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2013 Seismic swarm recorded in Galati area, Romania: focal mechanism solutions

Andreea Craiu[1] · Marius Craiu[1] · Mihail Diaconescu[1] · Alexandru Marmureanu[1]

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Abstract An unusual seismic swarm started on September 23, 2013, close to Galati city, in Izvoarele region (Romania), and lasted until November 12, 2013. 406 earthquakes were recorded during several phases of seismic activity. The strongest events—a magnitude 3.9 earthquake, occurred on September 29, and two M_L 3.8 shocks, occurred on October 3 and 4, respectively, were accompanied by specific seismicity bursts. The seismogenic region of the swarm is situated between two main crustal faults, which builds up the primary fault system, oriented SE–NW: New Trotus Fault (at the limit between North Dobrogea and Scythian Platform) to the North and east, and Peceneaga Camena fault (which separates North Dobrogea block from the Moesian Platform) to the South. The epicentral zone belongs to a complex tectonic area, in which a secondary fault system—lying NE–SW, perpendicular to the primary system—is also present. The focal mechanisms show normal faulting, with an important strike-slip component, one of the nodal planes being oriented roughly in a NE–SW direction. The objective of this study is to investigate the seismic swarm recorded in a new seismic area of Romania, near the town Galati in Izvoarele region. We show detailed hypocentral location, focal mechanisms and the correlation between seismicity and tectonic structures.

Keywords Seismic swarm · Focal mechanism · Galati area · Romania

1 Introduction

The seismic activity of Romania is concentrated at the contact between the principal tectonic units. Most of the seismic activity is represented by the intermediate depth earthquakes, situated at the Eastern Carpathian Arc Bend (Vrancea zone), but also by

✉ Andreea Craiu
atugui@infp.ro

[1] National Institute for Earth Physics, Magurele, Ilfov, Romania

shallow earthquakes, some seismic areas are represented by seismic sequences or swarms. Seismic sequences and swarms occur in Romania in: Sinaia region, where the dominant focal mechanism is a combination of normal with strike slip fault and shows an extensional regime (Enescu et al. 1996; Popescu et al. 2000); Ramnicu Sarat seismic area of the Carpathians foredeep, where the seismic zone is characterised by a complex tension field, creating a transition zone from a dominant compressional regime in Vrancea intermediate-depth area, to an extensional regime in the Moesian Platform (Ardeleanu and Cioflan 2005; Popescu and Radulian 2001); Vrancioaia area, where Radu and Oncescu (1992) presented a composed strike slip focal mechanism having the horizontal compression axis, result correlated with the tension field in the region obtained by Radulian et al. (2000), and nowadays in Izvoarele region, being studied for the first time from seismological point of view.

Earthquake swarms are events where a local area experiences sequences of many earthquakes striking in a relatively short period of time. The length of time used to define the swarm itself varies, but the United States Geological Survey points out that an event may be on the order of days, weeks, or month [21]. The seismic swarms are occurring when the stress fields is released through an inhomogeneous structure. They are differentiated from earthquakes succeeded by a series of aftershocks with the observation that no single earthquake in the sequence is obviously the main shock.

The seismic swarm analyzed in this study, started on September 23, 2013, close to Galati city, in Izvoarele region (Romania), and lasted until November 12, 2013. 406 earthquakes were located, during several phases of seismic activity. The significant seismic

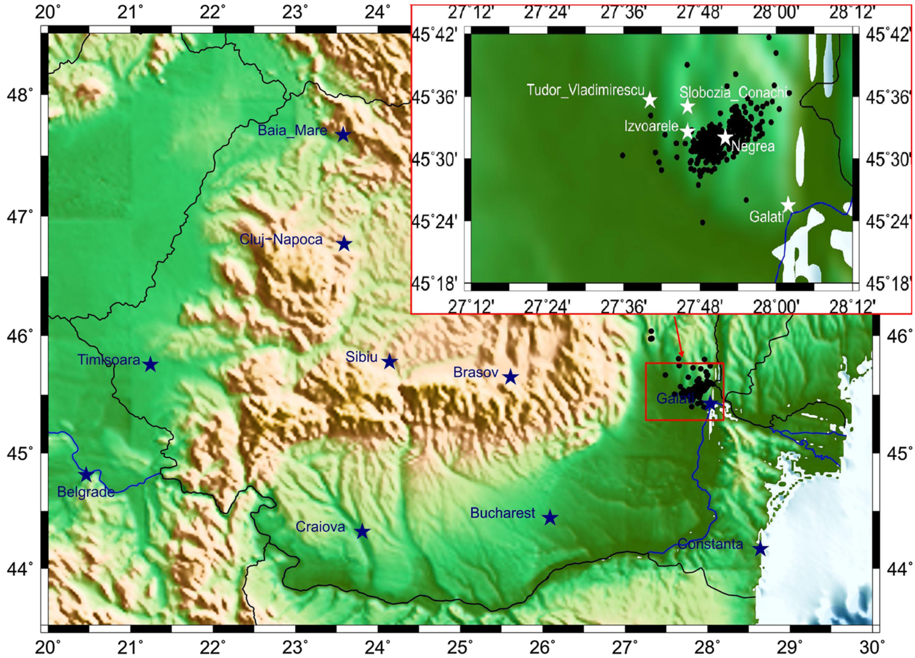

Fig. 1 Location and epicenters distribution of the seismic swarm recorded in Izvoarele area (Romania), in 2013

events were strongly felt by the population, they created panic and produced damages, having a macroseismic intensity of V–VI.

The main objective of this study is to investigate the seismic swarm recorded in a new seismic area of Romania, near the city of Galati in Izvoarele region (Fig. 1). We show detailed hypocentral location, focal mechanisms and the correlation between seismicity and the tectonic structures.

2 Tectonic settings

The area affected by the earthquake swarm is located on the prolongation of the Macin nappe (the most Western tectonic unit of the North Dobrogea block, known also as the North Dobrogea Orogen), to the North-West of the Danube river. The North Dobrogea block represents a relative narrow area situated between the Scythian Platform at North and the Moesian Platform to the South. Basically, the North Dobrogea represents a Hercynian Orogen which was subjected to Mesozoic rifting and inversion (Leever et al. 2006a). This narrow area presents a considerable development towards Northwest of the Danube river where it is known as North Dobrogea Promontory, as well as towards to the East, on the

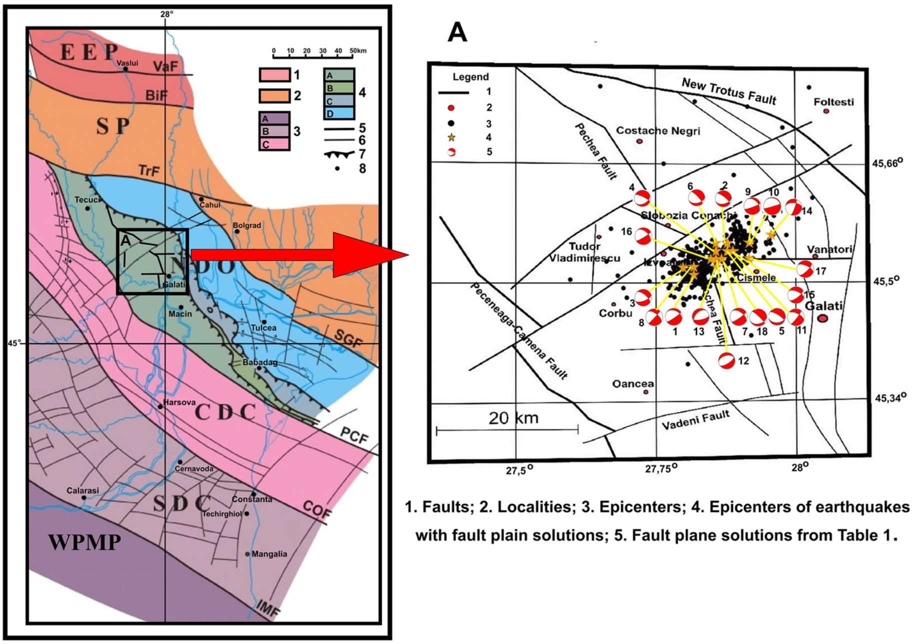

Fig. 2 Tectonic map of the Dobrogea and A—swarm distribution, compiled after Paraschiv et al. (1983), Visarion et al. (1988), 1990 and Matenco et al. 2007. *1* East European Platform-EEP; *2* Scythian Platform-SP; *3* Moesian Platform: A. Walachian Sector Moesian Platform-WPMP; B. South Dobrogea Compartment-SDC; C. Central Dobrogea Compartment-CDC; *4* North Dobrogea Orogen-NDO: A. Macin Nappe; B. Babadag Basin; C. Niculitel Nappe; D. Tulcea Nappe; *5* Transcrustal fault: *IMF* intramoesian fault, *COF* Capidava-Ovidiu fault, *PCF* peceneaga-camena fault, *SGF* Sfantu Gheorghe fault, *NTrF* new Trotus fault, *TrF* Trotus fault, *BiF* Bistrita fault, *VaF* Vaslui fault; *6* Fault; *7* Thrust; *8* Cities; *black frame* represents the seismic swarm area

Black Sea shelf. The North Dobrogea block has a complex structure, consisting of several tectonic units, such as Macin, Niculitel and Tulcea nappes and a post tectonic cover as in the Babadag Basin (Fig. 2).

The epicentral zone of the swarm is situated in the Macin nappe area of the North Dobrogea Promontory. The North Dobrogea promontory is bordered to the South of the Moesian Platform by Peceneaga-Camena fault, also this fault, separates the North Dobrogea Promontory from Focsani Basin to the West. The Northern limit of the North Dobrogea promontory is marked by the Trotus fault, which separates it from the Scythian platform and to the East by the New Trotus Fault (the former prolongation of the Sfantu Gheorghe fault, in Visarion et al. 1988) which delimits the North Dobrogea Promontory from the same Scythian Platform. (Matenco et al. 2007; Leever et al. 2006b; Paraschiv et al. 1983).

The Peceneaga Camena fault is a deep crustal fracture with a Moho offset of $\sim$5 km (Radulescu 1976) and an offset of $\sim$200 m at the basement-sedimentary cover contact (Visarion et al. 1988). In fact, the Peceneaga Camena fault is part of a regional system of normal faults. This system was activated during the Sarmatian period only along the Peceneaga-Camena fault, in Quaternary, to the East of this fault, a large area was activated creating this system of normal faults (Leever et al. 2006b). The New Trotus Fault is a deep crustal fracture with a strike-slip character with sinisterly movement direction. The New Trotus fault is a part of a larger system of strike slip faults, activated in Sarmatian and developed in Quaternary. The contact area between this two faults systems, normal and strike slip, is a reactivation of an older pre-Neogene fault into the North Dobrogea Promontory (Matenco et al. 2007), which seems to follow the direction of Pechea fault. A strike slip fault with repeated movements, located at half distance between Peceneaga-Camena and Sfântu Gheorghe faults, is Pechea fault (Paraschiv et al. 1983). It passes eastward from Izvoarele and Braniştea villages, crossing the South-Western part of the epicenters swarm (Fig. 2). Another fault is Izvoarele-Negrea-Vânători cross fault, oriented West-East (Fig. 2). It overlaps the epicenters swarm crosswise, separating a Northern area, with higher magnitude earthquakes, and a South–South-Western area with lower magnitude earthquakes.

3 Method

3.1 Data acquisition

The recent upgrade of the seismic network in Romania allows unclipped recordings of moderate to large events at very small epicentral distances. The present digital network has 158 stations out of which 121 are in real time. At each station are used Quanterra Q330 or Kinemetrics ROCK/ROCK+ digitizers. All the real-time seismic stations send data at 100 samples per second to National Institute for Earth Physics (NIEP). At each site there are collocated both strong motion acceleration sensors (model EpiSensor) together with broadband velocity sensors (Streckeisen STS2 or Guralp CMG40T).

The National Institute for Earth Physics has deployed in the Galati area, immediately after the swarm started, a set of five temporary seismic stations. At each site there were installed a Kinemetrics ROCK-Basalt digitizer together with strong motion (EpiSensor) and broadband sensor (CMG40T). Strong motion sensors were installed in order to avoid clipped data on the velocity channels. Data is sent in real time at 100 samples per second and also stored locally, such that it can be retrieved after a communication failure. These

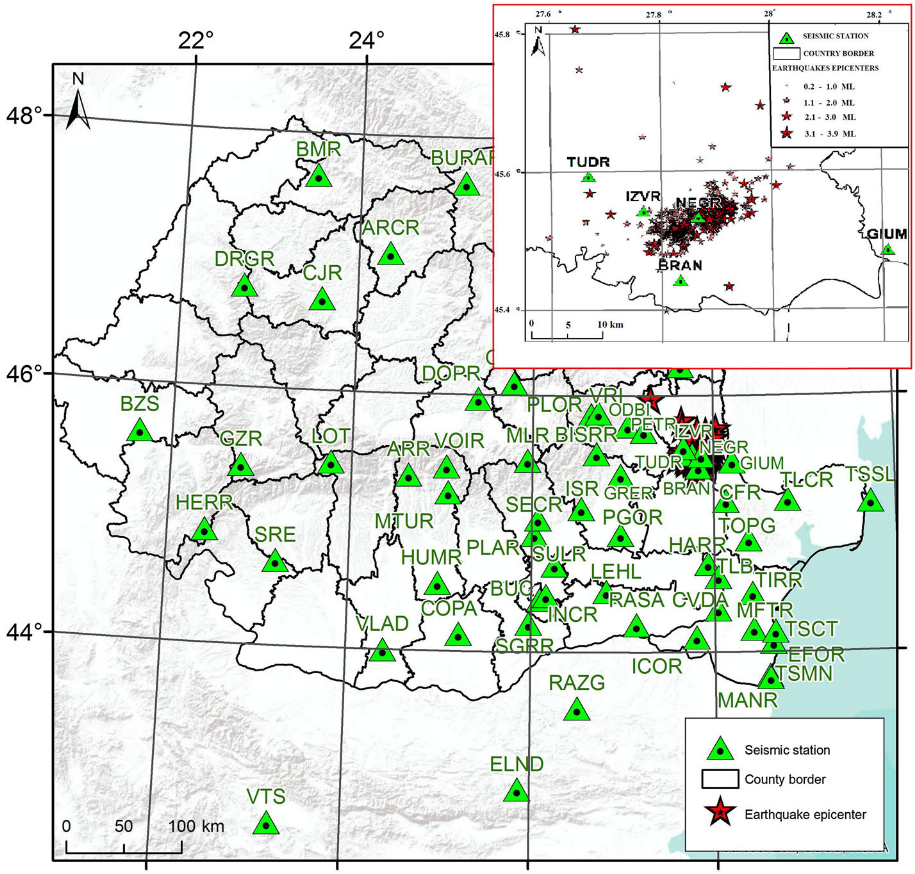

Fig. 3 Seismic stations used in locating seismicswarm from Izvoarele area (Section—stations vs. epicenters at local scale) (www.infp.ro)

stations together with the existing infrastructure of the Romanian Seismic Network (Fig. 3) has made possible the recording and monitoring of the unusual seismic swarm that started on September 23, 2013, close to Galati city, in Izvoarele region (Romania), and lasted until November 12, 2013.

An example of waveforms recorded by the National Seismic Network (velocity sensors, vertical and horizontal components) is pictured in Fig. 4.

3.2 Location and magnitude

Real time data is acquired using Antelope acquisition and processing software (http://www.brtt.com/software.html). The location algorithm implemented at NIEP uses LocSAT locator and the IASP91 velocity model. For all the events occurred in Galati area were picked P and S phases manually and the locations produced were refined. The magnitude for all the events of the seismic swarm was computed using the same relation used for the earthquakes catalogue available at www.infp.ro (independent towards the focal depth) (Richter 1958):

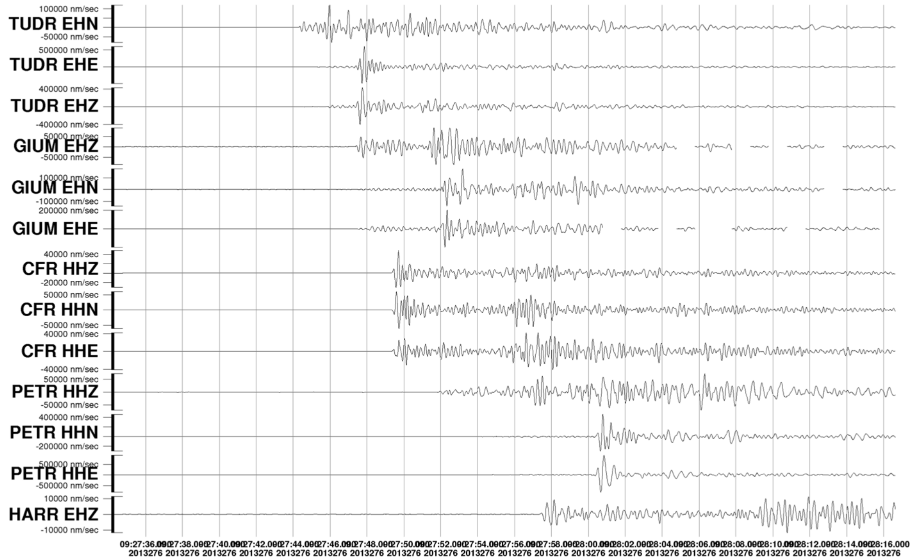

Fig. 4 Examples of waveforms for the 03.10.2013 (09:27:23 GMT) seismic event (detail of few first arrivals instead)

$$M_L = \log A + 2.56 \times \log D - 1.67$$

where A is the measured ground motion (in micrometers) and D is the distance from the event's location (in km). This is also used for measuring the magnitude of shallow events at distances less than 600 km (today called the local magnitude). For events larger than magnitude 8 this scale saturates and gives magnitude estimates that are too small.

The seismic activity recorded in NW of Galati county, has been identified as a seismic swarm, and has started on 23 September 3013 and lasted until 12 November 2013, and consists of 620 earthquakes recorded by the National Seismic Network. Only 406 of these seismic events were located, with M_L between 0.2 and 3.9, the rest of 214 seismic events didn't accomplish the minimum requirements to be located (at least three records per event).

3.3 Focal mechanisms

We used FOCMEC code by Snoke et al. (1984), from SEISAN software by Havskov (2003), to determine the focal mechanisms of the events. The program performs an efficient systematic search of the focal sphere and reports acceptable solutions based on selection criteria for the number of polarity uncertainties. The selection criteria for both polarities and angles allow correction or weightings for near-nodal solutions. The program makes a grid-search and finds how many polarities fit each possible solution. All solutions with less than a given number of wrong polarities within given error limits are then written out and can be plotted. The complete description of how the program works is found in the manual by Snoke et al. (1984).

To study the seismic swarm in Izvoarele area, the solutions estimated from P-wave polarities were obtained by using at least ten observations, therefore they might be considered as quite confident; the maximum number of polarities is 24 (for the 29 September 2013 event). The polarities and number of misfits is also presented in Table 1, for each

Table 1 The parameters of the focal mechanisms for major events recorded in the studied seismic swarm

	Date	Time	Lat (°N)	Lon (°E)	H (km)	M_L	Plane 1			Plane 2			P-axis		T-axis		Polarities no./Err. Pol.
							STRIKE	DIP	RAKE	STRIKE	DIP	RAKE	AZM	PLG	AZM	PLG	
1	23.09.2013	10:08:40	45.51	27.82	10	3.3	297.54	24.54	−30.37	55.6	77.88	−111.5	300.5	52.35	162.96	29.65	12/1
2	25.09.2013	00:36:10	45.55	27.88	5	3.5	308.53	68.19	−64.02	75.86	33.43	−137.59	254.93	58.53	19.4	19.11	15/1
3	25.09.2013	02:50:41	45.52	27.80	15.7	3.4	309.72	55.11	−44.22	68.83	55.11	−135.78	279.27	54	9.27	0	16/2
4	25.09.2013	15:43:23	45.54	27.86	9	3.5	295.74	71.79	−64.65	59.14	30.86	−142.47	238.42	55.89	6.58	22.71	10/0
5	27.09.2013	16:11:11	45.54	27.88	12	3.4	301.71	66.76	−74.73	87.04	27.57	−121.51	237.78	64.94	20.26	20.35	12/1
6	29.09.2013	18:10:51	45.55	27.86	5	3.9	316.13	71.94	−63.61	78.12	31.61	−143.74	259.57	55.22	26.24	22.52	24/2
7	30.09.2013	05:01:57	45.53	27.87	5	3.8	307.25	39.7	−23.04	55.37	75.52	−127.38	287.1	46.12	172.85	21.55	20/0
8	30.09.2013	21:18:04	45.52	27.82	4.1	3.0	307.69	48.50	−7.14	42.44	84.66	−138.28	273.80	32.30	167.65	23.75	12/1
9	02.10.2013	23:47:07	45.55	27.92	12	3.0	316.88	26.67	−25.03	69.53	79.05	−114.47	312.41	50.01	179.26	29.84	15/0
10	02.10.2013	23:52:36	45.55	27.92	7.4	3.5	304.28	7.8	−39.67	73.68	85.03	−96.02	337.11	49.63	169.22	39.74	14/0
11	03.10.2013	04:37:39	45.54	27.89	8.9	3.6	296.95	47.62	−13.15	35.9	80.33	−136.86	265.94	36.54	159.44	20.96	19/1
12	03.10.2013	05:52:49	45.53	27.86	12.9	3.0	255.08	32.88	−75.15	57.56	58.35	−99.41	301.44	74.77	154.37	12.87	12/0
13	03.10.2013	06:41:46	45.52	27.86	6.1	3.1	225.27	35.39	−118.42	78.84	59.38	−71.32	29.12	69.49	155.43	12.49	11/0
14	03.10.2013	09:27:39	45.56	27.96	7	3.6	274.3	43.23	−20.22	19.32	76.31	−131.42	249.52	43.04	139.25	20.35	13/0
15	04.10.2013	14:29:26	45.54	27.89	8.3	3.8	293.81	50.39	−40.28	52.19	60.13	−132.68	268.65	53.42	170.98	5.66	17/0
16	04.10.2013	21:08:10	45.53	27.85	15.2	3.6	312.08	37.70	−20.29	58.38	77.76	−125.94	292.31	45.19	175.44	24.18	18/1
17	05.10.2013	15:19:06	45.53	27.92	8	3.5	294.84	53.04	−33.14	46.27	64.10	−138.06	265.52	47.22	168.25	6.68	11/0
18	05.10.2013	15:20:19	45.53	27.87	8.2	3.3	313.31	76.95	−68.42	73.04	25.06	−147.78	249.02	53.15	26.06	28.74	10/0

seismic event that was investigated. The unique solution presented here is the solution with the best correlation with the minimum misfits number and in perfect correlation with the spatial distribution of the epicenters.

4 Results and discussions

The strongest events—a magnitude 3.9 earthquake, occurred on September 29, and two $M_L = 3.8$ shocks, occurred on October 3 and 4, respectively and 19 earthquakes with $M_L \geq 3$, were accompanied by specific seismicity bursts.

The seismic activity has reached a peak in the very beginning of October, following that, after 21 October 2013, the seismic activity registered a significant decrease, the occurring frequency is very small, and the events magnitudes are under 2.0 (M_L). The daily activities during the whole swarm are shown in Fig. 5.

Figure 6 shows the magnitude-frequency distribution for the earthquakes swarm. According to Gutenberg and Richter (1944), the frequency-magnitude distribution power law can be expressed as (Gutenberg and Richter 1944):

$$\log N = a - bM;$$

where N is the cumulative number of earthquakes with a magnitude $\geq$M. The a and b coefficient values vary in any specific time and space window.

Globally, b-values (the log-linear slope of the magnitude-frequency relation) are around 1. Our frequency-magnitude distribution plot shows a b-value = 0.6, indicating that the swarm is deficient in larger magnitude events compared to small earthquakes. A rather small value of b can be explained by the narrow time window of the swarm records.

Real time estimation of the seismic energy provides very important clues about the dynamic of the seismogenic area. The seismic cumulative energy is calculated with the formulas mentioned below.

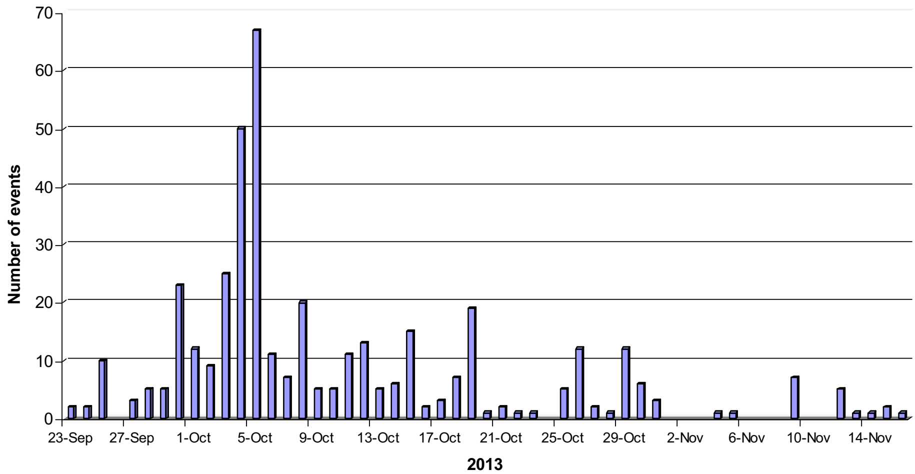

Fig. 5 Temporal distribution of seismicity in Izvoarele region (Romania), September 23–November 16, 2013. The *vertical bars* indicate the number of events detected by the network of stations in the studied epicentral area

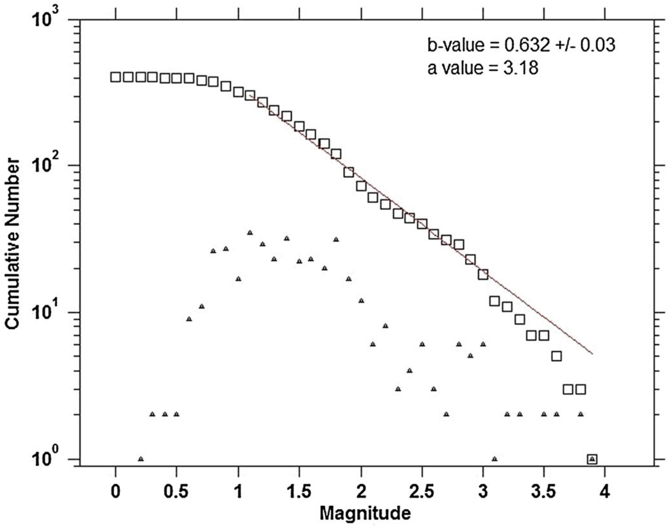

Fig. 6 Frequency-magnitude distribution (FMD) plots of the studied seismic swarm. *Triangle* and *squares* represent the number and cumulative number of each individual magnitude level of earthquake, respectively. The *lines* represent the FMD linear regression fitted with the observed data

To estimate the released seismic energy (Richter 1958):

$$\log E = 11.8 + 1.5\ M_s$$

where energy, E, is expressed in ergs, and magnitude M_s (surface waves magnitude was computed using local magnitude M_L (Båth 1983):

$$M_s = -2.14 + 1.43\ M_L - 0.018\ M_L^2.$$

The seismic energy released during the seismic swarm evidences a marked increase in the first part, where the biggest magnitude events were recorded and, following this period, there was no a significant increase (Fig. 7).

The focal depth of the events ranges from 1 to 27 km, most of them were situated in the 1–10 km depth interval (Fig. 8). The earthquakes hypocenters show a growth in depth from NE (Sf. Gheorghe fault) towards SW (Peceneaga Camena fault). Almost all, more than 95 %, of the hypocenters are located in the basement of the zone. In the area where the swarm occurred the basement is situated around 1000 m depth, while to the east of Danube river basement outcrop.

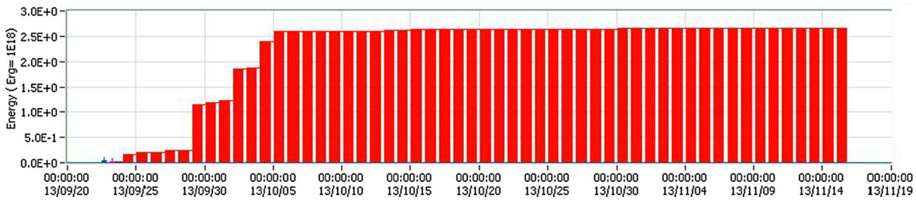

Fig. 7 Cumulative seismic energy (Toader et al. 2015)

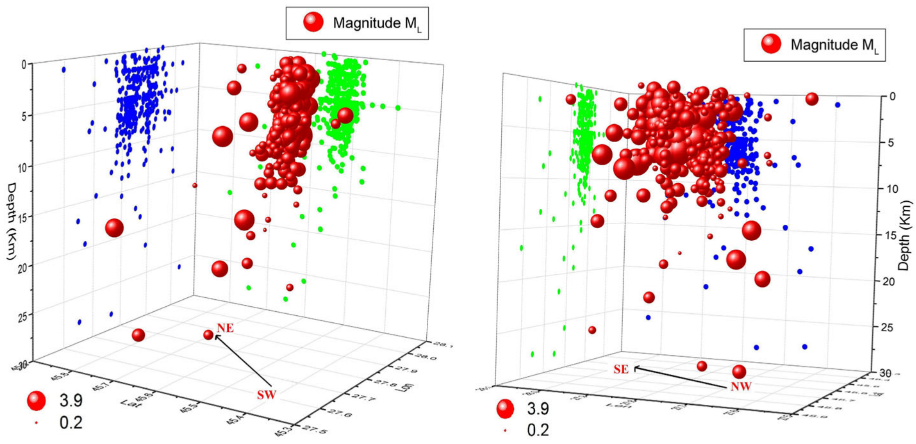

Fig. 8 3D hypocenters distribution of the seismic swarm

The epicenters of this seismic swarm are aligned on a NE–SW direction (Fig. 9). This distribution is parallel with the two transversal faults, situated in NW by the epicentral area of the seismic swarm (strike slip and normal fault, Matenco et al. 2007) and perpendicular to the dominant fault system lying NE–SW, between the Sf. Gheorghe fault in the Northern part and Peceneaga Camena in the Southern part, Pechea fault is crossing the seismic swarm diagonally (Fig. 2).

Taking into account the spatial overlap of seismicity in the studied area, recorded in 2012, and the seismic swarm occurred in September–November 2013, we can notice that the epicenters distribution follows the same direction NE–SW, fitting the line of Schela and Negrea villages (Fig. 9).

The parameters of the focal mechanisms for the major events recorded in the studied seismic swarm are presented in Table 1. The parameters of focal mechanisms are given in the two nodal planes (strike, dip and rake for Plane 1 and Plane 2) and P, T axis (azimuth and plunge) following the convention by Aki and Richards (1980).

Below are displayed the fault plane solutions, obtained for the main events of the studied seismic swarm (Figs. 10, 11, 12).

For the 29 September ($M_L = 3.9$) event, the focal mechanism obtained using the P waves polarities (24 stations used) shows a normal fault with a strike slip component, having the extension axis oriented towards NE–SW, the compression axis oriented towards NW–SE, the nodal planes are oriented NE–SW, respectively, NW–SE (Fig. 10). For the next two events, 30 September ($M_L = 3.8$, 20 polarities) and 4 October ($M_L = 3.8$, 17 polarities) the focal mechanisms show a normal fault with a strike slip component, having the T axis oriented towards N–S, P axis oriented E-W, and the nodal planes oriented on the same direction NE–SW, respectively, NW–SE (Figs. 11, 12). The focal mechanism solutions of the studied earthquakes obtained from P-wave polarities show generally a normal faulting, with an important strike-slip component in several cases. A constant feature is a fault plane oriented roughly in the NE–SW direction, dipping to SE (Figs. 2, 10, 11, 12). The main axis of the moment tensor P and T may show the stress field regime in the seismic zone, in this case indicating a predominant extensional stress field (T plunge is lower than 45°, and P plunge in most cases is greater than 45°) (Fig. 13). The principal axes of the moment tensor presents a fairly high variability in azimuth. It can be observed

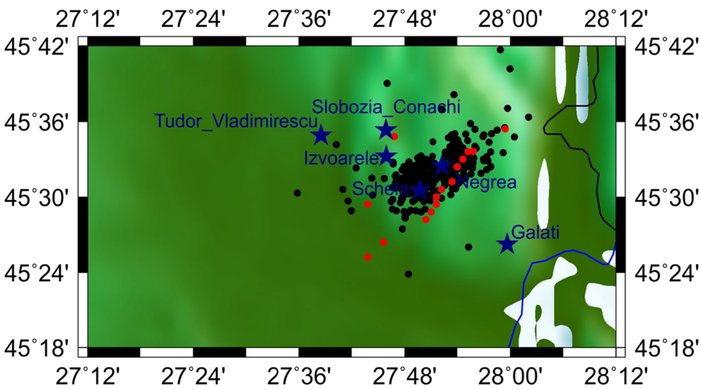

Fig. 9 Epicenters distribution of the earthquakes recorded in study area (*red dots* in 2012, *black dots* in 2013) (www.infp.ro)

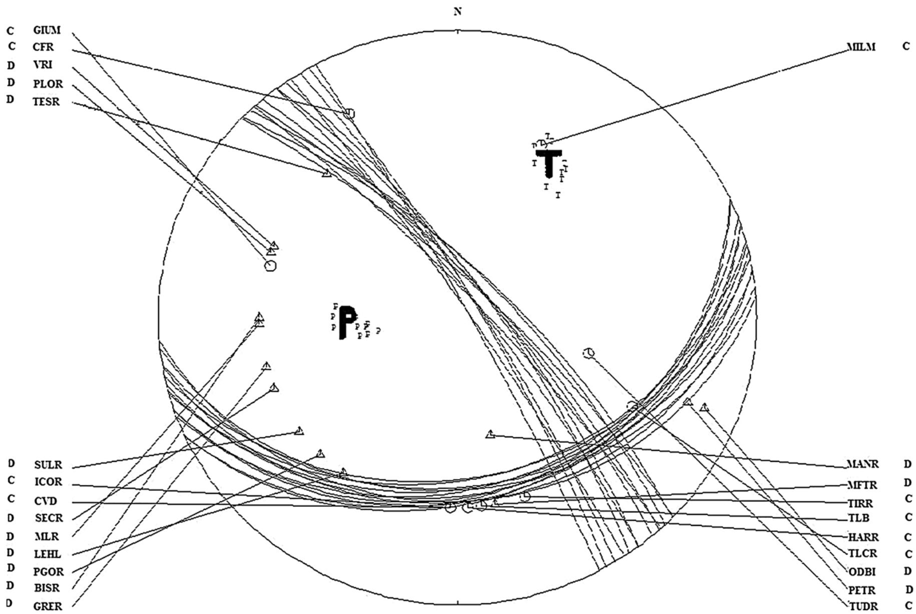

Fig. 10 Focal mechanism solutions with available first-motion polarities, P and T axes for the event from 29.09.2013, 18:10:51, *o* compression, Δ dilatation

that the T-axis shows two prevailing directions NE–SW, respectively, NW–SE (in most cases), while the P-axis direction is more random (Fig. 13).

To select the fault plane solution generated by this seismic swarm, we have taken into account the spatial distribution, the alignment of the epicenters towards NE–SW, the nodal planes obtained in this study show the re-activation of a fault system oriented towards NE–SW. These micro earthquakes have reactivated, most likely a local faults system (small dimensions), situated between two major tectonic units Sf Gheorghe and Peceneaga

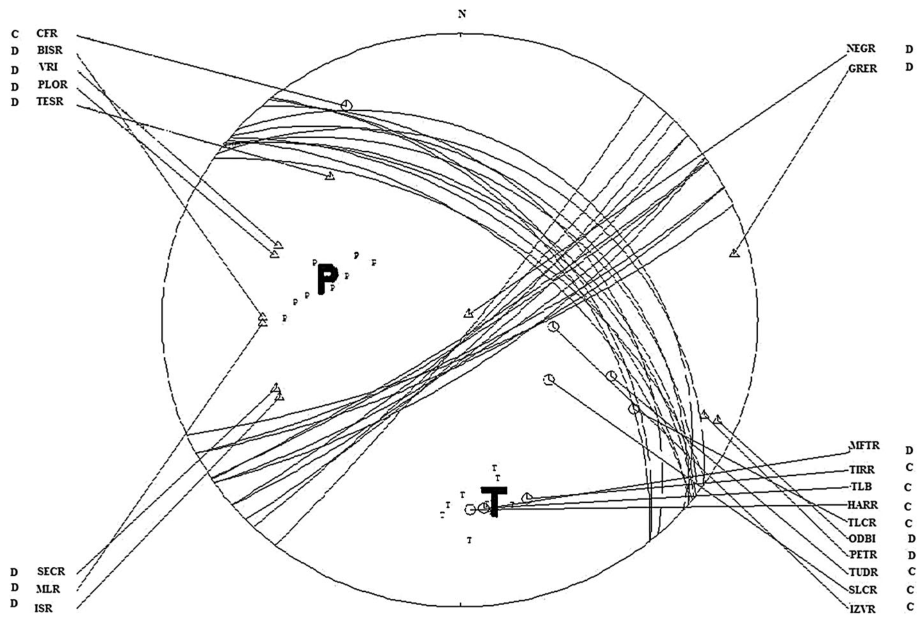

Fig. 11 Focal mechanism solutions with available first-motion polarities, P and T axes for the event from 30.09.2013, 05:01:57, *o* compression, Δ dilatation

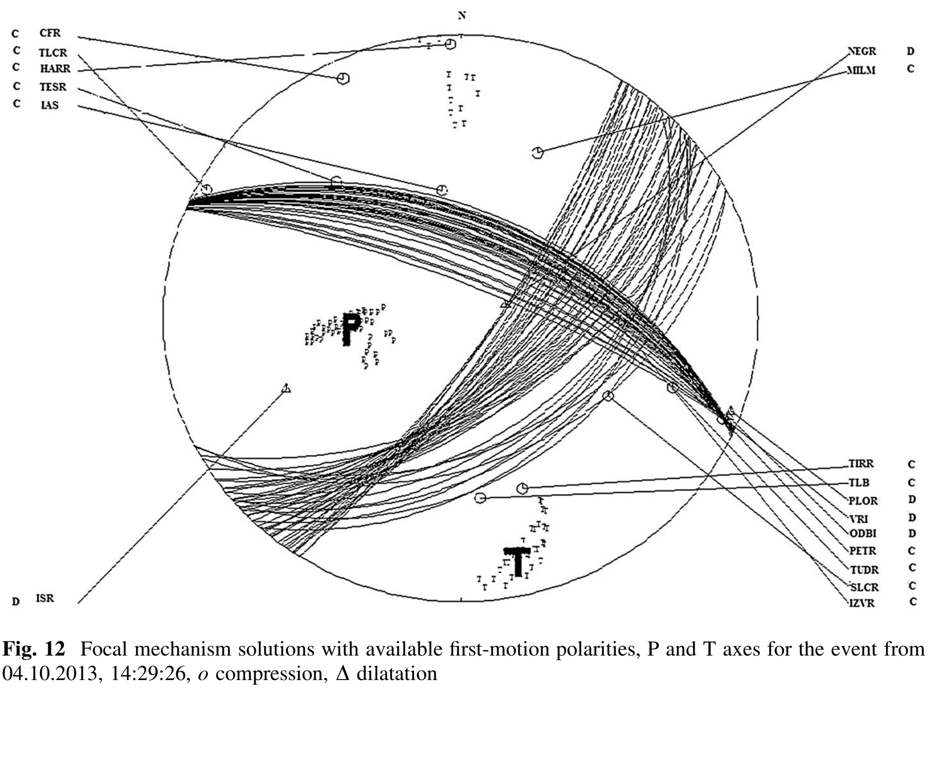

Fig. 12 Focal mechanism solutions with available first-motion polarities, P and T axes for the event from 04.10.2013, 14:29:26, *o* compression, Δ dilatation

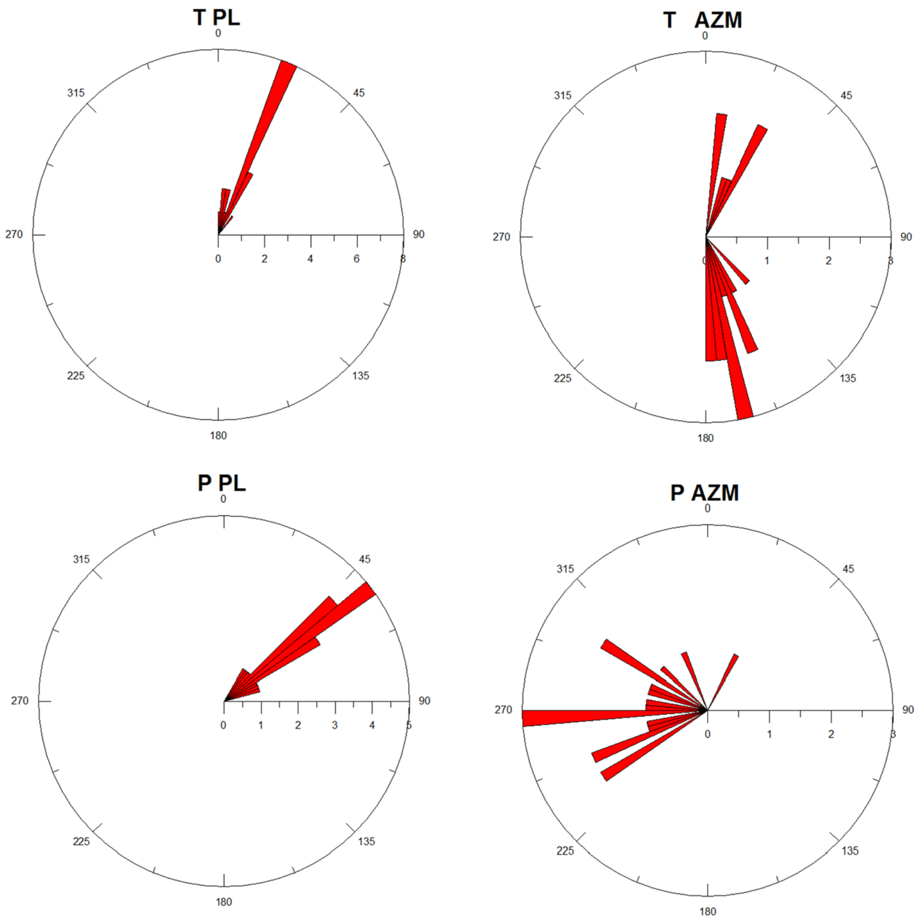

Fig. 13 Diagrams of the azimuth and plunge of the compression (P) and tension (T) axes of the moment tensor of the investigated earthquakes

Camena, and parallel with the transversal faults that crosses the above mentioned system (Fig. 2).

The estimated focal mechanisms are the first solutions obtained for this seismic zone.

5 Conclusions

The seismic swarm is very unusual for the Galati area through its scale (magnitude and duration), if we are reporting to the available data from our seismic catalogue (www.infp.ro).

The seismic swarm phenomenon is not unique in Romania, it can be found in other seismic regions (the foreland of the Carpathian Bend, Sinaia region). In Romania, however, from the instrumental data, the Galati seismic swarm is significantly larger, also in duration and events number compared to similar seismic swarms.

The epicenters of this seismic swarm are aligned on a NE–SW direction with focal depth of the events that ranges from 1 to 27 km, most of them were situated in the 1–10 km depth interval. This spatial distribution of epicenters is parallel with the two transversal faults situated at NW from the epicentral area of the seismic swarm (strike slip and normal fault, Matenco (2007) and perpendicular to the dominant fault system lying NE–SW, between the Sf. Gheorghe fault in the Northern part and Peceneaga Camena in the Southern part, Pechea fault is crossing the seismic swarm diagonally.

These micro-earthquakes have reactivated, most likely a local fault system (small dimensions), situated between two major tectonic units Sf. Gheorghe and Peceneaga Camena, and parallel with the transversal faults that crosses the above mentioned system.

The focal mechanism solutions of the studied earthquakes obtained from P-wave polarities show generally a normal faulting, with an important strike-slip component in several cases. A constant feature is a fault plane oriented roughly in the NE–SW direction, dipping to SE.

The principal axes of the moment tensor show a fairly high variability in azimuth: T-axis show two prevailing directions NE–SW, respectively, NW–SE (in most cases), while the P-axis direction is more random. The stress field regime in the seismic zone, indicates a predominant extensional stress field (T plunge is lower than 45°, and P plunge in most cases is greater than 45°).

The seismic swarm occurred in 2013 is considered the most representative from the seismic swarms that occurred in Romania and has no implications for seismic hazard assessment in the Galati area.

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