Geomagnetic Field Behaviour at Muntele Rosu (Romania) and Anomaly Interpretation

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Abstract. In this study were used geomagnetic data recorded during last 5 years, from 2013 till present. The records were corrected for missing and wrong data induced by malfunction of the data acquisition system. The main purpose of the paper is to identify the magnetic field behaviour in relation with space weather, meteorological phenomenon including annual/diurnal temperature variation, local and regional seismic activity. The paper is focusing on geomagnetic anomalies detected on the recorded field at one magnetometer located near Vrancea seismogenic zone prior to Mw>4.5 crustal and intermediate depth earthquakes. During these 5 years of investigations one crustal earthquake and three subcrustal earthquakes with a moment magnitude Mw between 5.0 and 6.0, occurred in the Vrancea zone. All three intermediate depth events were accompanied by significant anomalies on Y axis (EW component) of local geomagnetic field measured at MLR observatory. The MLR magnetometer was outside the preparation zone of the crustal earthquake, located at 100km distance from the epicenter, so no anomaly was observed. In order to highlight the anomalies recorded at Muntele Rosu (MLR) seismological observatory, these data were compared with data from Surlari (SUA) observatory, located about 150 Km South-East outside the Vrancea seismogenic zone. Similarly, earthquakes with Mw between 4.5 and 5 are accompanied by same type but smaller amplitude anomalies, were the drop on Y axis was less than 10 nT instead of 20-30 nT as those occurred prior to earthquakes with Mw>5.0. The latter ones are harder to observe during the summer time when these anomalies are hidden by large diurnal variations. The anomaly duration extends from days to sometimes months, without correlation with the earthquake magnitude. To better distinguish the local/regional anomalies from global geomagnetic behaviour, both MLR and SUA datasets were also corelated with the geomagnetic indices from NOAA/Space Prediction Center. The presence of geomagnetic storms creates a specific type of anomalies that sometimes might hide the ones related to earthquakes. The geomagnetic measurements were also compared with temperature values recorded at MLR station both for avoiding wrong interpretation of instrument response related to temperature variations, and to highlight possible correlations of magnetic field behaviour with ambient temperature. The three medium sized intermediate earthquakes that have occurred in the studied time interval provided a good opportunity to investigate the link between the presence of anomalies on geomagnetic records at Muntele Rosu observatory and seismicity in Vrancea zone.

1. Introduction

The Vrancea seismogenic area is located at the curvature of Carpathians (Figure 1), at the intersection of three major tectonic units: (i) East European Platform to northeast; (ii) Moesian platform to south; (iii) Moesian platform to south;. Crustal activity (0-40km) in Vrancea zone is weak, with an activity rate of 0.514 events per year, for earthquakes with Mw >3.0 [1]. The intermediate depth seismic zone (60 - 200km) has a higher activity rate of 10.48 events with Mw>4.0 per year. The seismic activity is concentrated inside a small perimeter with a length of 80km long and a width of 40 km (figure 1). The occurrence of intermediate earthquakes was debated by many authors and there were proposed some theories regarding subduction process which affected this area. The oldest one suggested that the intermediate earthquakes beneath Vrancea zone occur in a relict oceanic slab hanging vertically in the mantle [2]. Another model suggested to Vrancea zone was the delamination mechanism [3],[4], refers to the foundering of the portion of the lowermost lithosphere from the tectonic plate to which it was attached. Delamination process seems to be more suitable for continent-continent collisions and is include sudden mafic volcanism and acceleration of uplift.

According to [5] the absence of intermediate seismicity in the northern part of the Carpathians indicate that in this zone the collision was followed by a slab break-off and in our days the last slab hangs beneath Vrancea zone.

To study the geomagnetic field, large ground-based instruments [6],[7],[8],[9] (e.g. the International Real-Time Magnetic Observatory Network, INTERMAGNET) have been installed around the world. The magnetic measurements have been carried not only on the ground but also throughout space technologies with magnetometers installed on satellites [10],[11],[12],[13].

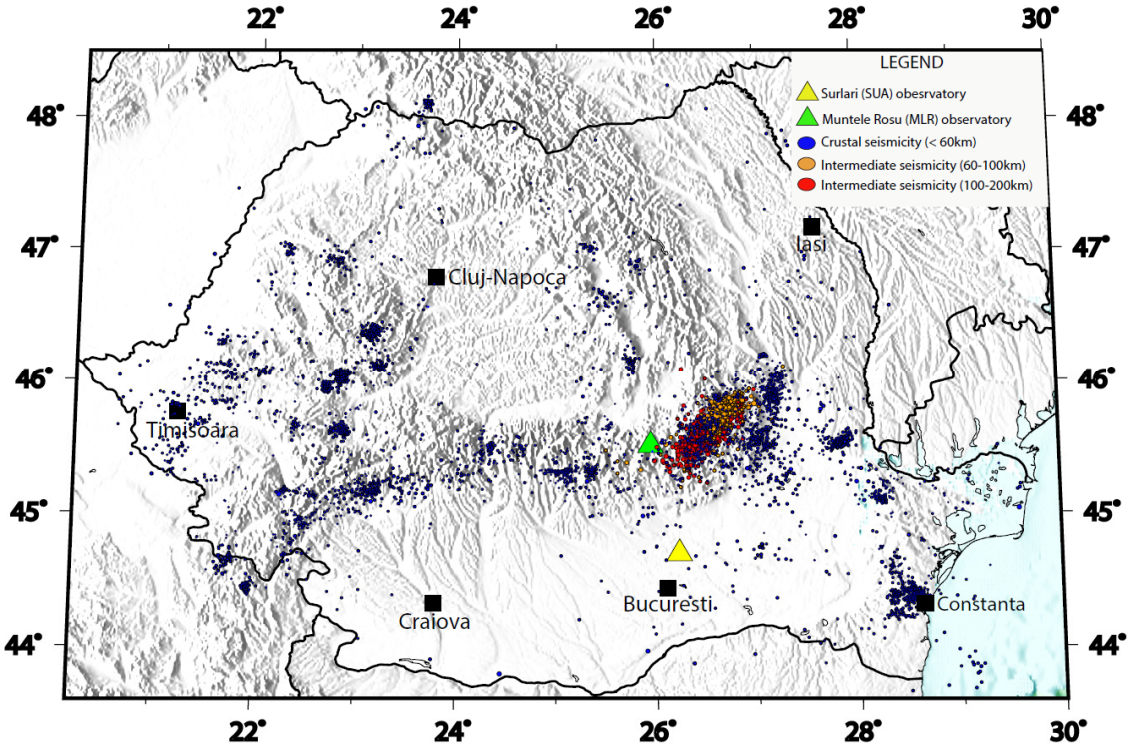

Figure 1. Crustal seismicity (blue dots) and intermediate seismicity (orange and red dots) of Romania and the location of geomagnetic observers included in the study.

Anomalous magnetic signals were observed prior to earthquakes occurrences [14-18]. These anomalous signals happen as a response to the crustal deformation which creates piezomagnetic phenomena due to stress applied on rocks with ferromagnetic mineral composition [19]. [20] came with,

"Peroxy defect theory", which describes an activation of electronic charges (electrons and positive holes) in rocks with the increasing of tectonic stress due to the rupture of peroxy bonds (peroxy links, O3X-OO-YO3). The release of positive holes can generate currents that are accompanied by changes in magnetic field. Anomalies in the magnetic field were observed before several earthquakes in Peru and California (USA) as positive pulses [21],[22].

Some researchers [23] combined the petrological and petromagnetic properties of rocks and demonstrated that significant amounts of mafic /ultramafic rocks may account for some magnetic anomalies. Unweathered outcrops sample were heated and then cooled in an argon atmosphere in order to minimize mineral reaction with oxygen during heating/cooling. All samples analyzed were indicated a variation of magnetic susceptibility with the temperature. During the heating process, the samples show a decrease in susceptibility near 580°C then. During the cooling process, the samples recovered their magnetic susceptibilities but not at initial values.

The purpose of this study is to examine the correlation between crustal and intermediate seismic activity and the geomagnetic anomalies observed before earthquakes occurrence to Vrancea seismogenic zone. During 5 years of investigations (2013-2018), three intermediate earthquakes and one crustal earthquake with a moment magnitude Mw greater than 5, occurred in the Vrancea zone and create the possibility to compare the geomagnetic behaviour between crustal and intermediate earthquakes. This paper is a continuation of [18] study, which aimed at examining the magnetic field variations in relation to Vrancea seismic activity.

The largest intermediate depth earthquakes that occurred in the study time interval had the next moment magnitudes: October 06, 2013, with Mw =5.2, September 23, 2016, with Mw= 5.5 and December 27, 2016, with Mw= 5.6. If the previous study [18] had a lack of crustal earthquakes with Mw>5, during this study a crustal earthquake with Mw=5.4 occurred on November 22, 2014 despite to a weak activity rate for crustal earthquakes with Mw>5. Analysed geomagnetic data sets and the occurrence of one crustal earthquake along other three intermediate earthquakes provided the opportunity to investigate the link between crustal seismicity versus intermediate seismicity and the presence of magnetic anomalies recorded at MLR station.

Using only the magnetic field from MLR station is not sufficient to obtain a reliable earthquake forecasting method. The major earthquake can occur at the beginning, in the middle and at the end of the anomaly being surrounded by smaller earthquakes and the exact time of occurrence is impossible to guess. Monitoring the magnetic field in Vrancea zone, in more than one station can create an idea about the next earthquakes strike (not the exact date) and increase the knowledge background about the deep tectonic environment and the associated seismicity.

2. Data and equipment

For more than 5 years, the geomagnetic field was monitored on Muntele Rosu observatory (MLR – Figure 1), which is situated at the Western edge of the Vrancea seismogenic zone. Data from MLR observatory were compared with SUA observatory, an observatory located outside the Vrancea seismogenic zone. The MLR observatory location, near to Vrancea seismic area (Figure 1), provides a good opportunity to study the local geomagnetic anomalies of Vrancea zone. Also, this site was built inside a tunnel to avoid the temperature variations of the instrument and far away from roads, railways and any type of noise, to avoid the anthropic anomalies.

The present study used the following data:

- The seismic bulletins for the Vrancea source zone were taken from „Romplus" seismic catalog developed by National Institute for Earth Physics
- The geomagnetic data from 2013 till present were taken from Muntele Rosu observatory (National Institute for Earth Physics), and from Surlari (SUA) INTERMAGNET Observatory
- The planetary K-index were used to characterize the magnitude of geomagnetic storms were taken from the National Oceanic and Atmospheric Administration (NOAA)/ Space Weather Prediction Center.

- Temperature measurements were made by using a temperature sensor installed together with a radon sensor.

The MLR magnetometer is a three-axis fluxgate type with a measuring range at +/- 70μT , developed by Bartington Instruments, UK. The magnetic field sensor is a low noise with a band larger than 2 kHz but up to 3kHz and 15pT rms /(Hz^1/2) noise, which make it sensitive to small variations. The data-logger acquisition designed by same Bartington company has six channels, 24-bits resolution. Data-logger acquisition parameters are controlled by a software program which displays the average of 12 samples recorded in one minute.

3. Data correction and uncertainty of the data

For MLR data, a LabVIEW program was developed to correct automatically the datasets, highlighting the missing data or the bad data. The missing data blocks were automatically replaced with the last correct value. Datasets taken from SUA (INTERMAGNET Observatory) were already corrected but the missing values were replaced with the number, "999999'' and it was necessary to replace this number with the last good value. The Kp indices were recorded at every 3 hours, but for graphical reasons, it was necessary to represent a day sum of all Kp indices.

Solar storms represent the main phenomena that disturbs the geomagnetic field most often, creating an increase in amplitude and frequency of geomagnetic representation. In previous studies [24], these perturbations created by solar storms were falsely identified as seismo-magnetic anomalies. To avoid this kind of misinterpretations the geomagnetic field was correlated alongside the daily sum of Kp indices. The strong solar storms are well defined when the sum of the Kp indices reach the value of 20 (figure 2). An intense solar activity can hide the small local seismo-magnetic anomalies. At the top of the atmosphere, solar radiation creates an ionized region (ionosphere) and during daytime the ionosphere is heated by the sun radiation causing convection move of charged particles through earth's magnetic field. These moves of charges particles create a dynamo action that drives ionospheric electric currents above the earth surface which were carried by earth rotation, creating a 12 hours' variation (diurnal variation), [25]. The quantity of solar radiation varies over one year, showing high values during summer and small values during winter. Because the solar radiation is not constant the diurnal variations are bigger during summer and hide the small seismo-magnetic anomalies.

The second source of interpretation errors were variations induced by bad data that was created artificially during personnel visits at the location or during maintenance operations. This kind of anomalies are a short time and are visible on all magnetic components. The anthropic measurements are very easy to see because these bring with them a significant increase of geomagnetic field, these are removed automated using a LABview program. Measurement of magnetic field could vary with the temperature and for that it was used a temperature sensor. Unfortunately, this sensor worked for only one year then it broke, but this one-year period is enough to see the temperature variations between winter and summer.

4. Results and discussions

Over 5 years of geomagnetic data from MLR and SUA observatory were plotted every month to highlight the local anomalies and see the seismicity associated with these anomalies. During this 5 years were found 8 anomalies (table 1 and table 2) and a ninth anomaly at the beginning of the 2018 year which was not included in this study. As can be seen in Table 1, the anomaly can vary from two weeks-one month (see table 1 I, III, IV, V, VI, VIII anomalies) to almost six months (see table 1, II and VII anomalies). Most of the anomalies start with a slow or pregnant decrease of By magnetic component than the anomaly can stabilize for a short or long period to almost the same value and then the value of By start to increase to normal.

The earthquakes which occurred on a decrease of By component were called generic: "head earthquakes". The" tail-earthquakes" are the last earthquakes that earthquakes and are associated with a return of By magnetic field component. Between "head-earthquakes" and "tail-earthquakes" are found

the “middle-earthquakes” which occur on a steady low anomaly. Table 1 contains the earthquakes parameters for all earthquakes with Mw >3.0, the sum of Kp indices, which magnetic component was affected, and the shape of the anomaly.

Table 1. The seismic sequences (I - VII) with seismological parameters and Kp indices of all Vrancea earthquakes of magnitude Mw >3 that occurred alongside the geomagnetic anomalies

DATE	TIME	LATITUDE	LONGITUDE	DEPTH	ΣKp	Mw	Magnetic component affected	Types of earthquakes	Shape of anomaly
I									
18/09/2013	0:27:28	45.67	26.57	149.9	14	3.6	By	head earthquake	Short time anomaly with a decrease of ~40nT
06/10/2013	1:37:21	45.67	26.58	135.1	7	5.2	By	middle earthquake	
15/10/2013	19:33:12	45.62	26.55	141.5	31	4.4	By	tail earthquake	
22/10/2013	7:16:50	45.75	26.69	132	8	3.6	By	tailearthquake	
II									
14/11/2013	21:44:32	45.5	26.26	124.2	4	3.6	By	head earthquake	Long anomaly with a decrease of ~40nT. The earthquakes are present along the decreasing trend (head earthquakes), when the trend is steady (middle earthquakes) and when the magnetic anomaly trend increase (tail earthquakes). This anomaly decrease in steps having two series of head earthquakes.
21/11/2013	6:38:53	45.76	26.71	89	2	4.3	By	head earthquake	
28/11/2013	04:21.6	45.56	26.4	126.7	2	3.7	By	head earthquake	
05/12/2013	1:24:52	45.65	26.47	120.3	9	3.4	By	head earthquake	
05/12/2013	3:48:24	45.51	26.38	118.9	9	3.2	By	head earthquake	
09/12/2013	17:55:45	45.69	26.48	94.2	6	3.4	By	head earthquake	
27/12/2013	7:58:32	45.74	26.65	93	6	3.5	By	middle earthquake	
29/12/2013	19:22:12	45.65	26.44	151.7	9	3.8	By	middle earthquake	
12/01/2014	18:26:02	45.5129	26.4293	137.2	13	4.1	By	head earthquake`	
23/01/2014	6:15:05	45.4877	26.2537	132.3	12	4.4	By	head earthquake`	
24/01/2014	13:11:40	45.5867	26.5601	87.6	7	3.5	By	head earthquake`	
03/02/2014	0:26:31	45.6657	26.5202	139.2	12	4	By	middle earthquake	
24/02/2014	22:54.2	45.7414	26.6735	104	12	4.1	By	tail earthquake	
26/03/2014	19:46:29	45.6578	26.5406	133.3	14	4.2	By	tailearthquake	
29/03/2014	1:55:17	45.3462	26.2306	144.1	17	4	By	tailearthquake	
29/03/2014	19:18:05	45.6094	26.4709	134.4	17	4.6	By	tailearthquake	
31/03/2014	15:48:47	45.5751	26.4742	139.7	14	3.5	By	tailearthquake	
03/04/2014	12:38:57	45.4924	26.4003	127.9	13	4.3	By	tailearthquake	
07/04/2014	12:59:53	45.486	26.2667	112.3	17	3.8	By	tailearthquake	
11/04/2014	20:33:55	45.6311	26.4518	149.9	15	3.6	By	tailearthquake	
III									
22/12/2014	0.6858155	45.5457	26.4405	141.3	20	3.7	By	head earthquake	Short time anomaly with a decrease of ~20nT
24/12/2014	0.2629846	45.6853	26.6021	136.1	21	3.7	By	head earthquake	
03/01/2015	3:39:35	45.7782	26.6848	78.7	21	3.8	By	middle earthquake	
03/01/2015	10:08:45	45.4843	26.3674	138.4	21	3.7	By	middle earthquake	
04/01/2015	40:38.6	45.532	26.3744	120.2	20	4.1	By	middle earthquake	
14/01/2015	3:10:54	45.5501	26.3503	145.9	12	3.9	By	tailearthquake	
24/01/2015	7:55:47	45.7123	26.5712	88.4	11	4.3	By	tailearthquake	
28/01/2015	22:52:00	45.6405	26.494	128.7	11	3.8	By	tailearthquake	
IV									
28/01/2015	22:52:00	45.6405	26.494	128.7	11	3.8	By	head earthquake	Short time anomalie with a decrease of ~10nT
31/01/2015	22:47:35	45.6615	26.5441	148.5	13	3.1	By	head earthquake	
16/02/2015	19:34:12	45.634	26.5805	161.2	9	3.5	By	middle earthquake	
21/02/2015	19:10:13	45.6883	26.5791	141.3	16	3.8	By	middle earthquake	
27/02/2015	11:40.1	45.725	26.6709	129.6	5	3.9	By	tailearthquake	
V									
13/03/2015	22:31:19	45.5769	26.5355	118	10	3.7	By	middle earthquake	Short time anomalie with a decrease of ~10nT
15/03/2015	16:54:17	45.8038	26.9305	74.3	15	3.6	By	middle earthquake	
16/03/2015	15:49:49	45.5991	26.4484	118.2	18	4.3	By	tailearthquake	
27/03/2015	21:48:34	45.7861	26.6929	115.2	15	3.5	By	tailearthquake	
29/03/2015	0:44:58	45.6193	26.478	145.4	19	4.3	By	tailearthquake	
VI									
29/09/2015	53:49.1	45.7189	26.719	121.6	11	3.8	By	head earthquake	Short time anomalie with a decrease of ~10nT
07/10/2015	25:02.4	45.6621	26.8539	128.5	37	4.1	By	middle earthquake	
VII									
16/09/2016	9:10:57	45.6458	26.5912	140.8	16	3.5	By	head earthquake	Long anomaly with a decrease of ~100nT. The earthquakes are present along the decreasing trend (head earthquakes), when the trend is steady (middle earthquakes) and when the magnetic anomaly trend increase (tail earthquakes). This anomaly decrease in steps having two series of head earthquakes.
22/09/2016	7:18:45	45.658	26.5249	132.4	10	3.5	By	head earthquake	
23/09/2016	23:11:20	45.7148	26.6181	92	7	5.5	By	head earthquake	
16/10/2016	56:26.7	45.4762	26.3303	126	21	3.5	By	middle earthquake	
23/10/2016	3:10:34	45.631	26.4711	144.5	0	3.5	By	middle earthquake	
31/10/2016	11:59:50	45.8425	26.776	90.8	16	4	By	middle earthquake	
19/11/2016	11:30:39	45.6411	26.5083	140.8	6	4.1	By	middle earthquake	
30/11/2016	13:34:38	45.6814	26.5821	137	5	3.6	By	middle earthquake	
01/12/2016	9:01:20	45.832	26.8612	97.5	7	3.5	By	middle earthquake	
10/12/2016	7:31:31	45.5634	26.5405	128.5	19	3.5	By	head earthquake`	
17/12/2016	4:49:04	45.4986	26.096	70.7	8	3.5	By	head earthquake`	
17/12/2016	11:16:06	45.4924	26.3877	120.2	8	3.7	By	head earthquake`	
27/12/2016	23:20:56	45.7139	26.5987	96.9	16	5.6	By	head earthquake`	
05/01/2017	23:55.7	45.66	26.5317	141.6	23	3.7	By	head earthquake`	
05/01/2017	13:16:10	45.6339	26.5096	140.7	23	3.6	By	head earthquake`	
05/01/2017	14:47:44	45.7596	26.7259	114.4	23	3.7	By	head earthquake`	
06/01/2017	14:01:11	45.7001	26.6539	138.2	22	3.5	By	head earthquake`	
08/02/2017	9:52:06	45.6955	26.6727	129.9	8	4.1	By	tailearthquake	
08/02/2017	15:08:21	45.4874	26.2849	123.2	8	4.8	By	tailearthquake	
22/02/2017	9:29:45	45.6576	26.7623	139.3	15	3.5	By	tailearthquake	

Table 2. The seismic sequence VIII with seismological parameters and Kp indices of all Vrancea earthquakes of magnitude Mw >3 that occurred alongside the geomagnetic anomalies.

VIII									
06/05/2017	17:01:12	45.4819	26.375	130.5	12	3.8	By	tailearthquake	Short time anomaly with only tail earthquakes.
13/05/2017	9:21:59	45.5054	26.3495	119	11	3.6	By	tailearthquake	
19/05/2017	20:02:45	45.7228	26.7547	121.6	22	4.5	By	tailearthquake	
22/05/2017	8:27:40	45.7108	26.7238	124.5	17	3.5	By	tailearthquake	

Figure 2 shows a short-time anomaly with a significant decrease on By component of 40 nT, which starts with a weak head-earthquake (Mw=3.6), followed by a strong middle-earthquake with Mw=5.2. This geomagnetic sequence ends with two tail-earthquakes with Mw=4.4 and 3.6. Even this sequences were affected by three major solar storms, the anomaly is big enough to be visible.

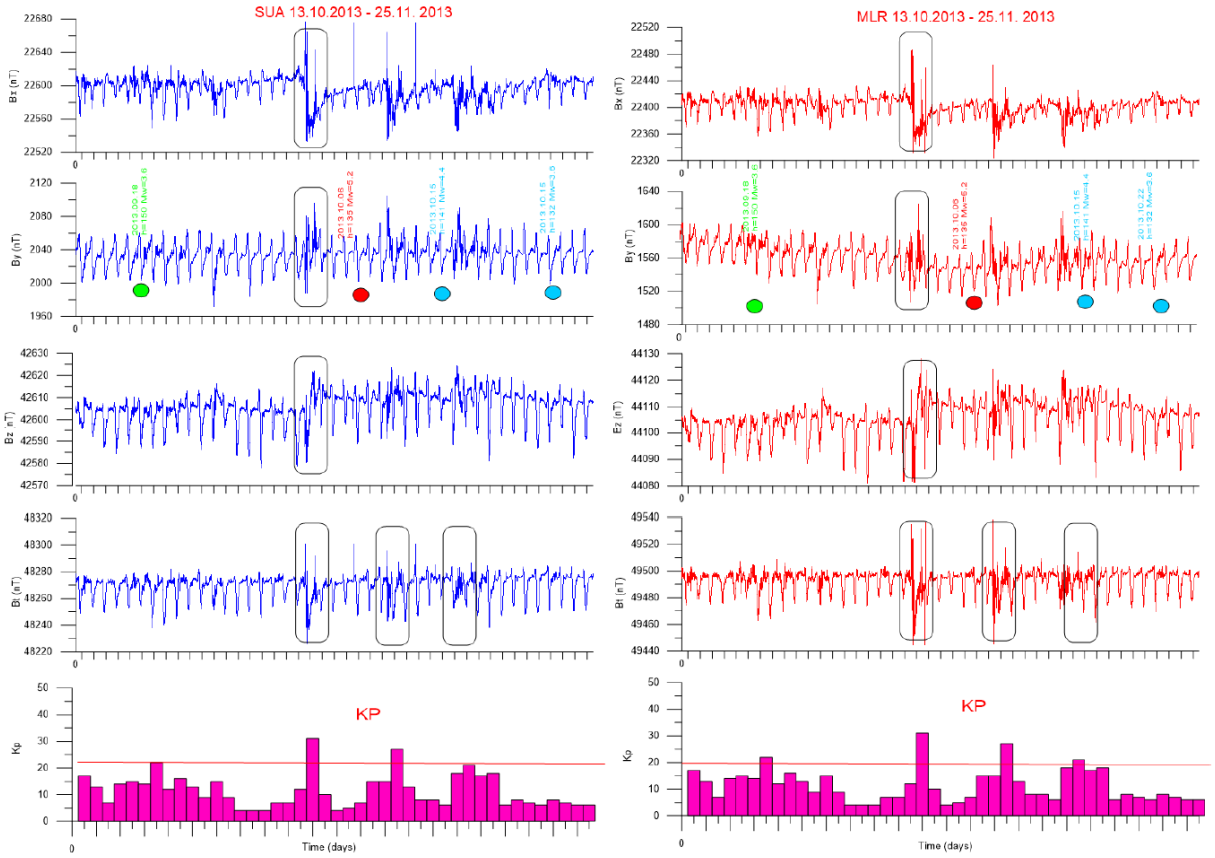

Figure 2. Anomaly number I on MLR By component with head-earthquakes (green dots), middle-earthquakes (red dots) and tail-earthquakes (blue dots) and with rounded rectangle are represented the solar storms

Figure 3 illustrates the components of the magnetic field, Bx, By, Bz, and Bt, for SUA observatory (blue graphs) and MLR observatory (red graphs). As seen in the figure above the total magnetic field (Bt), vertical component (Bz) and one of the horizontal component (Bx) look similar for both MLR and SUA observatory. The only affected component was the By horizontal component of MLR observatory which shows a decrease of around 40nT. The decrease is not continuous and is made in two steps, with of around 20 nT per each step. This long anomaly (14.11.2013-11.04.2014) is not so big and is accompanied by earthquakes with Mw=4.6.

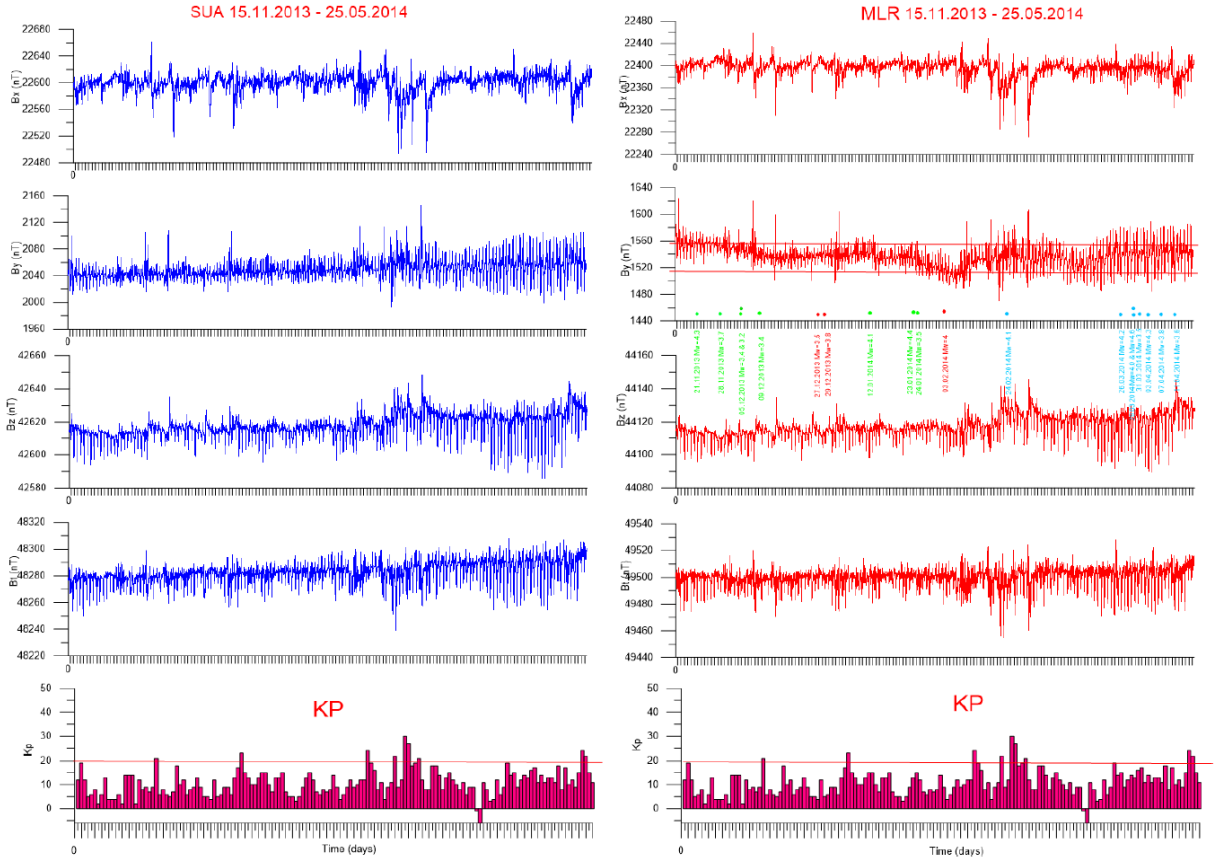

Figure 3. Anomaly number II on MLR By component and the earthquakes that occurred during this anomaly

The anomaly number VII is also a long period anomaly (figure 4) with a step-type change in By component but the decrease is more pregnant and shows a total decrease measured on By component of around 90nT. The earthquakes that accompanied this anomaly are proportional to the decrease recorded on MLR By component. If the anomaly number II was accompanied by earthquakes that did not exceed a Mw=4.6, the last long anomaly (number 7) was accompanied by two earthquakes with Mw >5. So there is a proportional correlation between the By drop and the seismic activity, high drop on By component gives bigger earthquakes. To zoom it the shape of MLR By component anomaly from figure 4, the geomagnetic data from SUA observatory were removed. Also, the vertical component (Bz) was replaced with the temperature measurements. The temperature data are plotted from November till January and the temperature drop is about 2 C°, which not justify the By drop with almost 100 nT.

On November 22, 2014, occurred a crustal earthquake with Mw=5.4 and the depth=40km, but this earthquake was not accompanied by a geomagnetic anomaly. So, it can be said that the anomalies recorded on By horizontal component are determined by processes that occur at high depths. The nature of this processes are probably thermic one, and the drop of By component may be due to a temperature increase of rock stacks [23]. Minerals are magnetically stable at shallow depths with high heat flow regions and, to greater depths in low heat flow areas. [26] proposed that some magnetic anomalies can appear from partially serpentinized ultramafic bodies which have metal alloys as the magnetic source material with a Curie temperature in the range 620° -1100°C. Based on P-wave tomography [27] develop a model of temperature beneath SE-Carpathians and pointed a hotter area west to the Vrancea slab beginning with 75 km depth.

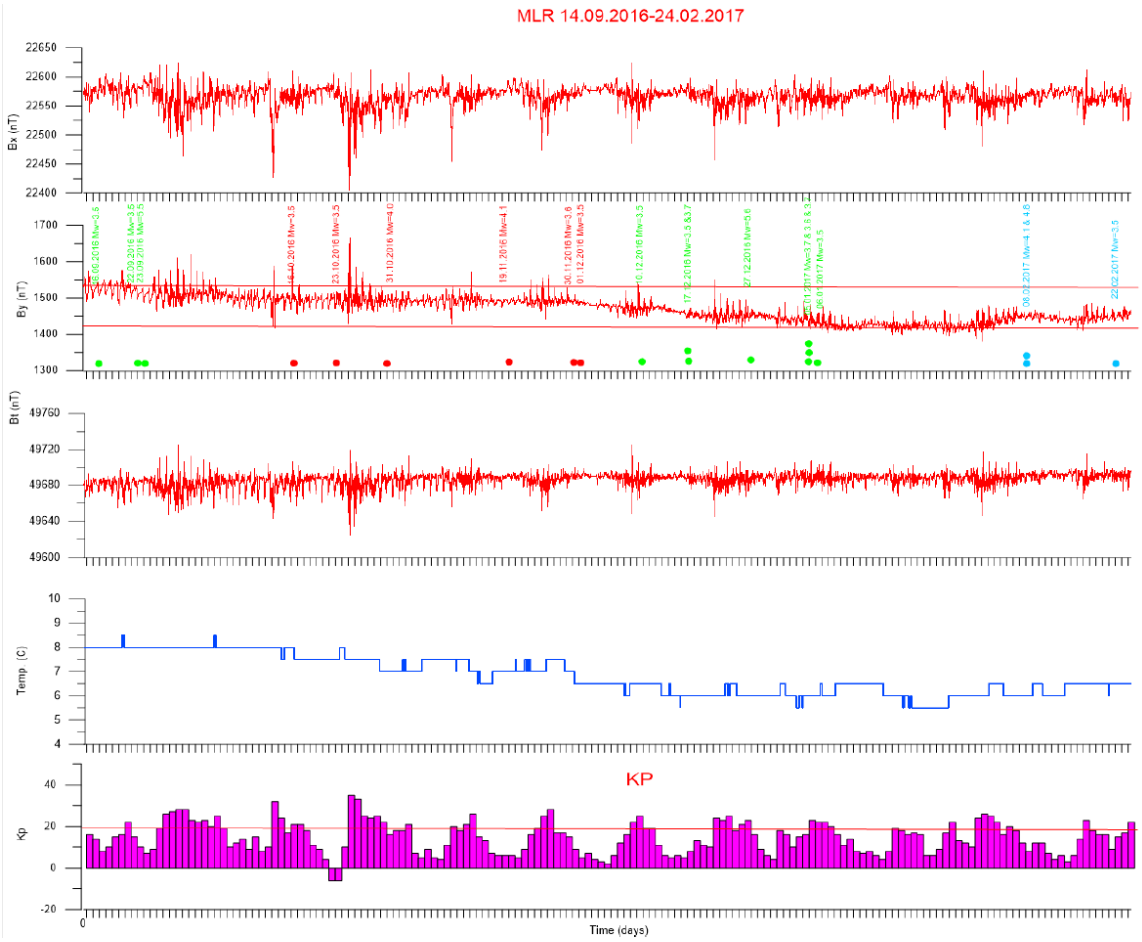

Figure 4. Anomaly number VII on MLR By component and the temperature variation (blue line) from September 2016 till January 2017

Thus, a magnetic signature of these partial meltings or serpentinization reactions can be seen on surface throughout magnetometer measurements on By component. These thermal processes can influence, either directly or indirectly the earthquakes generation by decrease the friction between the slab and hot western neighboring area. So, a drop on magnetic By component measured on MLR magnetometer, located west to slab position (figure 1) could indicate a partial melting or serpentinization of slab western part. The By component return can be explained by a reverse process pointed above (recrystallization) of rock bodies. The presence of anomaly only on By component can be explained due to instrument orientation which gives low readings on By component (1600nT) instead of high readings, like on Bx component (22600nT). An anomaly of 40nT recorded on By component gives an anomaly of 2-3nT the on the horizontal magnetic field ($BH = \sqrt{Bx^2 + By^2}$), which make impossible to highlight a visible variance on BH field.

5. Conclusions

The main purpose of the present study was to evaluate the data obtained after 5 years of geomagnetic surveillance and to obtain more arguments which prove a relationship between local geomagnetic anomalies and the seismicity of Vrancea zone. The whole geomagnetic dataset recorded on MLR and SUA were evaluated and correlated with the solar activity. The following observations were made:

- During 5 years of investigation (2013-2018) there were found 8 anomalies with periods of time between two weeks-one month and six months, where only the By component was affected.

Almost all anomalies were accompanied by three types of earthquakes: i) head-earthquakes, earthquakes which occur during a By component drop; ii) mid-earthquakes which occur when the By component readings stay for a significant period at low values. iii) tail-earthquakes, earthquakes which occur during the By increase;

- The seismic activity from Vrancea zone and the released seismic energy is directly proportional to the sum of By component drop. A significant drop on By component is accompanied with larger earthquakes. Also, when the long anomalies show a step decrease, every step was accompanied by earthquakes.
- This kind of anomaly was not detected during a major crustal earthquake occurrence so there was no evidence that this kind of geomagnetic anomaly is correlated with the crustal earthquakes, placing the disruptive process at high depth.
- The By anomalies presence may be due to thermal processes that affect the rocks in the western vicinity of Vrancea slab. These thermal processes are well highlighted by horizontal By component drop and can be correlated to the intermediate earthquakes.

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