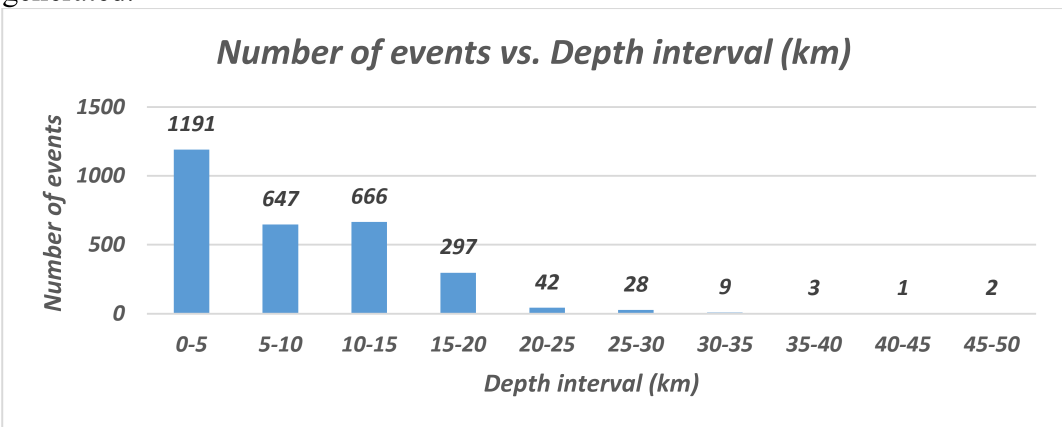


Fig. 21. Number of events versus focal depth.

Most of the events (97%) are located within first 20 km depth (upper crust) as shown in the Figure 21. A large number of these events are related to quarry activities.

2.5 Muntenia

From tectonic point of view, Muntenia and Oltenia belong to the Moesian Platform. According to the foundation constitution, the platform is divided into two distinct sectors separated by the Intramoesian Fault. To the north and east of this fault there is the Dobrogean compartment of the platform, and to the south the Wallachian compartment. The Pecenega-Camena fault is the north-eastern limit of the Moesian Platform. It is a crustal fracture with a jump of over 10 km at Moho discontinuity. To the southeast it extends to the area of the Black Sea continental shelf, and to the northwest to the Trotuş Fault. At a rapid glance we note the difference in the seismic regime between the eastern and western sectors of the Moesian Platform. The western sector (Oltenia) is almost aseismic except the contact with the orogeny, while the eastern sector (Muntenia) is characterized by a small-to-moderate and diffuse seismicity.

The seismic activity is plotted in the Figure 22. The catalogue for this region contains 587 of events (3 historical events from SHEEC catalogue + 584 events from ROMPLUS catalogue).

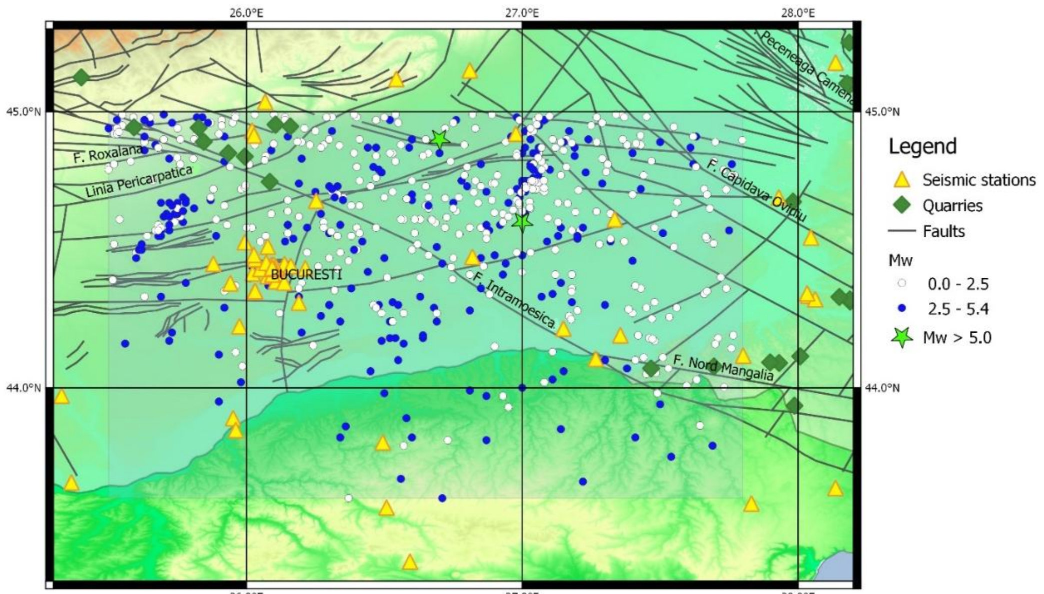


Fig. 22. Epicenters of the events located in the Muntenia region. Seismic stations and quarries situated inside the area (shaded polygon) and in its vicinity are plotted as well. Fault traces are extracted from [47]

Some possible quarry activities are located in the north-western edge of the region. However, the distributions of events per month, weekday and hour (see Figure 23) are complying with tectonic earthquakes regime. A slight interference with the activity (including quarry activities) in the Făgăraş-Câmpulung zone is expected for the north-western corner of the region. This can explain some increase barely visible in the number of events in the mid-day interval.

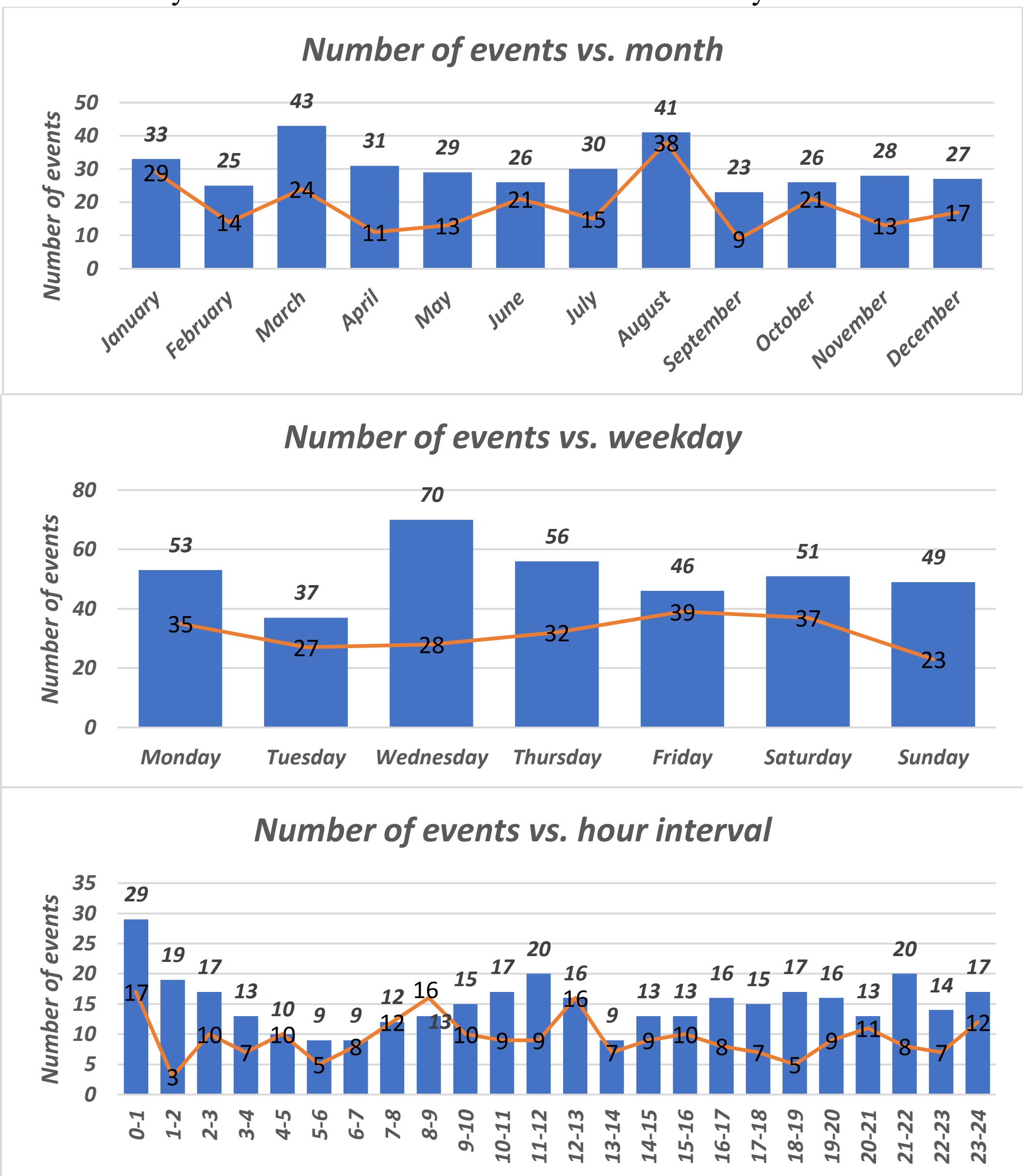


Fig. 23. Distributions of number of events as a function of month (top), weekday (middle) and hour (bottom). Number on top of bars – number of LM events ($M_w < 2.5$); number on orange curve – number of HM events ($M_w \geq 2.5$).

The seismic activity represented since 1900 in the Figure 24 shows a general increasing trend after 1980 and several peaks of activity superposed on this trend. The peak in 1977 contains the south-eastern extremity of aftershock activity following the strong Vrancea shock of March 1977. The peak in 1982 is a simple statistical fluctuation. In 1993 a small earthquake sequence (7 events) was recorded between 18 and 27 June. In 2005 an earthquake sequence started on 20 August (M_w = 2.6) and continued until 3 September (30 events with magnitudes between 2.3 and 3.1). A sequence of 36 events was recorded between December 2007 and January 2008 (the largest magnitude of 3.1 recorded on 26 January 2008). A sequence of 19 events was recorded in March 2015 ($1.9 \leq M_w \leq 2.3$).

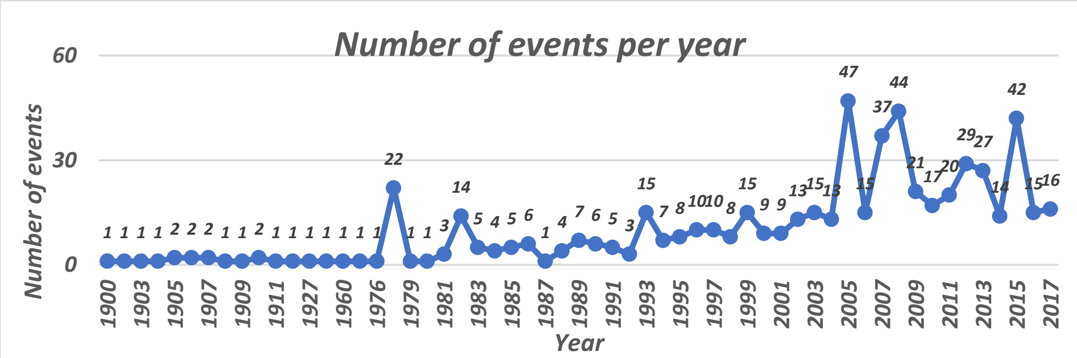


Fig. 24. Time evolution of the number of events/year since 1900.

The distribution on magnitude (see Figure 25) reveals the magnitude threshold of completeness around M_w = 2.5 – 2.6. The largest event (M_w = 5.4) was recorded on 4 January 1960 on the median segment of the Intra-Moesian Fault at 41 km depth, close to Cazanesti (Ialomita). The earthquake was felt in the entire eastern Muntenia region, including in Bucharest. The slope of the frequency-magnitude distribution is greater than 1 which indicates either catalogue incompleteness (for events above 3.5 magnitude), or catalogue contamination (at smaller magnitudes), or both.

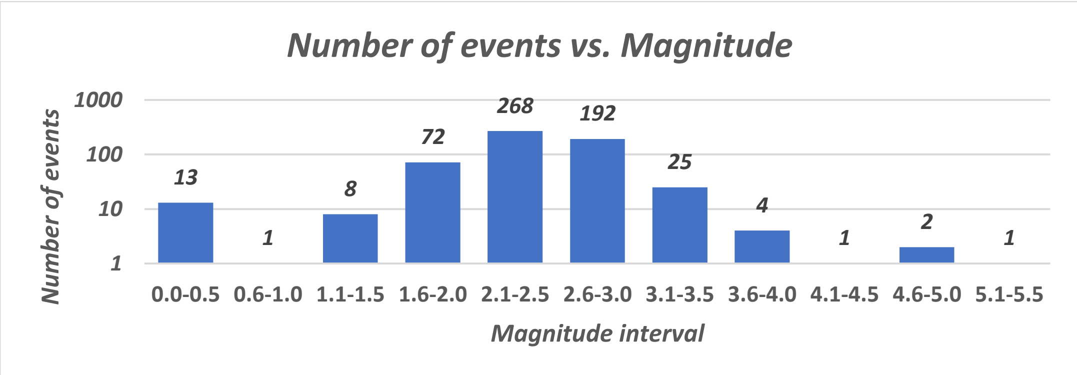


Figure 25. Number of events versus moment magnitude.

The majority of the events are located in the upper crust (0 – 15 km) – see Figure 26. The 8 events with depth below crust (h > 50 km) are recorded before 2004 with poorly constrained locations (GAPs above 220^0). Three of them were aftershocks of the March 1977 major earthquake.

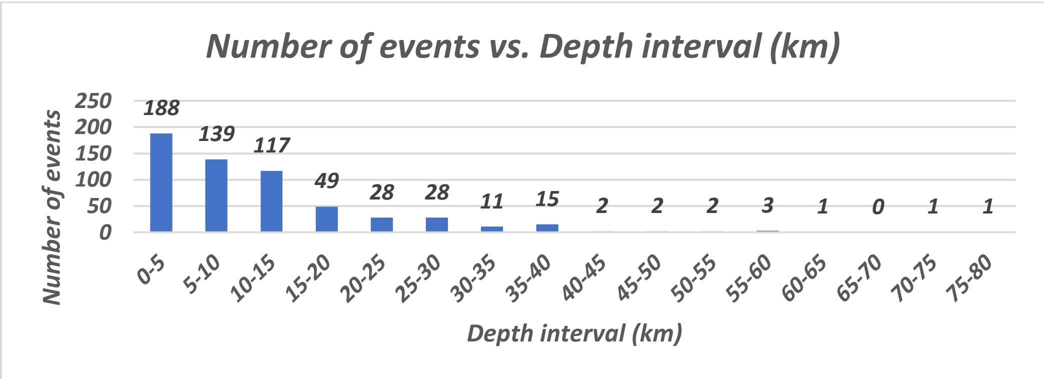


Fig. 26. Number of events versus focal depth

2.6 Oltenia

Oltenia region, conventionally defined as in the Figure 27, comprises on most of the territory the western sector of the Moesian Platform which is practically aseismic, and the contact along the Carpathians to the north which is active both as tectonic events and quarry blasts (several quarries are operating in this region).

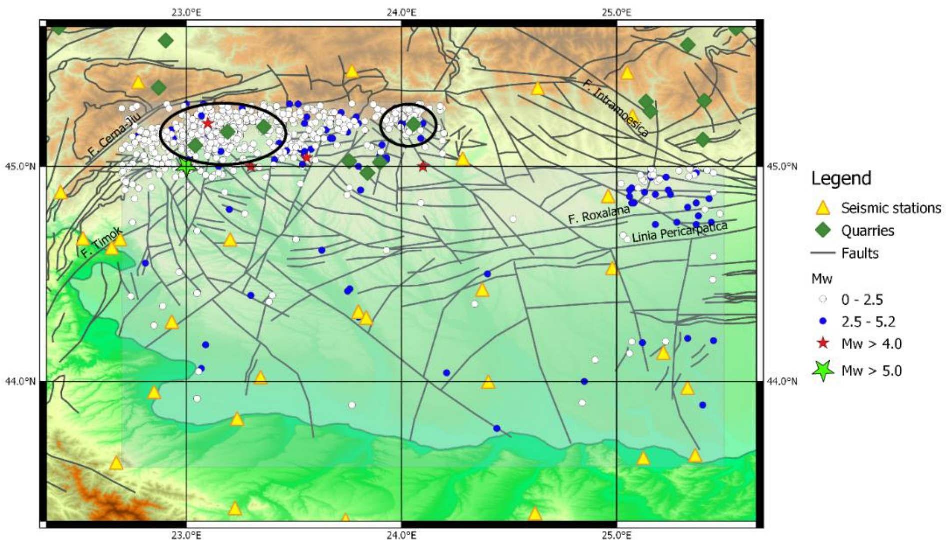


Fig. 27. Epicenters of the events located in the Oltenia region. Seismic stations and quarries situated inside the area (shaded polygon) and in its vicinity are plotted as well. Fault traces are extracted from [47]. The ellipse areas denote quarry events activity.

The borders to the north and west separate rather conventionally the seismicity in the central segment and south-western segment of the Carpathians.

Therefore, we shall consider finally as more appropriate the seismicity characterization on both sides of these borders.

The Getic Depression is the most internal and deformed part of the foredeep in the South Carpathians foreland.

It is bordered to the south by the Pericarpathian Fault, at the contact with Moesian Platform.

As representative earthquakes generated at the contact of Getic Depression and the South Carpathians, we mention the earthquake sequence produced in December 2011 – January 2012 in the vicinity of Tg-Jiu city.

The largest shock ($M_w = 4.5$) occurred on January 01, 2012, being preceded by 7 foreshocks and followed by 32 aftershocks. The focal mechanisms for three of the events reveal a reverse faulting process with nodal planes following a NE-SW orientation [44].

Five earthquakes with magnitude above 4 have been recorded in the region in 23 June 1900 07:06 ($M_w = 4.2$), 9 July 1912 21:46 ($M_w = 4.5$), 20 June 1943 01:00 ($M_w = 5.2$), 4 May 1963 16:48 ($M_w = 4.5$) and 1 January 2012 23:57 ($M_w = 4.5$).

All these events occurred along the contact of Getic Depression with the South Carpathians which shows the largest potential for earthquake generation.

The entire area situated south of 45^0N latitude is almost aseismic, with only sporadic events of magnitude above 3.

All the quarries identified in the region are situated in the northern side, in the Carpathians or at the contact between orogen and platform, coinciding roughly with the areas where seismic activity is recorded (elliptic areas in Figure 27).

The distribution in space of the number of events recorded during day time versus night time outlines a significant contribution of the artificial events in the two areas marked by ellipses in the Figure 27 (in the Jiu Valley and north of Tg-Jiu city – western site, and close to Bistriţa town – eastern site).

The quarries situated further south seem to be less active or harder detectable.

The distributions of number of events as a function of month, week day and hour (Figure 28) reflect the mix of tectonic and man-made events.

However, according to these distributions, the percentage of earthquakes is estimated at about 80% from the total catalogue number for the Oltenia region.

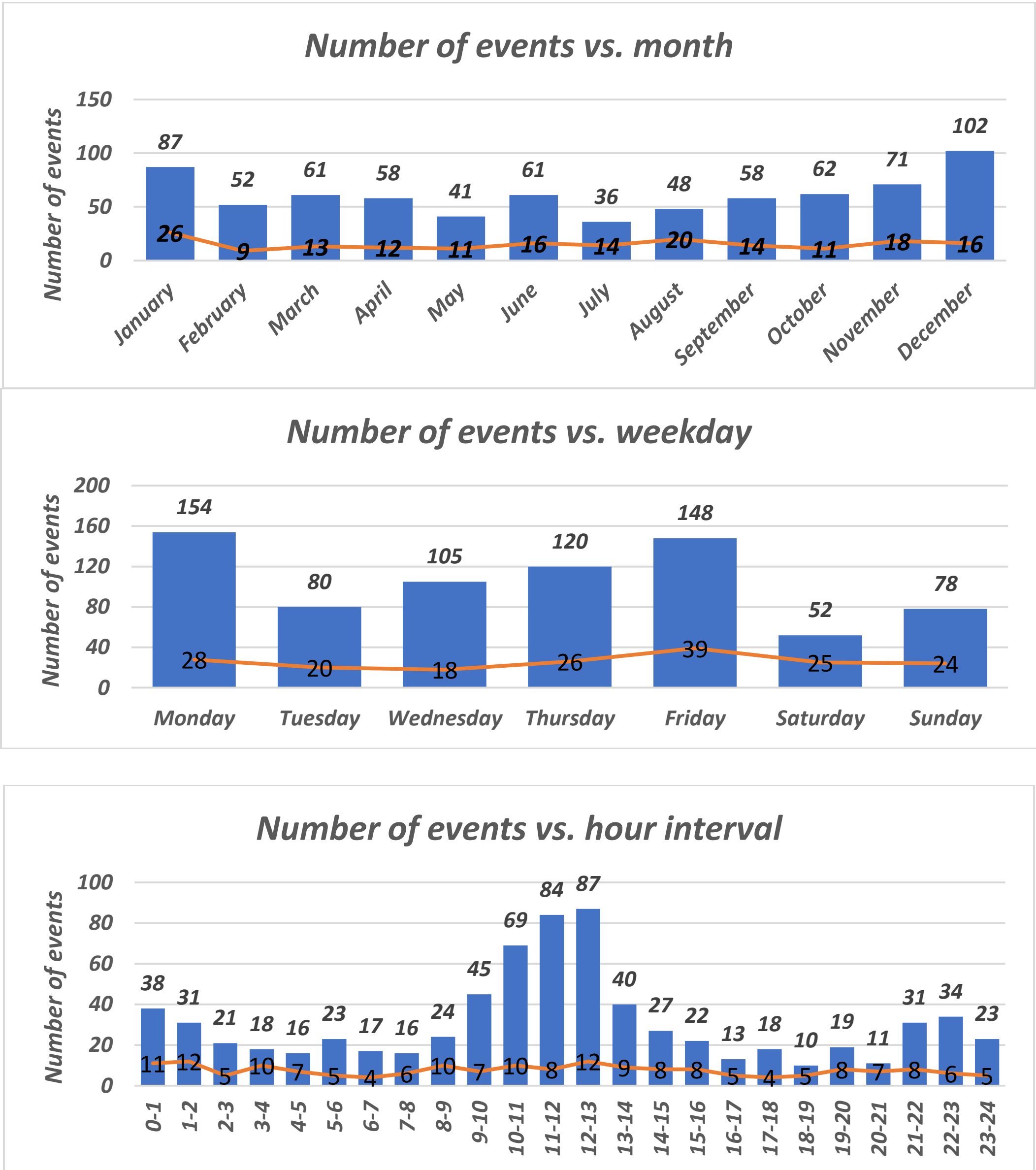


Fig. 28. Distributions of number of events as a function of month (top), weekday (middle) and hour (bottom). Number on top of bars – number of LM events ($M_w < 2.5$); number on orange curve – number of HM events ($M_w \geq 2.5$).

The rate of events detected and located by the seismic network (see Figure 29) has been steadily rising since 2006, as a result of continuous seismic network improvement. Thus, the number of events/year detected and located in 2012 – 2017 reaches a level of about 100 events/year, more than 20 times as compared with the level before 2006. The jump in 2010 is due to the occurrence of the sequence in the Tg-Jiu area.

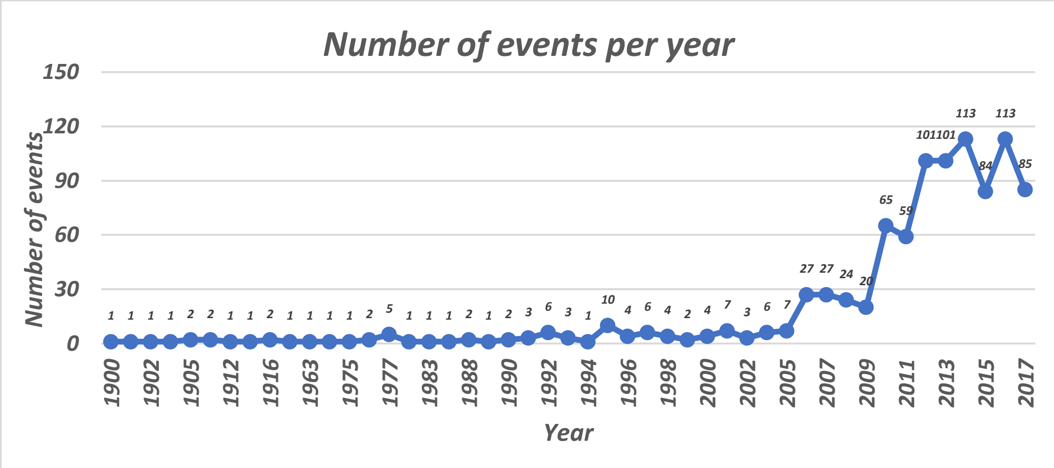


Fig. 29. Time evolution of the number of events/year since 1900.

The distribution on magnitude (see Figure 30) looks like a bimodal distribution. The peak at $M_w = 1.8$ is probably related to quarry blasts events, while the peak at $M_w = 2.3$ is related to the magnitude threshold of completeness for earthquakes.

The largest event ($M_w = 5.2$) was recorded in 20 June 1943.

The largest event recently recorded close to Tg-Jiu city (1 January 2012) has the magnitude $M_w = 4.5$ according to [44].

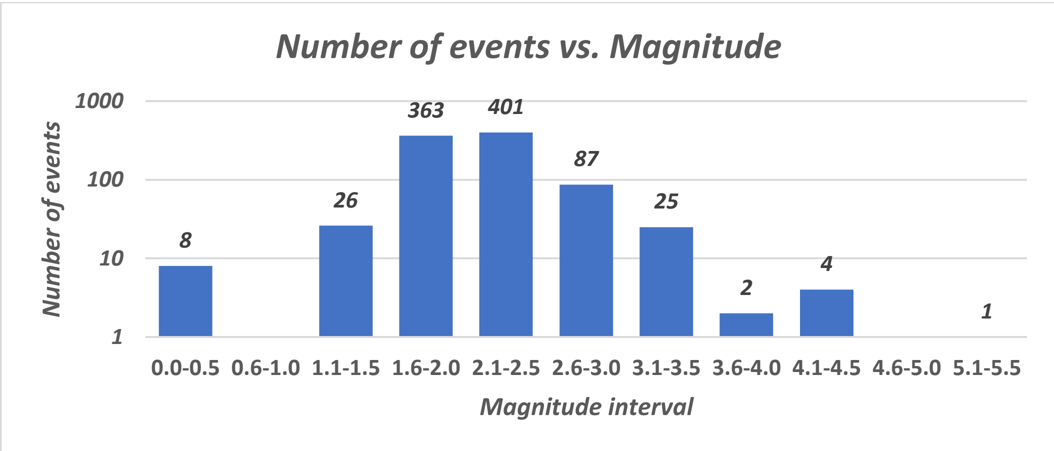


Fig. 30. Number of events versus moment magnitude

The focal depth concentrates within the first 20 km depth (see Figure 31). Only ~2.5% from the total number of events (22 events) have hypocenters at depth greater than 20 km and we assume they are likely to be miss-located.

The isolated event located at 73 km depth was recorded on 19 May 2005, with estimated magnitude of 2.7 and probably is wrongly located.

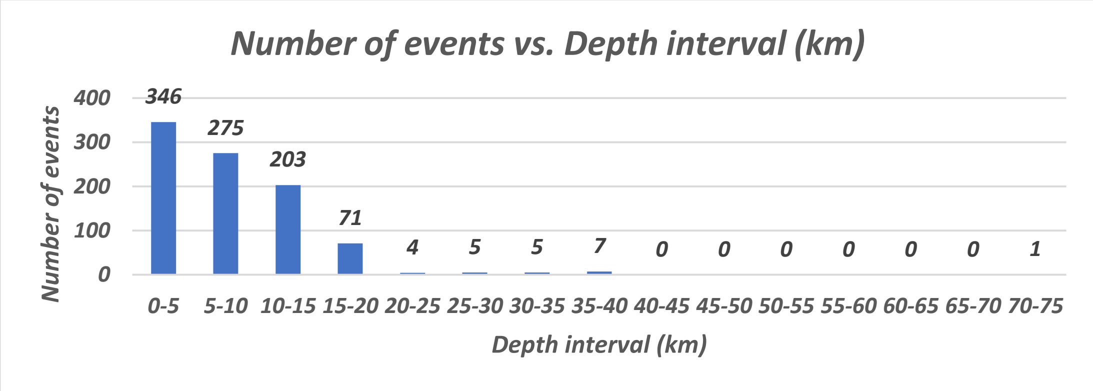


Fig. 31. Number of events versus focal depth.

2.7 Făgăraş-Câmpulung

Făgăraş-Câmpulung region represents the eastern segment of the Southern Carpathians which includes the chain of the highest mountains in Romania. Several active faults are crossing the area which are supposed to generate the seismicity in the region. One important fault is the South Transylvanian Fault which separates the northern part of the Făgăraş Mountains from the Transylvania Plateau. It is assumed that this fault generated the earthquake of 26 October 1550 (M_w= 6.5) that severely affected the cities of Sibiu and Făgăraş (maximum intensity of IX). Lovştei Fault is another significant active fault which caused the strong earthquakes of 1746, 1832 and 1916. The fault is developed west of Olt river and crosses the Loviştei Depression.

Frequently the earthquakes are generated in sequences. A few examples of earthquake sequences are:

- 12 April 1969: the mainshock of magnitude M_w = 5.2 followed by 488 aftershocks. The focal mechanism was of strike-slip faulting with the axis of maximum compression on E-W direction,
- 4 May – June 1993: 345 events located in the Sinaia region (mainshock of magnitude M_w = 3.4 occurred on 23 May)

In all cases the estimated depth was around 10 km. According to historical documents (see [1] for references), the earthquakes have been often reported as sequences, such as in 10 April – 19 May 1571, 7 December 1746 – the main shock was followed by aftershock activity until mid of January 1747 and 19 February - 7 April 1832. The shock of 26 January 1916 was followed by numerous aftershocks until 6 May 1916. Some of them were triggered outside the epicentral area of the main shock and were considered by [1] as „delayed aftershocks‟. The largest earthquakes produced in Făgăraş-Câmpulung region ($M_w \geq 5$) are given in Table 2.

Table 2. The largest earthquakes recorded in Făgăraş-Câmpulung region

year	*month*	*day*	*hour*	*Lat.* *(^{0}N)*	*Lon.* *(^{0}E)*	*h* *(km)*	M_w
1550	10	26	01:00	45.80	24.20	10	6.5
1569	8	17	05:00	45.40	24.50	10	6.4
1571	4	10	07:00	45.50	24.60	10	6.5
1590	8	10	20:00	45.40	24.40	10	6.5
1639	4	9	01:00	45.40	24.20	10	5.3
1746	12	7	01:00	45.50	24.60	10	5.9
1832	2	19	07:08	45.40	24.20	10	5.6
1916	1	16	07:37	45.21	25.37	16	6.4
1916	1	16	08:15	45.40	24.20	10	5.2
1916	1	16	08:30	45.40	24.20	15	5.0
1969	4	12	20:38	45.25	25.02	8	5.2

The earthquake of 26 January 1916 was felt over an extended area elongated more than 300 km to north - to Tisa river and to south - to Sofia. There were effects recorded westwards as well – to the Timiş river. Instead the movement was strongly attenuated to the east, so that no effects were reported in the Moldavian Plateau ([14], [28]). The relocation of the event made by [25] by reviewing the instrumental data available for this earthquake in the framework of EUORSEISMOS project (*sismos.ingv.it*) shows a substantial shift to the east (more than 60 km) as compared with the location in ROMPLUS. The stress regime characteristic for the South Carpathians is extensional as pointed out by the available fault plane solutions of strike-slip and normal type [11, 42]. More recent results show a contrary trend to reverse faulting in the Făgăraş-Câmpulung region [45]. However, since these results are based on a relatively small number of background seismicity events (magnitudes less than 3.3), it is hazardous to take on under these circumstances such a solution and the problem of the predominant stress field in the region remains open for future investigations.

The seismicity pattern (see Figure 32) outlines three active tectonic areas mixed with several active quarries. We can distinguish Făgăraş-Loviştea Depression (to the west), Câmpulung area and Sinaia area (to the east). In the western side of the region tectonic events prevail, in agreement with the lack of quarries in this region. The seismicity patterns in the eastern side are related both to tectonic faults and man-made activities as reflected in the distributions of the events per month, per weekday and per hour (see Figure 33).

Thus, the monthly distribution shows seasonal variation due to man-made activities (minimum in the winter time), minimum number of events in the weekend days and a distinctive maximum in the working hours. A rough estimation using these diagrams indicates a large percentage (about 60%) of the events as being artificially generated.

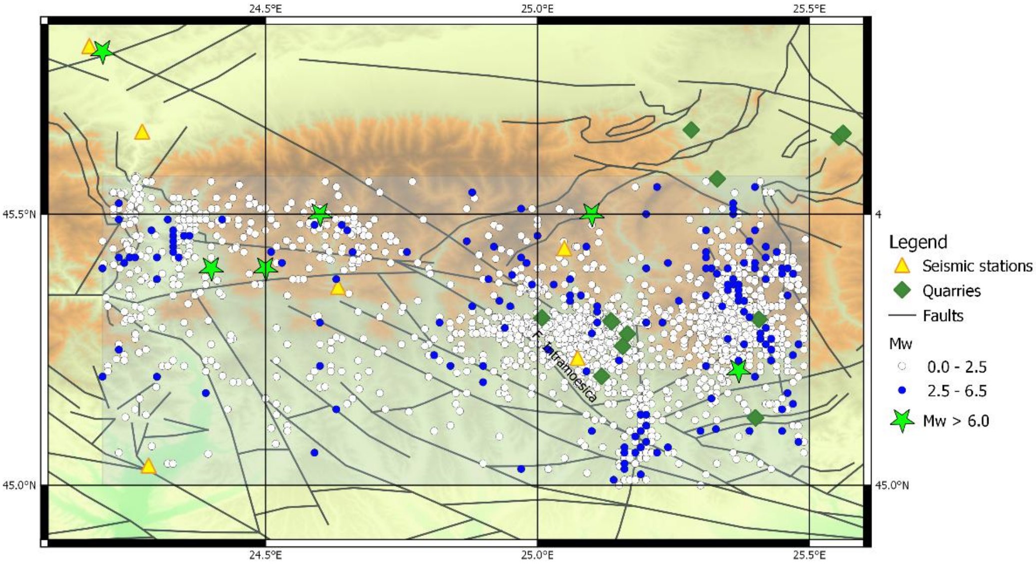
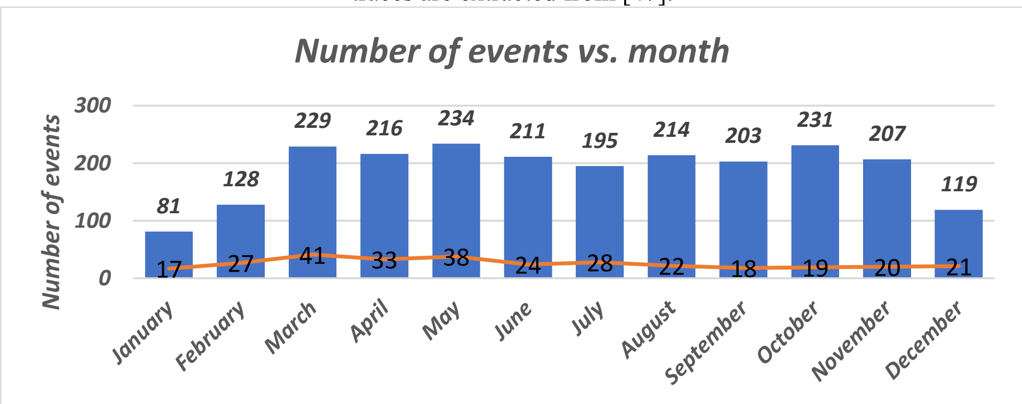
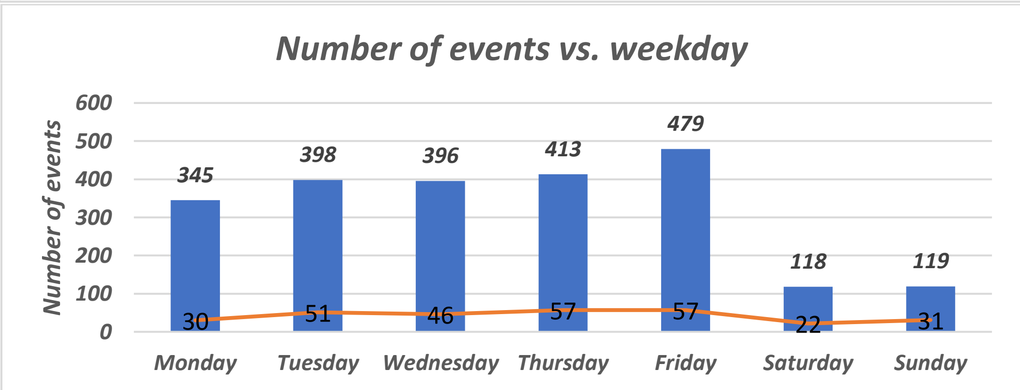


Fig. 32. Epicenters of the events located in the Făgăraş-Câmpulung region. Seismic stations and quarries situated inside the area (shaded polygon) and in its vicinity are plotted as well. Fault traces are extracted from [47].





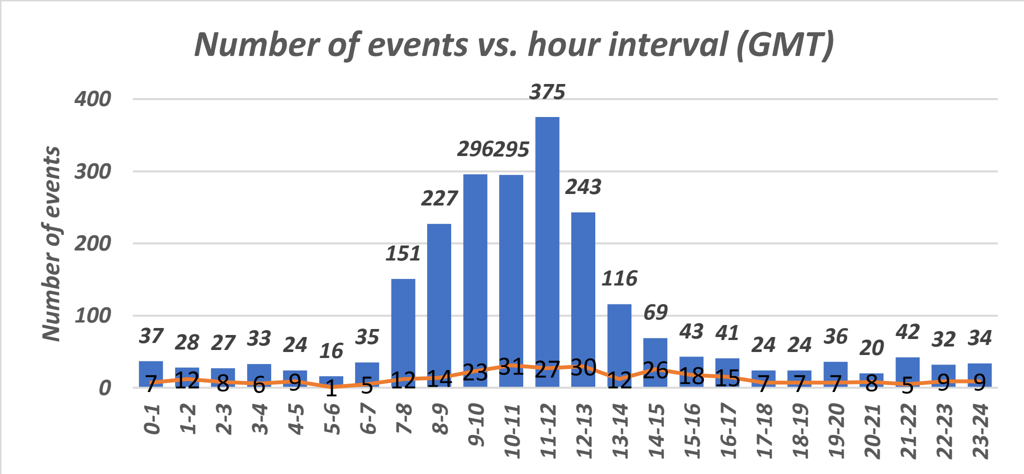


Fig. 33. Distributions of number of events as a function of month (top), weekday (middle) and hour (bottom). Number on top of bars – number of LM events ($M_w < 2.5$); number on orange curve – number of HM events ($M_w \geq 2.5$).

The maximum in the distribution of events on magnitude around 2.2 magnitude (see Figure 34) is a further proof of a considerable contamination with quarry blasts of the catalogue. The number of strong events ($M_w \geq 5$) relative to the number of small events ($M_w < 3$) is an indicator of the catalogue incompleteness for the entire magnitude range.

If we want to limit the frequency-magnitude analysis to smaller magnitude range, we have to be careful to the strong contamination with artificial events which disturbs the distribution for magnitudes around 2 (specific for quarry blasts energy release).

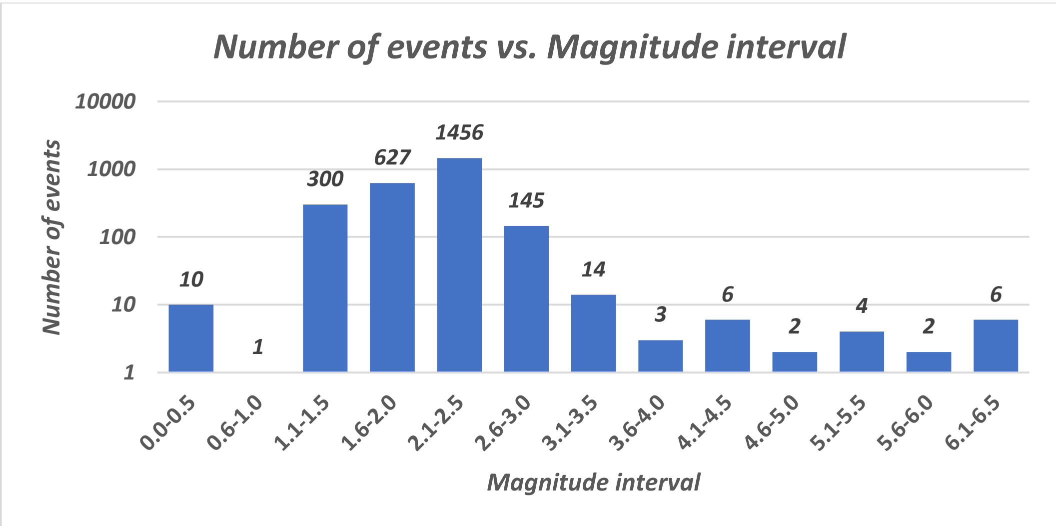


Fig. 34. Number of events versus moment magnitude (including historical events).

The variation in time of the seismic activity (see Figure 35) shows local fluctuations correlated with the earthquake sequence of Sinaia (1993) (local maximum) and the general trend of increasing the number of events monitorized by the seismic network in a continuou process of improvement.

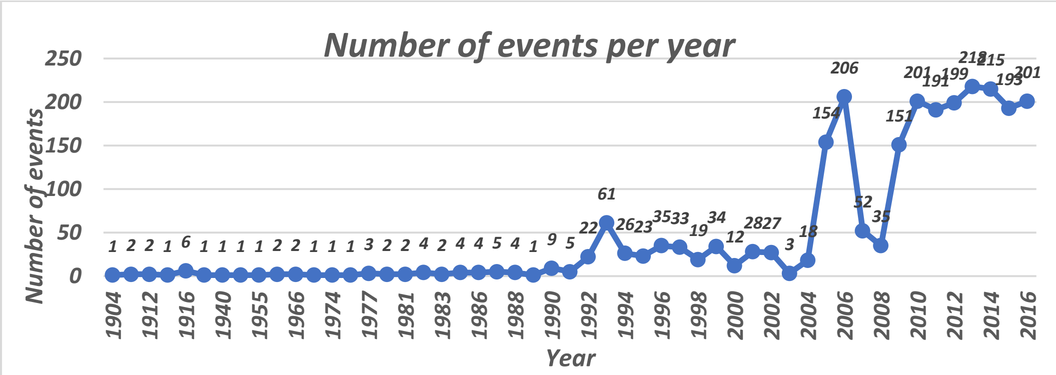


Fig. 35. Time evolution of the number of events/year since 1900.

The depth distribution of the events (Figure 36) shows the preference of the earthquakes to be generated in the upper 20 km. The high pick for 0 – 5 km depth interval is obviously related to the artificial events generated by quarry activity. The events located in the lower crust or even below crust belong to the eastern sector of the seismogenic zone.

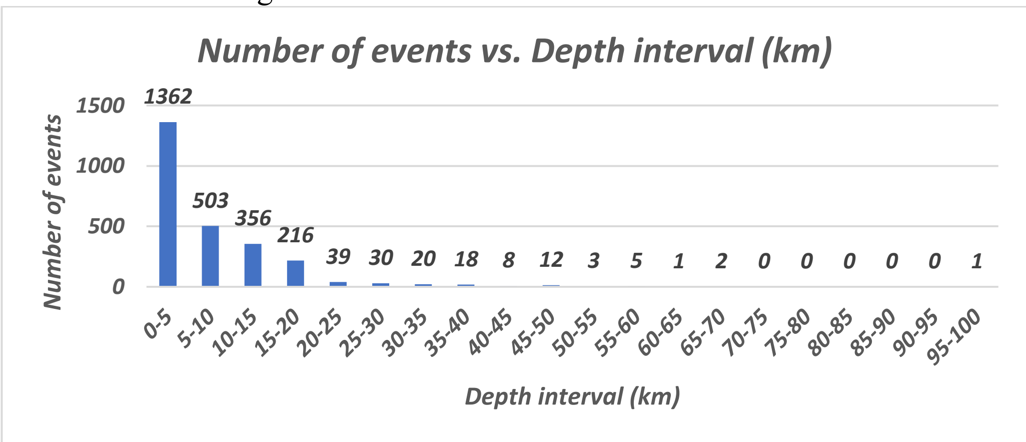


Fig. 36. Number of events versus focal depth

2.8 Banat

The Banat region is located at the contact between the Carpathians and Pannonian Depression where the stress field controlled by NE Adria Microplate pushing and the basin inversion processes (e.g., [2, 3]). The system of faults defines three geodynamic units, Pannonian, Geto-Danubian and Moesian Geodynamic blocks, assumed to control the seismic activity [53].

One system, located in the northern half of the region, consists of several E-W oriented faults crossing the region (South Transylvanian Fault, Sinnicolau Mare-Arad Fault). Another system, located in the southern half of the region, bends towards SW in parallel with the Carpathians belt (Oraviţa–Moldova Nouă Fault, Cerna-Jiu Fault systems).

[42] defined in the region two seismogenic zones, nominated as Banat seismogenic zone to the north and Danubian seismogenic zone to the south, respectively. Our proposal is to refine the analysis of seismicity patterns on the basis of updated catalogues in order to better delineate the earthquake-prone areas and to identify and separate sources with non-tectonic activity.

The map of seismicity is plotted in Figure 37 for two magnitude bands: LM - low magnitudes ($M_w < 2.5$) and HM - high magnitudes ($M_w \geq 2.5$). Within the polygonal boundary, as conventionally defined in the figure, we identified 1993 events in total (1961 from ROMPLUS catalogue, 30 from SHEEC catalogue and 2 from Oros et al., 2018).

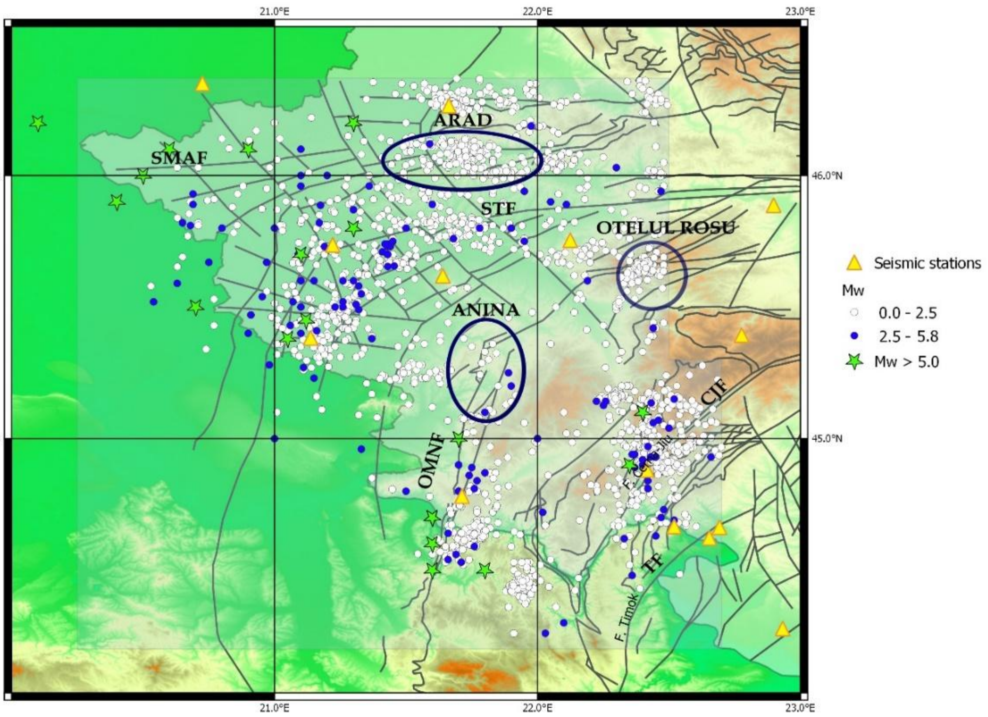


Fig. 37. Epicentres of the events located in the Banat region. Seismic stations (yellow triangles) situated inside the area (shaded polygon) and in its vicinity are plotted as well. The areas contaminated with man-made events are marked by ellipses.
Fault traces are extracted from [47]. **CJF**, **OMNF**, **STF** and **SMAF** are the main fault systems. The epicentres of some of the largest events coincide.

By simple visual inspection we can identify four earthquake-prone areas in correlation with the main fault systems in the region [27]:

1. Cerna – Jiu Fault (CJF) system
2. Oraviţa - Moldova Nouă Fault (OMNF) system
3. South Transylvanian Fault (STF) system
4. Sinnicolau Mare-Arad Fault (SMAF) area

Clusters of both LM and HM events are well individualized in each case, separated by stripes of activity deficit.

The largest earthquakes ($M_w \geq 5.0$) recorded in historical time as well as in the instrumental period (see Table 3) are fitting well the four systems of faults, as defined above.

Note the intensive seismicity recorded during 1879 – 1880 that disturbed all the major fault systems, except **CJF**.

A similar activation in 1991 (slightly less intensive) took place in **CJF** and **STF** systems.

Table 3. List of the largest earthquakes ($M_w \geq 5.0$) recorded before 1900 in the Banat region

Year	*Month*	*Day*	*Time*	Lat. (^{0}N)	Lon. (^{0}E)	*Depth (km)*	M_w	*No. of events*
CJF								
1886	1	10	12:15:00	45.1	22.4	9.9	5.1	***3***
1886	11	23	21:17:00	45.1	22.4	9.9	5.1	
1991	7	18	11:56:31	44.9	22.4	12	5.6	
OMNF								
1879	10	10	15:45:00	44.7	21.6	9.9	5.8	***15***
1879	10	10	18:30:00	44.7	21.6	9.9	5.1	
1879	10	10	19:30:00	44.7	21.6	9.9	5.1	
1879	10	11	1:00:00	44.7	21.6	9.9	5.1	
1879	10	11	2:45:00	44.7	21.6	9.9	5.8	
1879	10	11	10:45:00	44.7	21.6	9.9	5.1	
1879	10	17	2:53:00	44.7	21.6	9.9	5.1	
1879	10	20	10:45:00	44.7	21.6	9.9	5.1	
1879	12	22	4:03:00	44.7	21.6	9.9	5.1	
1880	2	23	21:30:00	44.5	21.6	9.9	5.1	
1880	3	1	2:45:00	44.7	21.6	9.9	5.1	
1880	4	13	12:20:00	44.6	21.6	9.9	5.1	
1884	12	1	0:00:00	44.5	21.8	9.9	5.1	
1887	2	8	7:50:00	45.0	21.7	9.9	5.1	
1894	12	19	22:30:00	45.0	21.7	9.9	5.1	

<table>
<tr><td colspan="9">SMAF</td></tr>
<tr><td>1444</td><td>8</td><td>4</td><td>0:00:00</td><td>46.2</td><td>20.1</td><td>40</td><td>5.8</td><td rowspan="7">7</td></tr>
<tr><td>1797</td><td>10</td><td>19</td><td>0:00:00</td><td>46.2</td><td>21.3</td><td>9.9</td><td>5.1</td></tr>
<tr><td>1847</td><td>10</td><td>15</td><td>6:15:00</td><td>46.2</td><td>21.3</td><td>9.9</td><td>5.1</td></tr>
<tr><td>1859</td><td>10</td><td>17</td><td>9:30:00</td><td>46.1</td><td>20.9</td><td>9.9</td><td>5.1</td></tr>
<tr><td>1879</td><td>10</td><td>31</td><td>18:30:00</td><td>46.1</td><td>20.6</td><td>9.9</td><td>5.1</td></tr>
<tr><td>1879</td><td>10</td><td>31</td><td>18:31:00</td><td>45.9</td><td>20.4</td><td>9.9</td><td>5.1</td></tr>
<tr><td>1879</td><td>11</td><td>1</td><td>6:00:00</td><td>46</td><td>20.5</td><td>9.9</td><td>5.1</td></tr>
<tr><td colspan="9">STF</td></tr>
<tr><td>1879</td><td>11</td><td>19</td><td>23:10:00</td><td>45.8</td><td>21.3</td><td>9.9</td><td>5.1</td><td rowspan="6">6</td></tr>
<tr><td>1885</td><td>2</td><td>25</td><td>19:30:00</td><td>45.8</td><td>21.3</td><td>9.9</td><td>5.1</td></tr>
<tr><td>1901</td><td>4</td><td>2</td><td>16:54:30</td><td>45.5</td><td>20.7</td><td>18</td><td>5</td></tr>
<tr><td>1959</td><td>5</td><td>27</td><td>20:38:26</td><td>45.7</td><td>21.1</td><td>5</td><td>5</td></tr>
<tr><td>1991</td><td>7</td><td>12</td><td>10:42:21</td><td>45.4</td><td>21.1</td><td>11</td><td>5.6</td></tr>
<tr><td>1991</td><td>12</td><td>2</td><td>8:49:41</td><td>45.5</td><td>21.1</td><td>9</td><td>5.5</td></tr>
</table>

An event of magnitude greater than 5 ($M_w = 5.6$) occurred before 18th century in the region (20.06.1443) is mentioned by [26]. The author agrees that additional documentation is needed to obtain more reliable location in space and time and better magnitude estimate. Without denying its authenticity, we prefer not to consider this event in our analysis.

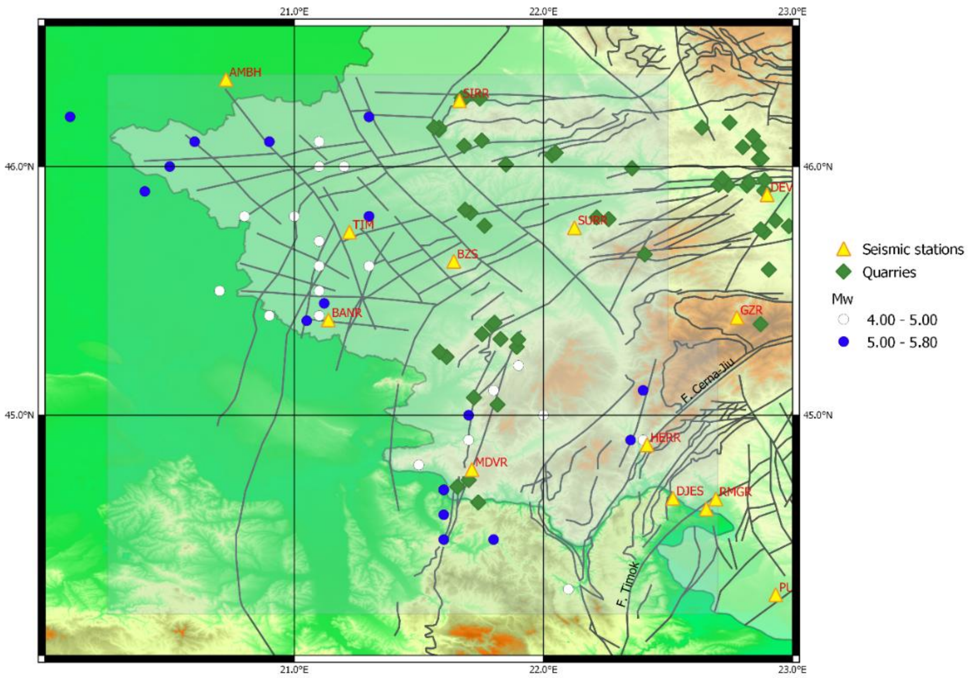


Fig. 38. Quarries identified in the Banat region and neighbourhood. The seismic stations with their codes and epicentres of events with magnitude greater or equal 4 are plotted as well.

Characteristic for the Banat area is the development from time to time of long-lasting multiple-shock sequences triggered on different fault systems, such as in 1879 (CJF, OMNF, STF, SMAF) and in 1991 (CJF and STF). Several months of increased seismicity are recorded in these cases.

Apart of these areas assumed to be seismically active, we can identify a few clusters of events related to sources of man-made activities: Oţelu Roşu (east), Anina (middle) and Arad (north), marked by ellipses in the Figure 37.

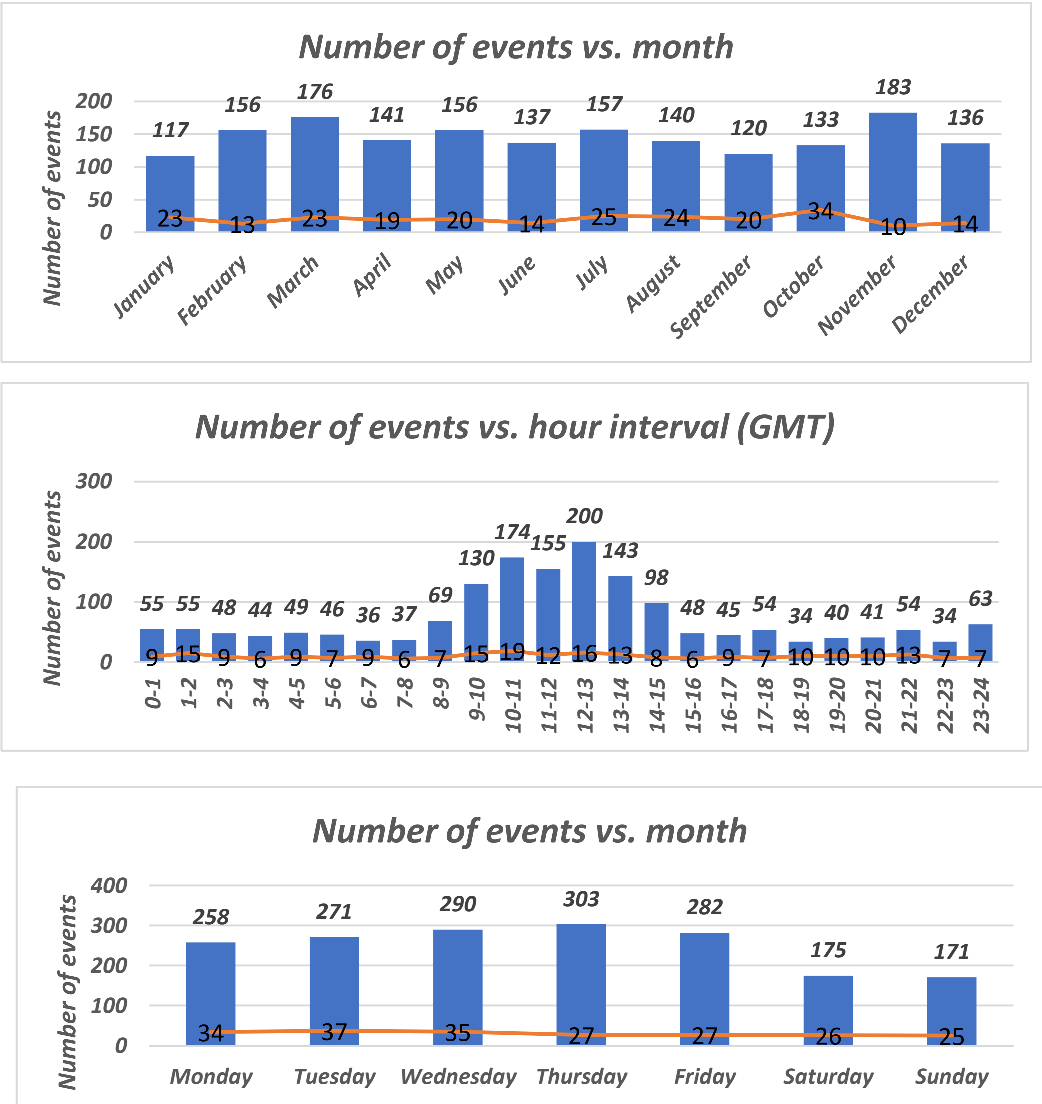


Fig. 39. Distributions of number of events as a function of month (top), weekday (middle) and hour (bottom). Number on top of bars – number of LM events ($M_w < 2.5$); number on top of orange curve – number of HM events ($M_w \geq 2.5$).

They correlate with the existence of active quarries, as shown in the Figure 38. The larger events are usually produced in non-quarry areas, except **CJF** where the quarries and earthquakes are often located in proximity. The distributions of number of events as a function of month, weekday and hour (see Figure 39) show some contamination of the tectonic events with man-made events (~ 33%). Note that this contamination is effective for the low-magnitude (LM) events. The distribution of number of events as a function of daily hours clearly shows a homogeneous repartition for HM events (as expected for tectonic events), while a strong focusing to day-time hours is noticed for LM events (as expected for man-made events). Similar deviations from homogeneous repartition for LM events against HM events are noticeable in the distributions of the number of events per day of the week and the number of events per month.

The distribution of number of events as a function of daily hours clearly shows a homogeneous repartition for HM events (as expected for tectonic events).
The rate of events detected and located by the seismic network (Figure 40) started to increase significantly after 2005 as the seismic network has improved. Until 2005, 5 stations have been operating in the Banat area (Timişoara, Siria, Gura Zlata, Banloc and Buziaş). In 2007 a new instrument was installed in Timişoara. In 2008 one new station was installed (Halanga), then other new stations in 2010 (Moldoviţa), 2011 (Herculane), 2012 (Mehedinţi) and 2016 (Surduc). The enhancement of activity in 2014-2015 corresponds to the occurrence of a large seismic sequence in the Caransebeş-Mehadia Basin belonging to **CJF** system [34]. In the present form, the seismic activity in 1991 is not complete in the ROMPLUS catalogue. This will be fixed as soon as possible in the revised version of the ROMPLUS catalogue.

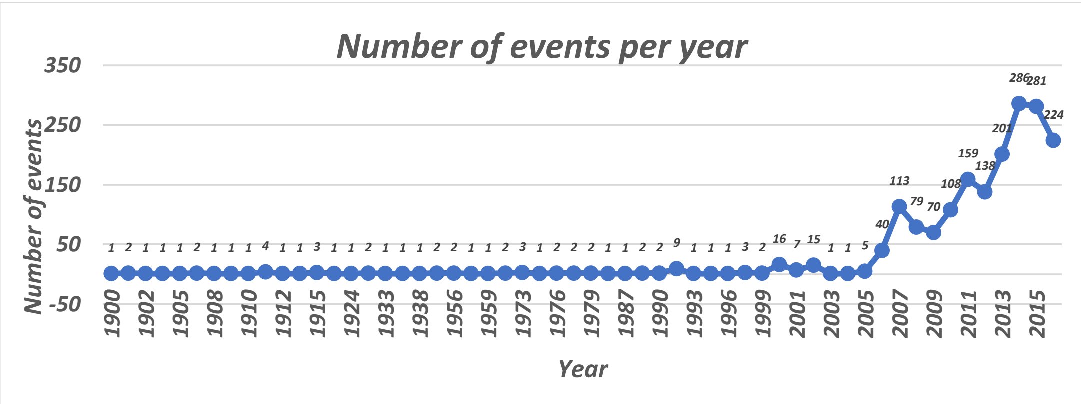


Fig. 40. Time evolution of the number of events/year since 1900.

The distribution on magnitude (see Figure 41) shows a strong deficit of events relative to a linear Gutenberg–Richter distribution for the magnitude interval 2.6-5.0, while a relative enhancement for the largest events ($M_w > 5$).

There are several possible factors explaining this behaviour: contamination with quarry events at low magnitudes, catalogue incompleteness for each of the four earthquake-prone areas (CJF, OMNF, STF, SMAF) and a tendency to overestimate the magnitude for the historical earthquakes.

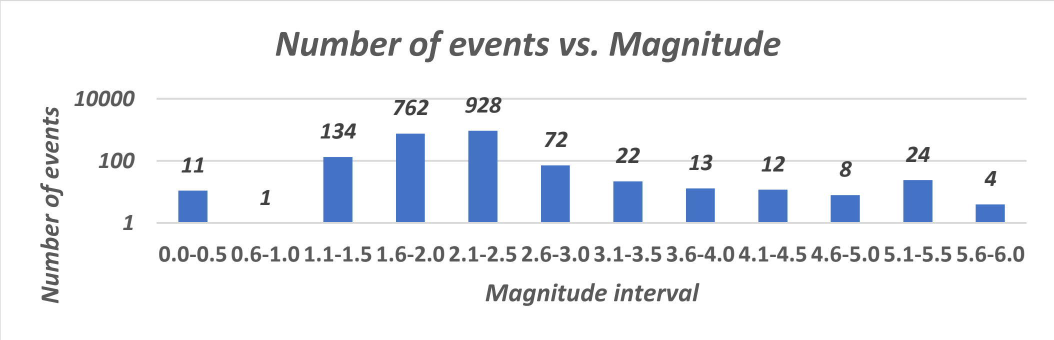


Fig. 41. Number of events versus moment magnitude.

The focal depth concentrates within the first 20 km depth (see Figure 42). Less than 4% from the total number of events (76 events) have hypocentres at depth greater than 20 km. All the 8 events with hypocentres located below crust (h > 40 km) are small-size earthquakes (M_w < 2.9) which we may assume that are miss-located.

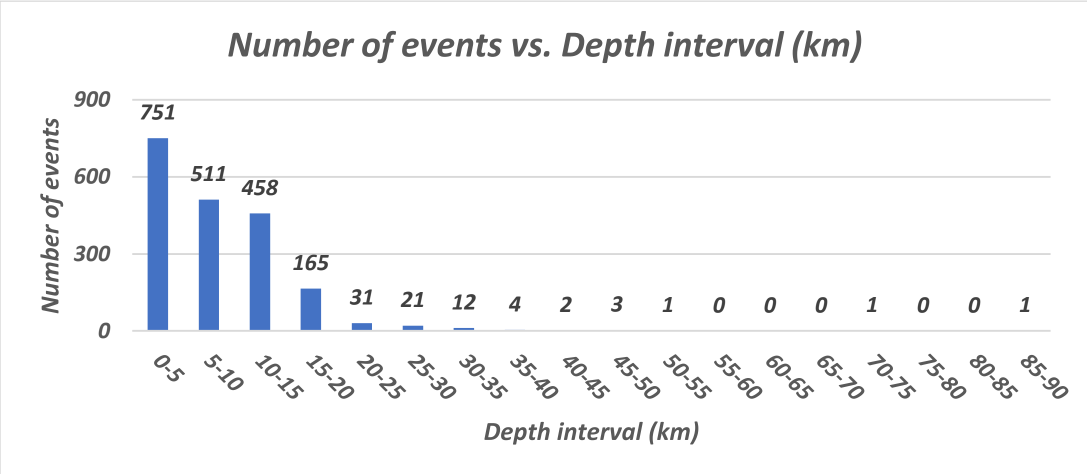


Fig. 42. Number of events (recorded after 1900) versus focal depth.

2.9 Transilvania

The Transylvania region comprises a wide area that extends between the Eastern and Southern Carpathians Arc to the Pannonian Basin to the west. As main tectonic structures developed in the region, we mention the Apuseni Mountains, the Transylvanian Basin and the Neogene–Quaternary volcanic area which lies along the inner side of the Eastern Carpathians.

The Apuseni Mountains are an example of an orogen in the interference zone between two other subduction systems located in the external Carpathians and Dinarides.

The Transylvanian Basin differs in several respects (high elevation, low surface heat flux, normal crustal thickness) from the other intra-Carpathian basins (e.g. the Vienna basin, the Transcarpathian and the Pannonian basins) [8, 16, 17, 48, 52].

The most striking difference, which is given special attention in this paper, is the generally low surface heat flux.

The surface heat flux of the Transylvanian Basin is $\sim$ 30 mWm^{-2} in the central part and increases to 50–60 mWm^{-2} towards the margins [7, 8, 9, 10].

The central heat-flux value is very low compared with the continental average heat flux of 65 $mW\ m^{-2}$ [29], and is in contrast to the generally larger heat flux of the neighboring tectonic areas (the Neogene–Quaternary volcanic area of the East Carpathians, the Apuseni Mountains and the Pannonian Basin) (e.g. [18]).

The seismic activity in Transylvania, represented in Figure 43, contains 3814 events (3800 occurred after 1900 – ROMPLUS catalogue, 14 historical events – SHEEC catalogue).

The historical events (before 1900) are of moderate magnitude (4.5 to 5.9) in strong contrast with the activity after 1900: not even one single event with magnitude above 4 has been reported since 1900 to date.

The emergence of these historical earthquakes in places which at present looks like aseismic (for example the central part of Transylvania) is surprising and odd.

Three events of magnitude above 5 located in the southernmost part may be rather classified within Făgăraş-Câmpulung zone, which is able to generate events greater than magnitude 6 at about one century return intervals.

Other three events of magnitude above 5 are located in the Harghita region, close to the Neogene volcanic intra-Carpathian chain. The rest of the largest events (M_w > 5.0) could be associated with the system of faults in the central Transylvania that appear to be inactive at present. Note that practically no even was recorded in the vicinity of these historical earthquakes since the instrumental survey has been operating in Romania.

The historical documents indicate intensities of VII and VIII for the events of 08.01.1223 (M_w = 5.1) and 19.11.1523 (M_w = 5.8) - close to Mediaş city, 15.02.1786 (M_w = 5.1) - close to Cluj city and 03.10.1880 (M_w = 5.8) with epicenter located in the centre of the Transylvanian Depression, between Târnava Mare and Tarnava Mica rivers.

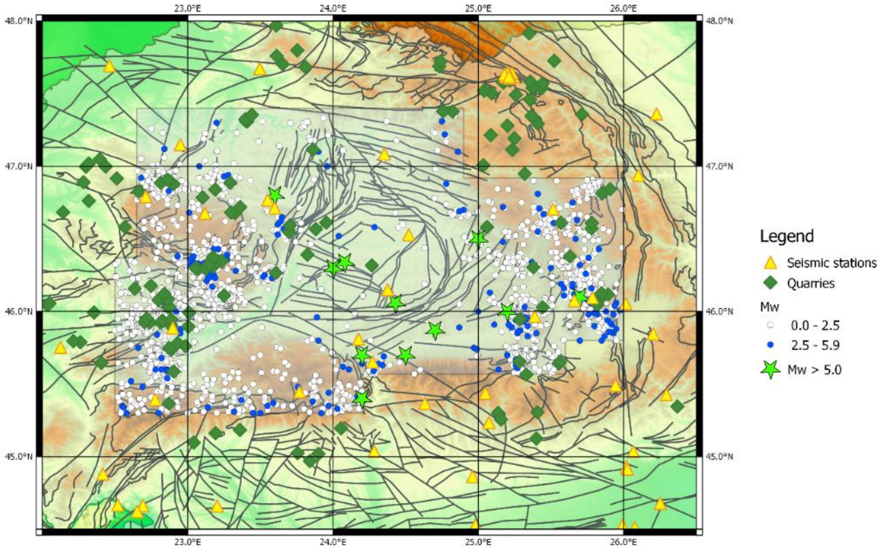


Fig. 43. Epicenters of the events located in the Transylvania region. Seismic stations and quarries situated inside the area (shaded polygon) and in its vicinity are plotted as well. Fault traces are extracted from [47]

Recent data indicate scarce and almost missing seismicity in the Apuseni Mountains and central Transylvanian Depression. Some reactivation of the deformation tectonic regime is observed in the intra-mountainous depressions in the south-western sector of the Carpathians (Haţeg Basin, Caransebeş-Mehadia Basin, see [34]). These pull-apart basins were developed on top of the Getic/Supragetic nappe system of the South Carpathians [54] as a result of the initial northward and subsequent right-lateral rotation of the tectonic units was in part accommodated by strike-slip deformation. Two sequences have been recorded in the Haţeg Basin, one in 17–31 March 2011 (19 events) and the other in 8 September to 31 October 2013 (31 events). The sequence of March 2011 was most likely a seismic swarm, with three shocks of M_w = 3.1–3.3. The sequence of September–October 2013 had the main shock of magnitude M_w = 4.0, one preshock of M_w = 3.6 and one aftershock of M_w = 3.6. All the other preshocks and aftershocks were below magnitude 3. Despite the shift in time of more than two years, the two sequences are located close each other in the upper crust (depth below 10 km). Relatively well-constrained fault-plane solutions were computed using first P-wave polarities and S/P ratio amplitudes for 13 events of the two sequences [34]. They show a combination of strike-slip with normal faulting along both NE-SW and NW-SE faults system.

The seismicity along Southern Carpathians is sporadic and weak (M_w < 4.0). It is roughly located between the South Transylvania Fault and South Carpathian Fault, but clustered more to the south and must be related to the seismic activity at the northern boundary of Oltenia region.

A relatively small percentage of events situated in the south-eastern corner of the region, close to the Vrancea region, are assumed to be tectonic earthquakes. It is interesting to note that all these events are small ($M_W \leq 3.1$) and some of them (24 events) are located below crust ($70 < h < 160$ km). They are generated somewhat outside the Vrancea active volume (red dots in the Figure 44) and could be tentatively attributed to the Neogene volcanic activity in the Ciomadu area [31].

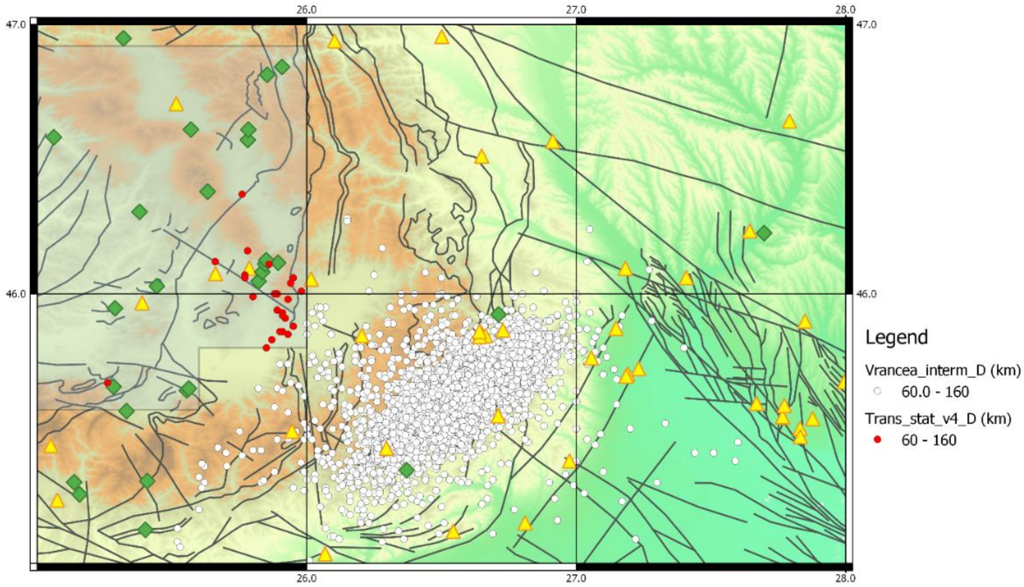


Fig. 44. Frame illustrating the epicentral distribution of the subcrustal earthquakes located in Vrancea and its neighborhood. The vast majority of epicenters concentrates above the lithospheric high-velocity body descending vertically in the mantle. Sporadic and small events are recorded along branches that move away, such the one going toward Harghita area (red symbols).

The activity at present is dominated by artificial events related to the mining operations concentrated in the marginal areas.

Thus, the events lying in the western side of the region are almost entirely artificially generated. We can thus individualize several groups of events in association with the quarries operating in the region:

1. North of the seismic area in the Haţeg Basin
2. North of Deva city (quarries of Ilia and Băiţa-Brad)
3. Zlatna quarry
4. Quarries in the Roşia Poieni region
5. Quarry close to Aiud city
6. Quarries south of Cluj-Napoca city
7. Quarries close to Huedin city
8. CBBR and MARR quarries.

Similarly, most of the events in the eastern side of the Transylvanian region (Harghita) are caused by quarry activities. Note the clusters of events located in the proximity of the following quarry blasts sites:

1. Quarry in the Moeciu area (south-west of Braşov city) ~ (25.3^{0}E, 45.6^{0}N)
2. A set of quarries north of Brasov city (Comana, Hoghiz, Lupşa, Barc, Bogata, Racoş, Mateiaşi quarries) ~ (25.3^{0}E, 46.0^{0}N)
3. Bixad quarry ~ (25.8^{0}E, 46.1^{0}N)
4. Quarries around Joseni city ~ (25.5^{0}E, 46.6^{0}N)
5. Quarries close to Bicaz city ~ (25.8^{0}E, 46.8^{0}N)

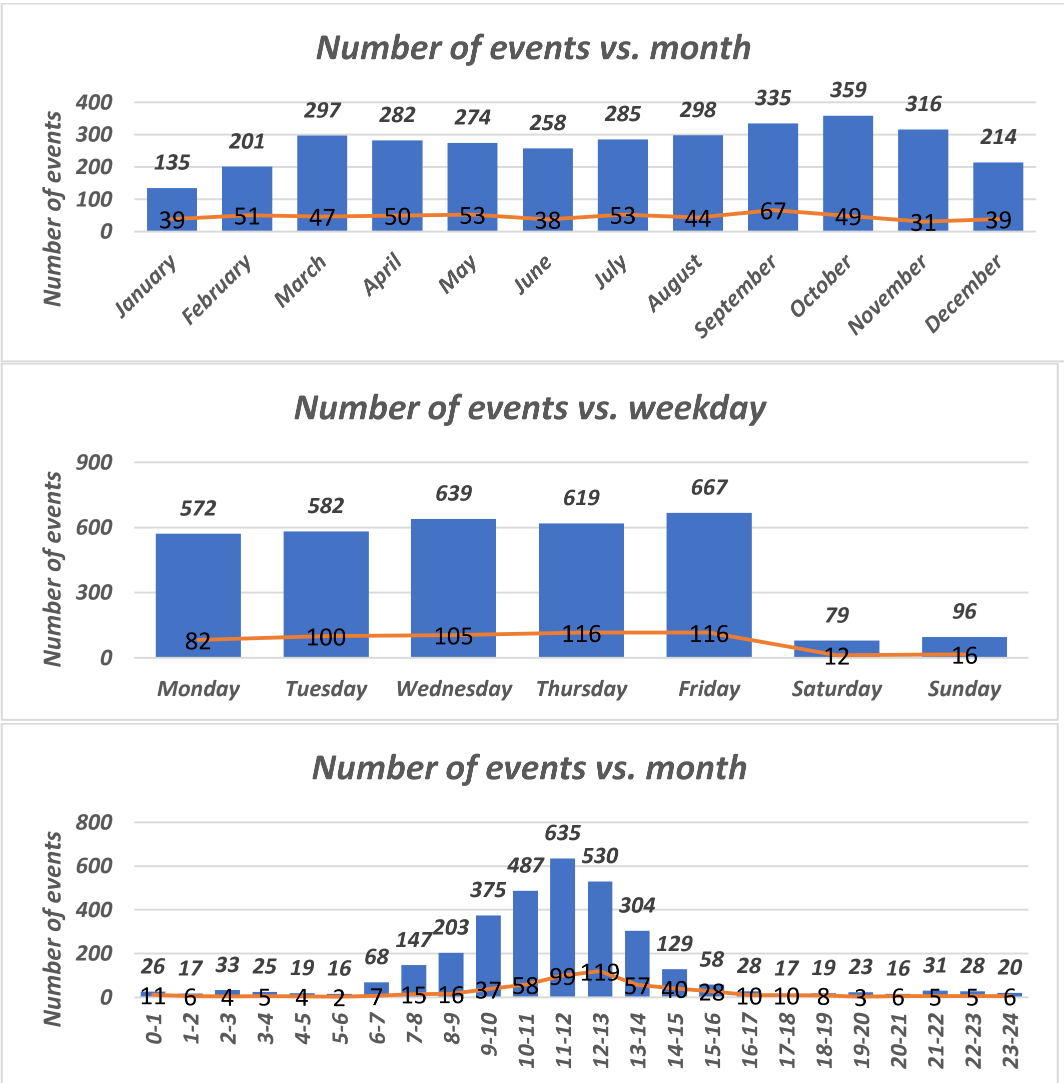


Fig. 45. Distributions of number of events as a function of month (top), weekday (middle) and hour (bottom). Number on top of bars – number of LM events (Mw < 2.5); number on top of orange curve – number of HM events (Mw ≥ 2.5).

The distributions of events per month and week day (see Figure 45) show a deficit in winter time and during the weekend, as expected for artificial events. The distribution per daily hour reveals a massive contribution in the catalogue of the quarry events in the Transylvania region (more than 75%). This is also obvious in the distribution on magnitude (see Figure 46): only 43 events are estimated with M_w greater than 3 in the catalogue and all the earthquakes with magnitude above 4 are historical (before 1900).

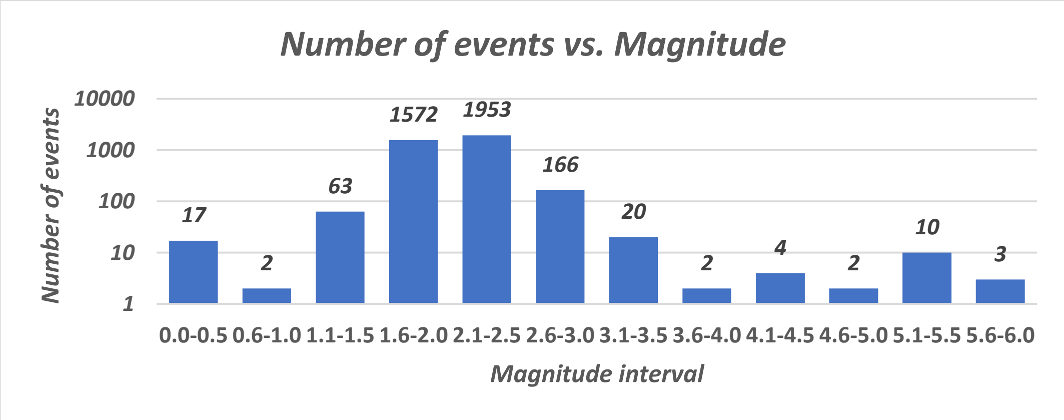


Fig. 46. Number of events versus moment magnitude.

The tremendous increase of the events detected and located in the catalogue starting with 2005 (see Figure 47) coincides with the improvement of the Romanian seismic network.

Thus, the seismic survey in the Transylvania region has increased from 4 stations in 2005 to 17 stations in 2017. The continuous seismic network upgrading has made it possible detection and location of events smaller than magnitude 2 and explains the continuous increase of events detected from 2004 to 2017.

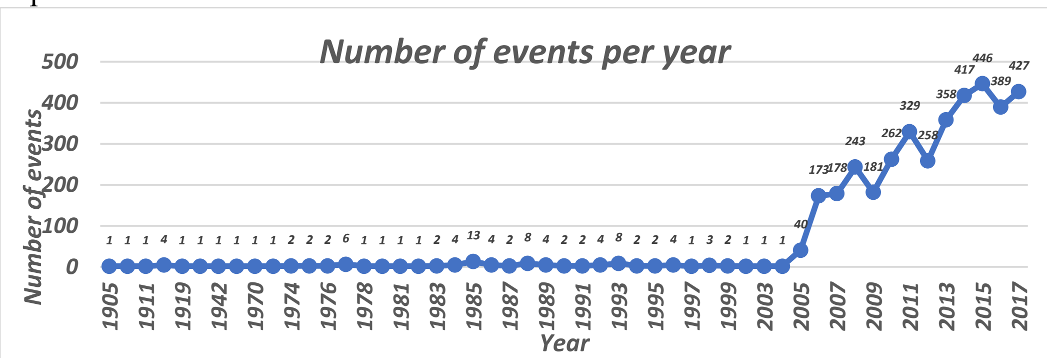


Fig. 47. Time evolution of the number of events/year since 1900.

The distribution on focal depth (see Figure 48) reveals the strong concentration in the upper crust, mainly in the top 10 km (as expected for quarry blasts). The few subcrustal events (h < 50 km) are located close to the north-western edge of the

Vrancea seismic region and can be attributed to small-scale inhomogeneous lithospheric pieces in an environment with possible ascending pathways of melted asthenospheric material [31, 54].

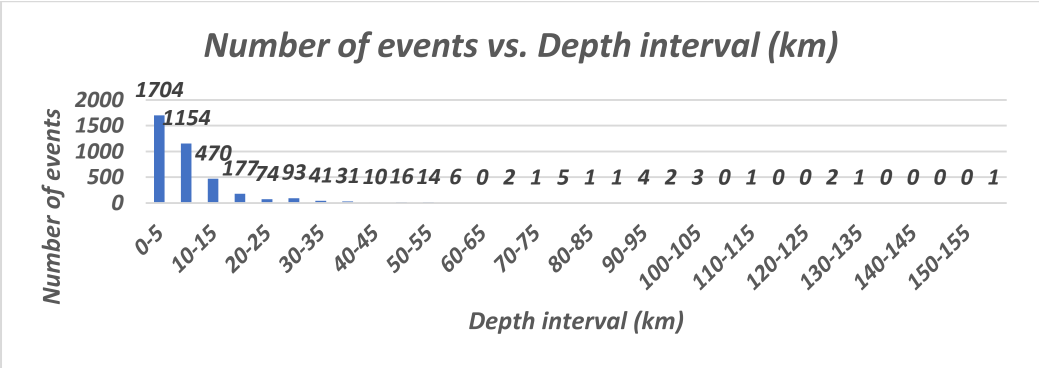


Fig. 48. Number of events versus focal depth.

2.10 Crişana

Crişana region is located in the north-western part of Romania and together with Banat and Maramureş regions represents the contact between Carpathians orogen and Pannonian Basin.

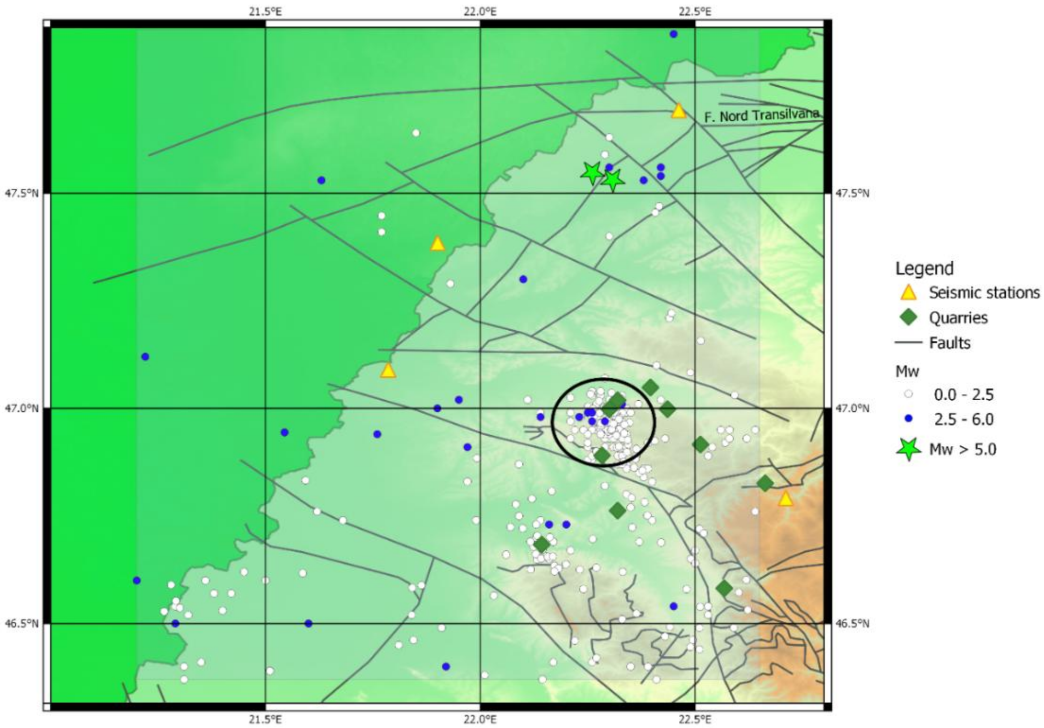


Fig. 49. Epicentres of the events located in the Maramureş region. Seismic stations and quarries situated inside the area (shaded polygon) and in its vicinity are plotted as well. Elliptical area is an area of quarry blast events. Fault traces are extracted from [47].

The seismicity represented in the Figure 49 (309 events recorded after 1900 in the ROMPLUS catalogue and 5 historical events SHEEC catalogue) is low according to the catalogue of instrumentally recorded events.

Thus, only a single earthquake of magnitude M_w= 5 has been recorded since 1900. However, in the past an event with M_w ~ 6.2 was recorded on 01 July 1829 19:30 and another event of magnitude 5.6 was recorded on 15 October 1834 06:00, both events located between Oradea and Carei, close to the border with Hungary.

The event of 1829 is the oldest earthquake in the ROMPLUS catalogue located in the Crişana region.

According to the catalogue, a possible preshock occurred in the same day at 01:37. There is no information on aftershock activity.

The seismic activity located around Oradea and Carei localities seems to be in connection with junctions of NE-SW oriented with E-W oriented faults.

Thus, the effects due to the earthquake that occurred on 12 April 1886 21:20 close to Oradea city (estimated magnitude M_w= 4.1) indicate isoseismals elongated NE-SW close to epicentre and elongated E-W at larger scale – the motion was felt over an area of more than 1000 km^2 [1].

It severely shook the city causing damage to some buildings and indicating intensities greater than V.

Since 1900 four events with M_w above 4 occurred from north of Arad to Oradea: M_w = 4.2 in 29 April 1906, M_w = 4.3 in 8 August 1910, M_w = 5.1 in 23 March 1939 and M_w = 4.6 in 1978.

According to Atanasiu, an intensity VI was recorded in the epicentral area of the 1906 earthquake, while the ground motion was strongly attenuated (the area of intensity greater than V was estimated at about 70 km^2).

The severe attenuation could be due to a very shallow hypocenter. The isoseismal of V degree was elongated along a N-S direction.

In the south-eastern part of the region a few clusters of events are obviously related to the quarries activating in this area (elliptical area in Figure 49), north and west to Beiuş city, while there is no man-made events identified to the west, along the border with Hungary.

The distributions on month, weekday and hour in Figure 50 are indicating a strong contamination of the catalogue (309 events since 1900) with artificial events (~240 events).

Most of these small events (see the distribution in Figure 51) have been recorded during the last ten years (see Figure 52).

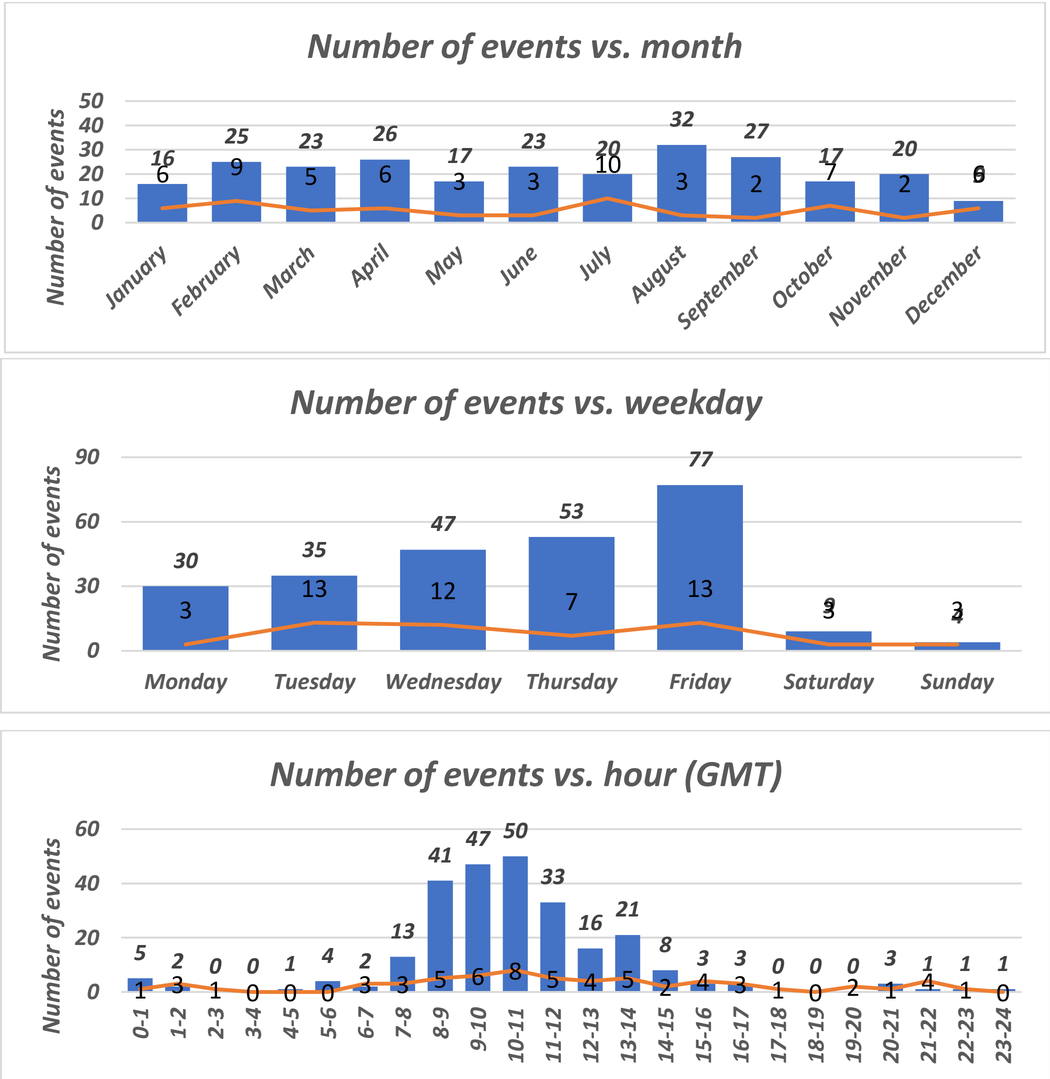


Fig. 50. Distributions of number of events as a function of month (top), weekday (middle) and hour (bottom). Number on top of bars – number of LM events ($M_w < 2.5$); number on orange curve – number of HM events ($M_w \geq 2.5$).

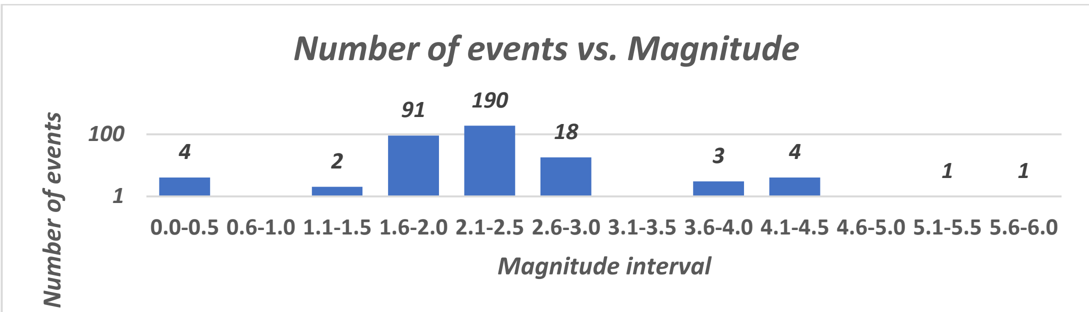


Fig. 51. Number of events versus moment magnitude.

Due to the strong catalogue contamination with man-made events, the size distribution in the Figure 51 has no real meaning in terms of a Gutenberg–Richter relation.

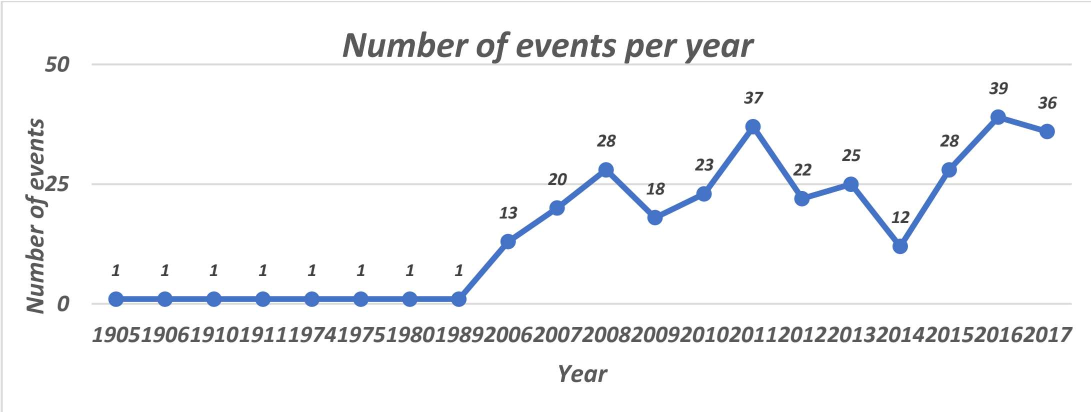


Fig. 52. Time evolution of the number of events/year since 1900.

The distribution on depth (see Figure 53) shows the predominance of the events located in the shallow crust.

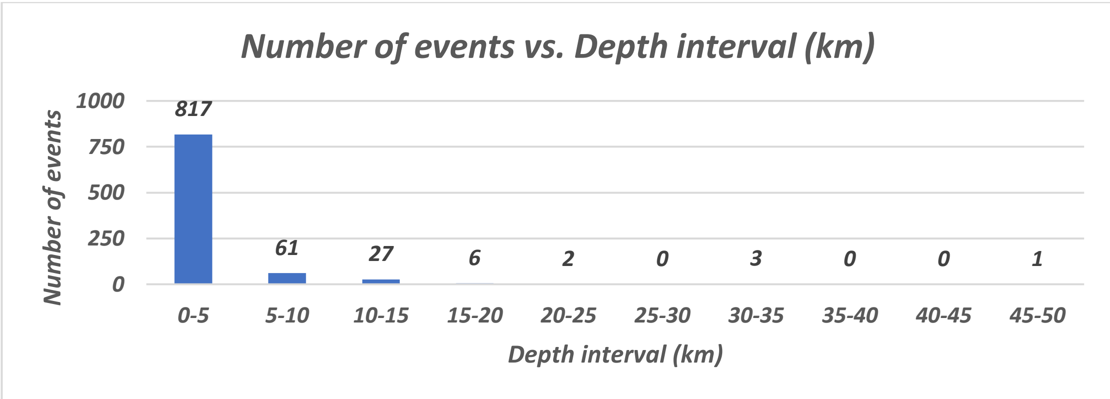


Fig. 53. Number of events versus focal depthț

2.11 Maramureş

The Maramureş region is situated in the north-western corner of Romania. Tectonic setting is close to that in the Crişana region, adjacent to the south-west, this is why the two zones are often considered together (e.g. [42]). The region is known to be seismically active [30]. However, its eccentric position relative to the national seismic network, makes it more difficult to monitor the specific seismic activity. Thus, only 185 events are listed in the ROMPLUS catalogue since 1900 (of which more than 160 occurred over the last 10 years) and 15 historical events in the SHEEC catalogue (see Figure 54).

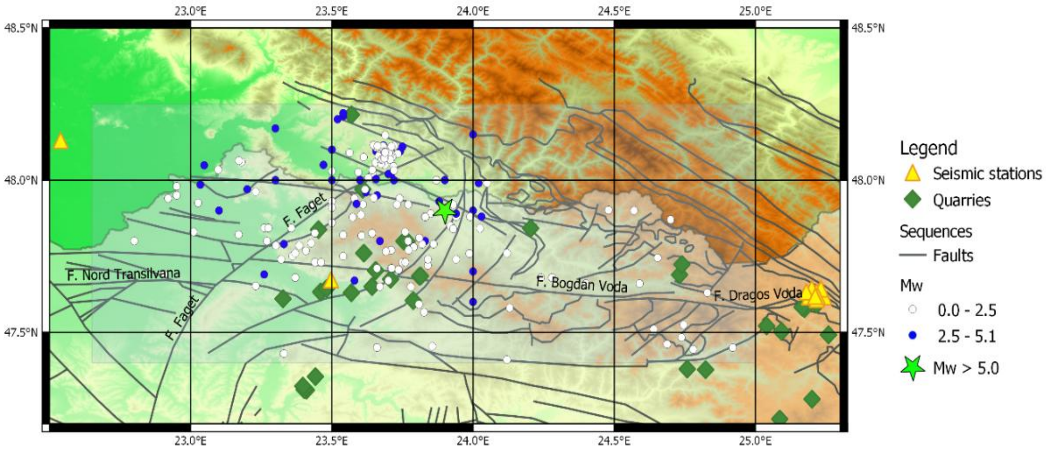


Fig. 54. Epicenters of the events located in the Maramureş region. Seismic stations and quarries situated inside the area (shaded polygon) and in its vicinity are plotted as well. Fault traces are extracted from [47].

From a tectonic point of view, the most obvious structure is the Bogdan-Dragoş Vodă Fault system, oriented E-W, with predominantly left-lateral strike slip [50]. Deformation associated with this fault system is dominated by sinistral strike-slip faulting often featuring a normal component.

The system of faults in the Maramureş area (Bogdan Vodă, Dragoş Vodă and Preluca Faults) seem to represent the continuation of the Mid-Hungarian Fault zone [15].

The earthquakes in Maramureş are of moderate size sometimes accompanied by aftershocks.

The largest event was recorded in 1784 (M_w=5.3) and was felt with intensity VII.

The largest events instrumentally recorded were produced on 30.06.1978 (M_w = 4) and on 30.03.1979 (M_w = 4.5) and were felt with V – VI intensity.

A sequence of earthquakes was recorded in 19 – 21 July 2015 at the border with Ukraine.

The distributions of the events number as a function of month, weekday and hour are represented in the Figure 55. The peak of activity in July is explained by the earthquake sequence of 25 events that occurred in 2015.

This is also highlighted in the time evolution of the seismicity rate (see Figure 56).

The distribution per day hour shows a slight enhancement during working hours that can be attributed to the mining activities in the Baia Mare district for exploitation of gold polymetallic ore deposits.

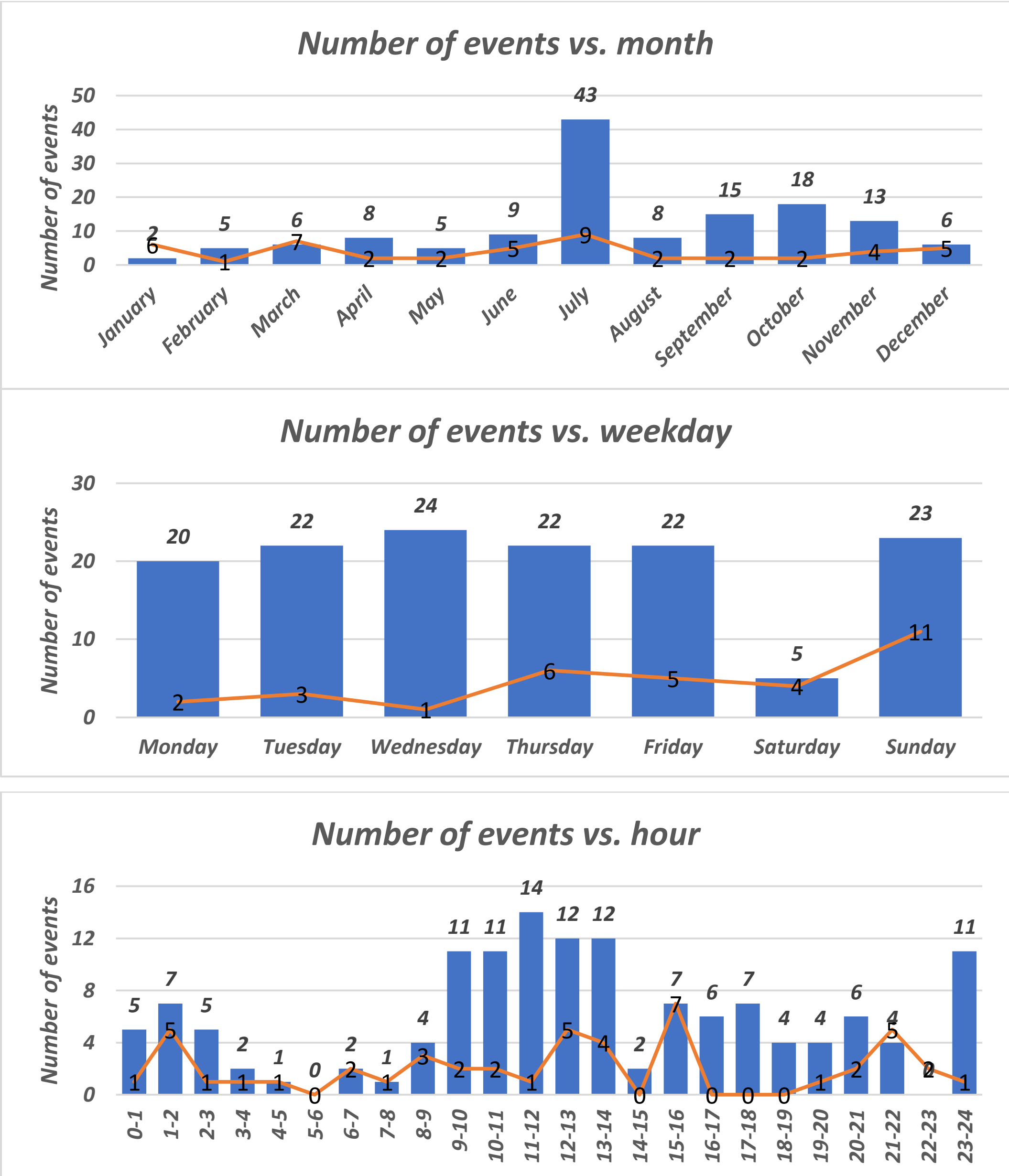


Fig. 55. Distributions of number of events as a function of month (top), weekday (middle) and hour (bottom).

The evolution in time of the activity in the Maramureş region (see Figure 56) shows a change in 2008 of about 10 times in the capacity of detecting/locating events.

A distinct overlapped increase points the sequence of events occurred in July 2015.

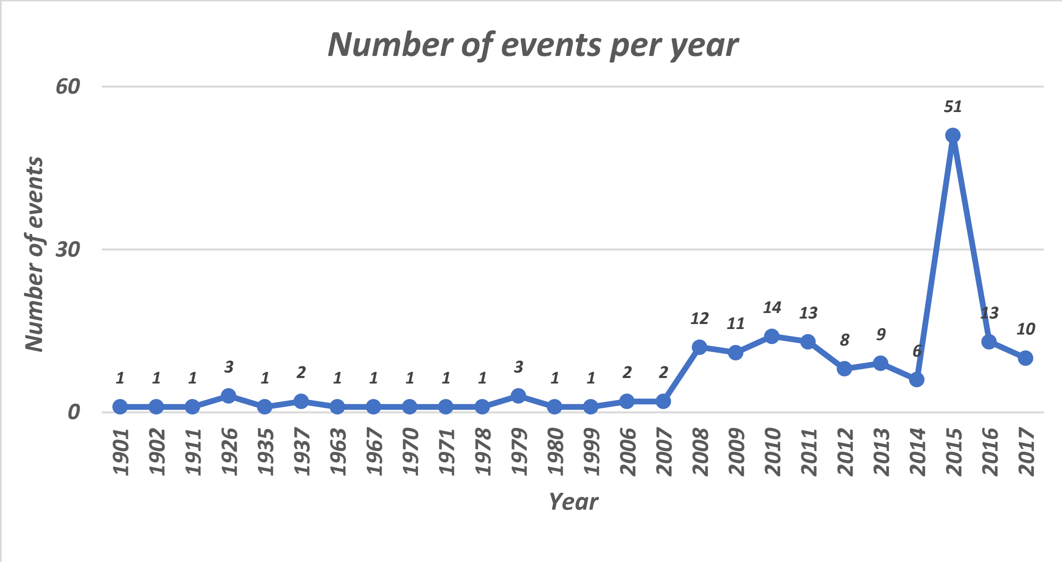


Fig. 56. Time evolution of the number of events/year since 1900.

The statistics for Maramureş is insufficient to define a relevant frequency – magnitude distribution (see Figure 57), a magnitude threshold for the catalogue completeness and a maximum expected magnitude.

In this case, for a better evaluation of the input parameters required by seismic hazard assessment, the way is to merge catalogues over a larger area including seismogenic zones of roughly similar regimes.

For example, Maramureş with Crişana and Bucovina, taking care to remove the artificial events.

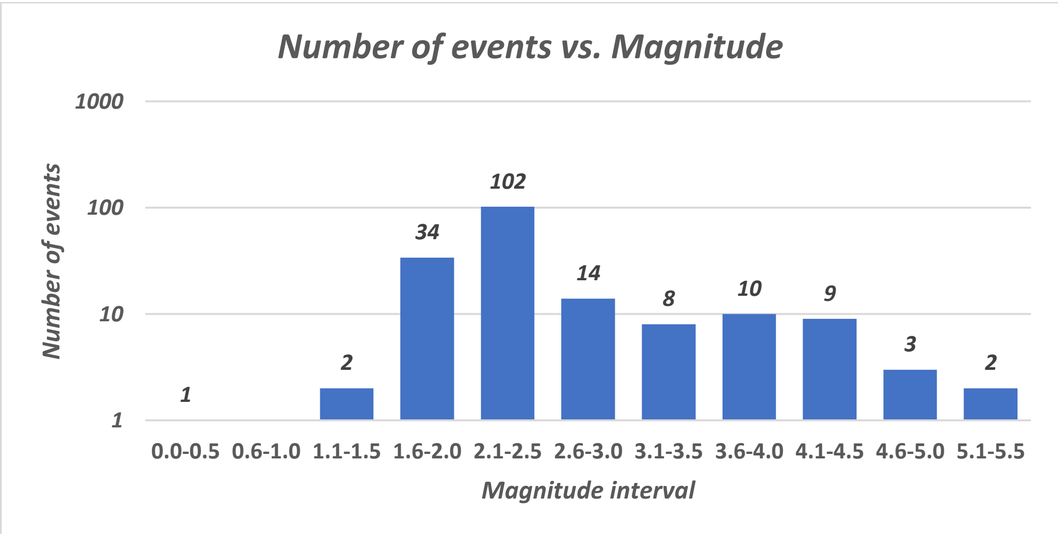


Fig. 57. Number of events versus moment magnitude.

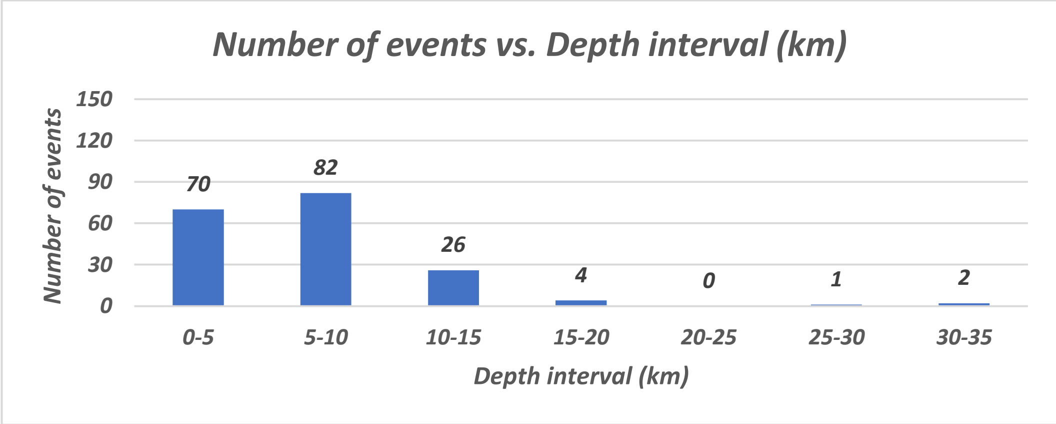


Fig. 58. Number of events versus focal depth.

According to the distribution on focal depth (see Figure 58) the seismicity is generated in the shallow crust.

3. Conclusions

The main purpose of the present paper is to better define the earthquake-prone areas over the entire Romanian territory benefiting of recent high-quality pool of data recorded by the national seismic network.

In addition to previous works on this subject [3, 6, 41, 42], the recent impetuous development of the Romanian seismic network made it possible now to identify with a high degree of confidence the geometrical configuration of seismicity patterns able to generate strong earthquakes.

At the same time, we are now able to separate the tectonic active zones from those contaminated by human activity and to define with higher accuracy the earthquake-prone areas.

In this respect, the paper sets the basis for the revision of current earthquake catalogues, so that they better reproduce the actual configuration of active tectonic areas.

In this stage of work, in order to cover the entire surface of the country, we prefer to investigate the spatial properties of seismicity in correlation with tectonic features and sources of man-made activity by simply dividing the country surface into 12 geographical areas following roughly the administrative regions, matching each other like in a puzzle game, even if they are following only approximately the tectonic and seismogenic provinces.

The next step of the work we shall focus our interest to the specific configurations closely related to the properties of seismic sources generating significant earthquakes.

The considerable increase of seismicity statistics within the last years led to a significant extension of the range of magnitude completeness and to a better assessment of specific variations in time and space of seismicity. In this way, we could identify both clusters of earthquakes and clusters of quarry blasts events that have distinct preferred geographical locations.

For some regions (Transylvania, Dobrogea, Făgăraş-Câmpulung, Banat), we show that the routine catalogue of Romanian earthquakes (ROMPLUS) is strongly contaminated by man-made events (most of them coming from quarry blasts sites) which distorts to a larger or smaller extent the actual seismicity patterns.

Except for some cases where the tectonic activity overlaps with human activity, commonly simple statistical distributions in space, time and size are sufficient to discriminate man-made from tectonic sources.

R E F E R E N C E S

[1] I. Atanasiu, *Romanian Earthquakes* (Romanian Academy Press, Bucharest, (**1961**).

[2] G. Bada , F. Horvath, P. Doveny, P. Szafian, G. Windhoffer, S. Cloetingh, *Present-day stress field and tectonic inversion in the Pannonian basin,* Glob Planet Change 58:165–180 (**2007**).

[3] A. Bălă, V. Răileanu, C. Dinu, M. Diaconescu, *Crustal seismicity and active fault systems in Romania*, Romanian Reports in Physics 67(3), 1176 – 1191 (**2015**).

[4] P. Bormann, M. Baumbach, G. Bock, H. Grosser, G. Choy, J. L. Boatwright, *Manual of Seismological Observatory Practice*, vol. **1**, (Chapter 3, Seismic Sources and Source Parameters, September, (**2002**).

[5] O. F. Cărbunar, M. Radulian, *Geometrical constraints for the configuration of the Vrancea (Romania) intermediate-depth seismicity nest*, Journal of Seismology, **15**, 579-598 (**2011**).

[6] L. Constantinescu, V. Mârza, A *Computer-compiled and Computer-oriented Catalogue of Romania's Earthquakes During a Millennium (AD 984 –1979)*, Rev. Roum. Géol., Géophys., Géogr., Ser Géophys. **24**, 171–191, Bucharest (**1980**).

[7] C. Demetrescu, M. Andreescu, *On the thermal regime of some tectonic units in a continental collision environment in Romania*, Tectonophysics, **230**, 265–276 (**1994**).

[8] C. Demetrescu, M. Ene, M. Andreescu, *On the geothermal regime of the Transylvanian Depression*, St. cerc. geol., geofiz., geogr., Geofizică, **19**, 61–71 (in Romanian) (**1981**).

[9] C. Demetrescu, M. Andreescu, M. Ene, *On the thermal structure of the lithosphere in Romania*, Rev. Roum. Géol., Géophys., Géogr., Géophysique, 28, 33–38 (**1984**).

[10] C. Demetrescu, S. Veliciu, D. Burst, *Heat flow map of Romania*, (in Geothermal Atlas of Europe, eds Hurtig, E., Cěrmák, V., Haenel, R. & Zui, V.), VEB Hermann Haack, Gotha, **1991/92**), pp. 123–124.

[11] D. Enescu, E. Popescu, M. Radulian, *Source characteristics of the Sinaia sequence of May-June 1993*, Tectonophysics, **261**, 39-49 (**1996**).

[12] M. Erdik, V. Doyuran, S. Yucemen, P. Gulkan, N. Akkas, *A probabilistic assessment of the seismic hazard in Turkey for long return periods*. In: 3rd International Earthquake Microzonation Conference, Seatlle, Washington (1982).

[13] A. Ganas, B. Grecu, E. Batsi, M. Radulian, *Vrancea slab earthquakes triggered by static stress transfer*, Nat. Hazards Earth Syst. Sci., **10**, 2565–2577 (**2010**).

[14] H. Grozescu, C. Gheocalescu, *Nota preliminara asupra fazei de seismicitatea Muntilor Fagarasului din perioada Ianuarie-Aprilie 1916*. D.S. Inst. Geol. Rom., vol. **VII**, p. 374-395, Bucuresti (**1917**).

[15] H.R. Gröger HR, *Thermal and structural evolution of the East Carpathians in northern Romania: from Cretaceous orogeny to final exhumation during Miocene collision*. PhD thesis, University of Basel, Switzerland, 114p, (**2006**).

[16] F. Horváth, *Towards a mechanical model for the formation of the Pannonian Basin*, Tectonophysics, **226**, 333–357, doi:10.1016/0040-1951(93)90126-5 (**1993**).

[17] R.S. Huismans, G. Bertotti, D. Ciulavu, C. A. E. Sanders, S. Cloetingh, C. Dinu, *Structural evolution of the Transylvanian Basin (Romania): A sedimentary basin in the bend of the Carpathians*, Tectonophysics, **272**, 249–268, doi:10.1016/S0040-1951(96)00261-2 (**1997**).

[18] E. Hurtig, V. Cěrmák, R. Haenel, V. Zui, *Geothermal Atlas of Europe*, VEB Hermann Haack, Gotha (**1991/92**).

[19] N. Hurukawa, M. Popa, M. Radulian, *Relocation of large intermediate-depth earthquakes in the Vrancea region, Romania, since 1934 and a seismic gap*, Earth Planets Space, **60**, 565–572 (**2008**).

[20] A. Ismail-Zadeh, L. Maţenco, M. Radulian, S. Cloetingh, G.F. Panza, *Geodynamics and intermediate-depth seismicity in Vrancea (The South-Eastern Carpathians): Current state-of-the art*, Tectonophyiscs, **[0–531**, 50–79, (**2012**).

[21] J. Karagjuleva, E. Bonchev, V. Kostandinov, *Tectonic map of Bulgaria*, Geological Institute of BAS, Sofia (1973).

[22] H. Mitrofan, F. Chitea, M. A. Anghelache, M. Vişan, *Possible triggered seismicity signatures associated with the Vrancea intermediate-depth strong earthquakes (Southeast Carpathians, Romania)*, Seismological Research Letters, **85** (2), 314-323, (**2014**).

[23] C. Neagoe, C. Ionescu, *Toward a dense real-time seismic network in Romania*, Romanian Reports in Physics **61**, 359–366 (**2009**).

[24] M.C. Oncescu, V. Marza, M. Rizescu, M. Popa, *The Romanian earthquakes catalogue between 984-1997*. In Vrancea Earthquakes: Tectonics, Hazard and Risk Mitigation (Kluwer Academic Publishers, F. Wenzel, D. Lungu (eds.), pp 43-47, 1999).

[25] E. Oros, D. Paulescu, M. Popa, *The M6.4, 26th January, 1916 earthquake under review: new data on the seismicity of Fagaras Seismogenic Region (Romania).* Proceedings, 31st General Assembly of the European Seismological Commission ESC 2008 (Hersonissos, Crete, Greece, 7-12 September **2008**, 4 pp).

[26] E. Oros, *Researches on seismic hazard for Banat Seismic region (*Phd. Thesis – unpublished dissertation. University of Bucharest, Bucharest, Romania (**2011**) *(*in Romanian).

[27] E. Oros, M. Popa, M. Diaconescu, *The seismogenic sources from the west and south-west of Romania*. (In: Vacareanu R., Ionescu C. (eds) Seismic Hazard and Risk Assessment. Springer Natural Hazards. Springer, 53 – 69, **2018**).

[28] E. Otetelisanu, *Cutremurele de pamant din Romania de la 26 ianuarie 1916 st.n. si zilele urmatoare*, Buletin lunar Observatorul Astron. Meteor., an. XXV, nr. 1, p. 11-15, Bucuresti (**1916**).

[29] H. N. Pollack, S.J. Hurter J.R. Johnson, *Heat flow from the Earth's interior: analysis of the global data set*, Rev. Geophys., 31, 267–280 (**1993**).

[30] G. Polonic, *Seismicity and Tectonics of the Baia Mare-Sighetul Marmatiei-Halmeu area*, Rev. Roum. Geol. Geophys. Geogr. – Geophysique, 24, 2, 255–268 (**1980**).

[31] M. Popa, M. Radulian, A. Szakács, I. Seghedi, B. Zaharia, *New seismic and tomography data in the southern part of the Harghita Mountains (Romania, south-eastern Carpathians): connection with recent volcanic activity*, Pure and Applied Geophysics, 169, 1557-1573 (**2012**).

[32] M. Popa, M. Radulian, D. Ghica, C. Neagoe, E. Năstase, *Romania seismic network since 1980 to the present*, in Nonlinear Mathematical Physics and Natural Hazards (B. Aneva and M. Kouteva-Guentcheva (eds.)), Springer Proceedings in Physics **163**, 117-133 (**2015**).

[33] M. Popa, E. Oros, C. Dinu, M. Radulian, F. Borleanu, M. Rogozea, I. Munteanu, C. Neagoe, *The 2013 earthquake swarm in the Galati area: First results for a seismotectonic interpretation*, in "Effects and Lessons from November 10th, 1940 Vrancea Earthquake" Proceedings of the Symposium Commemorating 75 Years from November 10, 1940 Vrancea Earthquake (R. Vacareanu, C. Ionescu (eds.)), Springer Natural Hazards, 253 – 265 (**2016**).

[34] M. Popa, I. Munteanu, F. Borleanu, E. Oros, M. Radulian, C. Dinu, *Active tectonic deformation and associated earthquakes: a case study—South West Carpathians Bend zone,* Acta Geodaetica et Geophysica, DOI: 10.1007/s40328-018-0224-1 (**2018**).

[35] E. Popescu, *Complex study of the earthquake sequences on the Romanian territory*, (PhD Thesis, 281p, Institute of Atomic Physics, Bucharest, **2000**) (in Romanian).

[36] E. Popescu, M. Radulian, *Source characteristics of the seismic sequences in the Eastern Carpathians foredeep region (Romania)*, Tectonophysics **338**, 325-337 (**2001**).

[37] E. Popescu, M. Popa, M. Radulian, A. O. Plăcintă, *Romanian crustal earthquake sequences: source scaling and clustering peculiarities*, St. cerc. Geofiz. **41**, 63-80 (**2003**).

[38] E. Popescu, C. Neagoe, M. Rogozea, I.A. Moldovan, F. Borleanu, M. Radulian, *Source parameters for the earthquake sequence occurred in the Ramnicu Sarat area (Romania) in November-December 2007*, Rom. Journ. Phys. **56**, 265-278 (**2011**).

[39] E. Popescu., F. Borleanu, M. Rogozea, M. Radulian, *Source analysis for earthquake sequence occurred in Vrancea (Romania) region on 6 to 30 September 2008*, Romanian Report Phys., **64**, 571-590 (**2012**).

[40] E. Popescu, A. O. Plăcintă, M. Radulian, F. Borleanu, M. Diaconescu, M. Popa, *Source parameters of the earthquake sequence that occurred close to the BURAR array (Romania) between 24 June and 1 July 2011*, Annals of Geophysics **60** (2), S0225; doi: 10.4401/ag-7285 (**2017**).

[41] C. Radu, I. Apopei, A. Utale, *Contributions to the study of the seismicity of Romania* (in Romanian), (In Progrese in Fizica Symposium,Cluj-Napoca **1980**).

[42] M. Radulian, N. Mândrescu, E. Popescu, A. Utale, G. Panza, *Characterization of Romanian seismic zones*, Pure and Applied Geophysics **157**, 57-77 (**2000a**).

[43] M. Radulian, F. Vaccari, N. Mândrescu, G. F. Panza, C. Moldoveanu, *Seismic hazard of Romania: A deterministic approach* (in "Seismic Hazard of the Circum-Pannonian Region", eds. G. F. Panza, M. Radulian, C.-I. Trifu,) Pure and Applied Geophysics **157**, 221-247 (**2000b**).

[44] M. Radulian, E. Popescu, F. Borleanu, M. Diaconescu, *Source parameters of the December 2011 - January 2012 earthquake sequence in Southern Carpathians, Romania*, Tectonophysics, **623**, 23-38 (**2014**).

[45] M. Radulian, A. Bala, E. Popescu, D. Toma-Danila, *Earthquake mechanism and characterization of seismogenic zones in south-eastern part of Romania*, Annals of Geophysics 61 (1), SE108, doi: 10.4401/ag-7443 (**2018**).

[46] V., Răileanu, C. Dinu, M. Radulian, V. Diaconescu, A. Bălă, E. Popescu, M. Popa, *Crustal seismicity and active fault systems in the SE of Romania*, Proceedings of the International Symposium on Seismic Risk reduction (Paper 14, Ed. Orizonturi Universitare Timisoara, **2007**) 269-276.

[47] V. Răileanu, C. Dinu, L. Ardeleanu, V. Diaconescu, E. Popescu, A. Bălă, *Crustal seismicity and associated fault systems in Romania*, Proceedings of the 27th ECGS Workshop: Seismicity Patterns in the Euro-Med Region (Luxembourg, 17-19 Nov.2008, in "Cahiers du Centre Europeen de Geodynamique et de Seismologie", **2009**) 153-159.

[48] L.H. Royden, F. Horváth, A. Nagymarosy, L. Stegena, *Evolution of the Pannonian Basin system. 2. Subsidence and thermal history*, Tectonics, **2**, p. 91–137 (**1983**).

[49] M. Stucchi, A. Rovida, A.A. Gomez Capera, P. Alexandre, T. Camelbeeck, M.B. Demircioglu, V. Kouskouna, P. Gasperini, R.M.W. Musson, M. Radulian, K. Sesetyan, S. Vilanova, D. Baumont, D. Faeh, W. Lenhardt, J. M. Martinez Solares, O. Scotti, M. Zivcic, P. Albini, J. Batllo, C. Papaioannou, R. Tatevossian, M. Locati, C. Meletti, D. Viganò, D. Giardini, *The SHARE European Earthquake Catalogue (SHEEC) 1000-1899*, J. of Seismology, **17**, 523-544 (**2013**).

[50] M. Tischler, H.R. Gröger, B. Fügenschuh, S.M. Schmid SM, *Miocene tectonics of the Maramures area (Northern Romania)—implications for the Mid-Hungarian fault zone*, International Journal of Earth Sciences, Online first: doi: 10.1007/s00531-006-0110-x (2006).

[51] C.I. Trifu, M. Radulian, *Frequency - magnitude distribution of earthquakes in Vrancea: relevance for a discrete model*, J. Geophys. Res. **96**, 4301-4311 (**1991**).

[52] M. Visarion, S. Veliciu, *Some geological and geophysical characteristics of the Transylvanian Basin*, Earth Evolution Sciences, **1**, no. 3–4, p. 212–217 (**1981**).

[53] B. Zaharia, B. Grecu, M. Popa, E. Oros, M. Radulian, *Crustal structure in the western part of Romania from local seismic tomography*, Proceedings of the World Multidisciplinary Earth Sciences Symposium WMESS 2017, Prague, IOP: Earth and Environmental Sciences, 95, doi:10.1088/1755-1315/95/3/032019 (**2017**).

[54] E. Willingshofer, P. Andriessen, S. Cloetingh, F. Neubauer, *Detrital fission track thermochronology of Upper Cretaceous syn- orogenic sediments in the South Carpathians (Romania): inferences on the tectonic evolution of a collisional hinterland*, Basin Research, vol. **13** (4), 379 – 395, (**2001**).