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THE GEOMAGNETIC FIELD VARIATIONS RECORDED IN VRANCEA ZONE DURING 2008–2013 AND THE SEISMIC ENERGY RELEASE

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Abstract. This paper discusses the use of ground magnetometer data to seismogenic zones and presents the relationship between anomalous geomagnetic variations and the occurrence of the intermediate-depth earthquakes. The present paper highlights the geomagnetic anomalies recorded at Muntele Rosu Seismological Observatory (MLR), between 2008 and 2013. To distinguish the global magnetic variations from possible seismo-electromagnetic anomalies presented in a seismic area like Vrancea zone, the data recorded on MLR were analyzed comparatively with the data recorded by the Surlari National Geomagnetic Observatory (SUA) which is located outside the Vrancea zone (150 km South-Est to Vrancea zone). Also, the geomagnetic indices taken from NOAA/Space Weather Prediction Center were plotted in order to separate these global variations caused by solar-terrestrial interaction. To highlight the relation between the geomagnetic anomalies and seismic activity of Vrancea zone, daily energy release, and total energy release calculations for each anomaly were performed.

Key words: geomagnetic anomalies, Vrancea zone, seismic energy release.

1. INTRODUCTION

The Vrancea zone, located at the strongly bent arc of the South-Eastern Carpathians, represents one of the most active seismic zones in Europe. The seismic activity in this area is generated both in the crust with moderate earthquakes ($M_w < 5.6$) and in the mantle at intermediate depth with strong earthquakes. The intermediate-depth earthquakes occur between 60 and 200 km depth in a confined epicentral area of only 40×80 km^2.

The crustal seismicity of Vrancea zone is shifted to the East and is concentrated in the Eastern Carpathians foredeep region (Focsani Basin) [1]. It reflects the recent deformations along the major faults developed in the Carpathians foredeep region, like Intramoesian fault to South and Peceneaga-Camena and Trotus faults to the

North [2]. The crustal earthquakes are affected by an extensional regime with normal and strike-slip faulting [3]. The seismic activity in the crustal domain is rare and diffuse and consists only in moderate-magnitude earthquakes [4].

The intermediate-depth seismicity of the Vrancea zone occurs in two active segments: the upper one, located at 90–100 km depth, and the lower one located at 130–180 km depth. The major Vrancea events ($M > 7$) are triggered alternatively in one and the other segment. The associated aftershocks are limited to one segment or the other, while the b slope of the frequency-magnitude distribution of the aftershocks seems to be smaller in the upper part of the subducting lithosphere (0.43 and 0.56 *versus* 0.68, respectively) [5]. The distribution of b value is a useful tool to distinguish the seismic zones with a high concentration of stress [6].

Intermediate-depth (60–300 km) earthquakes occur along convergent plate margins, but their causes remain unclear. Because of the high pressure at intermediate depths and the lack of pore pressure, the brittle failure is unlikely to happen at intermediate depths. Using only the mechanisms which affect the crustal earthquakes is not enough to explain the occurrence of intermediate-depth earthquakes and the brittle failure should be accompanied by a ductile deformation [7, 8].

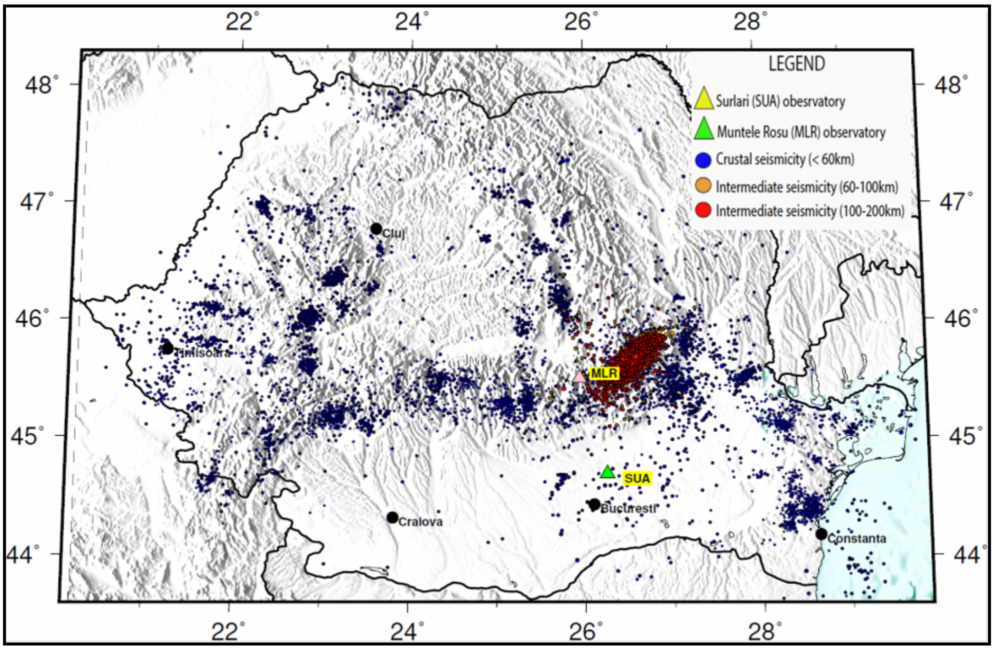

Fig. 1 – Crustal seismicity (blue dots) and intermediate seismicity (orange and red dots) of Romania during 2008–2013 and the location of geomagnetic observers included in the study (Color online).

Anomalous geomagnetic variations were observed prior to earthquake occurrences, but in many cases seismo-tectonic nature of these variations was strongly debated. In previous studies, the geomagnetic storms were falsely identified as earthquake precursors. Other authors, like [9] showed that these geomagnetic anomalies identified as precursory signals were induced by the increase of solar activity. A long-term anomaly was noticed prior to Molise Earthquakes at L'Aquila station situated at 140 km away from the epicenter. The anomaly was visible on the H component (North-South component) and appeared with four months prior to two large earthquakes with $M_w = 5.9$ in 2002 [10]. The same type of anomaly was also noticed in the eastern part of Taiwan prior to the 2009 Hualien earthquake that occurred on December 19 with $M_w = 6.4$ [11].

The investigation in the present paper focused on five years of geomagnetic monitoring from 2008 to 2013 supplements the previous study of [12] dealing with the time interval 2013–2018. The relationship between the geomagnetic field and the seismicity in Vrancea zone observed by [12] follows some patterns which must be proved. Like the previous paper, the daily seismic energy release was plotted alongside the identified geomagnetic anomalies to see how the seismicity is distributed. Additionally, to confirm the relation between the decrease of geomagnetic field recorded on B_y component and the seismic activity during the anomaly period (Table 1), the total energy release was calculated per each anomaly. More than that, the total energy release per time ratio was made in order to minimize the time effect on cumulated seismic energy.

Table 1

The anomalies recorded at MLR station during 2008–2013 and the most significant earthquakes occurred in this time interval

Nr.	Date	Period (days)	By decrease	Strongest eq.
1	01.09.2008-31.05.2009	273	110 nT	5.4 Mw
2	01.10.2009-30.04.2010	212	100 nT	4.7 Mw
3	01.10.2010-31.03.2011	182	50 nT	4.4 Mw
4	01.10.2011-31.05.2010	244	100 nT	4.8 Mw
5	01.10.2012-31.05.2013	243	75 nT	4.4 Mw

2. DATA AND METHODS

One minute averaged data of the all three magnetic components from MLR station (45.49° N and 25.94° E) and SUA station (44.67° N and 26.25° E) were compared with K_p index taken from NOA/SWPC (National Oceanic and Atmospheric Administration/Space weather prediction center) in order to discriminate the geomagnetic storms from the possible seismotectonic anomalies. To characterize the magnitude of geomagnetic storms and to distinguish the anomaly generated by them, the K_p-index was represented as a daily sum. Strong geomagnetic storms are well defined when the sum of K_p indices reaches the value of 20. The MLR station is located inside Vrancea seismogenic zone and is part of the National Institute of Earth

Physics. For better separation of global geomagnetic variations, besides K_p-index we used as remote data sets the geomagnetic data taken from SUA (Surlari) part of international network INTERMAGNET. Overlapping the two data sets makes it possible to distinguish the local geomagnetic anomalies from global anomalies.

The seismicity was plotted alongside every anomaly using seismic bulletins taken from "Romplus", the seismic catalogue developed by the National Institute for Earth Physics [13]. There was used a colour code (Fig. 2) chart to represent the seismicity distribution. The green dots represent the earthquakes that are generated when the horizontal component B_y of magnetic field decreases (head-earthquakes). Inside anomalies could be distinguished periods when B_y component remains steady and the earthquakes generated in these periods were plotted with red dots (middle-earthquakes). Blue dots have plotted the earthquakes that are generated when the horizontal component B_y increase (tail-earthquakes).

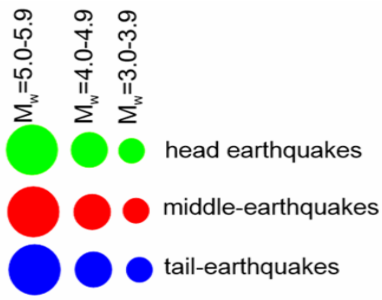

Fig. 2 – Color code used to describe the seismicity (Color online).

During 2011, inside MLR tunnel there were performed many maintenance operations which artificially induced jumps recorded on all magnetic components (Fig. 3). These jumps mess up the entire magnetogram and make it impossible to read any anomalies. To make all anomalies visible, these jumps were removed and the magnetogram was re-plotted.

Seismic energy release in Vrancea zone was calculated only for intermediate-depth earthquakes with $M_w > 3$. The small earthquakes with $M_w < 3$ were taken as background seismicity that releases almost constant the stress. To calculate the energy released daily, we used the Gutenberg-Richter magnitude-energy relation (1956) related the seismic energy, E_s, to surface-wave magnitude (M_s), and body wave magnitude (mB) by the next equations:

$$\log E = 1.5\, M_s + 11.8 \tag{1}$$

$$\log E = 2.4\, \text{mB} + 5.8. \tag{2}$$

Since the M_s scale saturates for large earthquakes, [14] used in the Gutenberg-Richter magnitude-energy relation a new magnitude scale (M_w) resulted from the seismic moment (M_o) parameter that measures the overall deformation in the source (eq. 3).

$$\log E = 1.5\, M_w + 11.8. \tag{3}$$

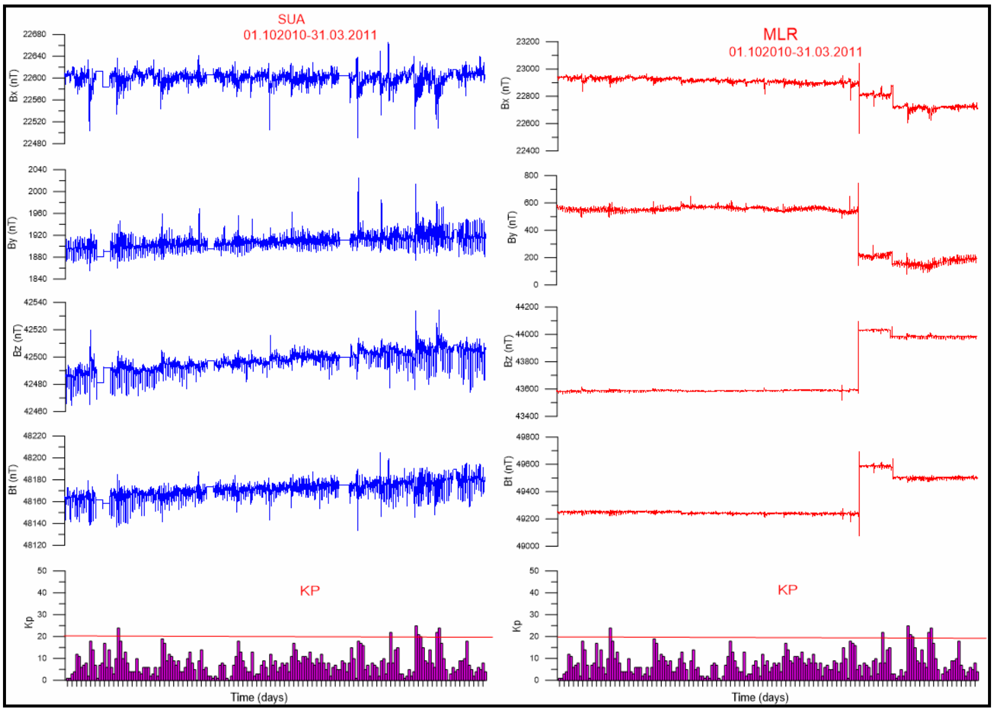

Fig. 3 – The comparison of the B_y-component recorded SUA station and B_y-component recorded MLR station and the jumps induced by the maintenance operations.

Furthermore, for each anomaly the total energy released was calculated and because the period of each anomaly wasn't equal at all, an energy release-to-time ratio is very useful to characterize the link between geomagnetic anomaly magnitude and the seismicity of Vrancea zone.

3. RESULTS

In order to detect the geomagnetic anomalies recorded during 2008–2013 related to Vrancea seismic activity, the geomagnetic data sets are analysed at MLR station in comparison with data sets recorded by SUA station that were used as remote data sets. It was noticed that the geomagnetic behavior recorded at Muntele Rosu (MLR) does not look similar to the geomagnetic field recorded at Surlari (SUA) observatory. The anomalies recorded at MLR station are seasonal, being visible mostly on the horizontal component B_y, but the decrease recorded on B_y component variate from year to year as seismicity too. That is why is interesting to correlate the energy released for each recorded anomaly in order to see if there exist a link between the geomagnetic behavior recorded in a seismic zone and the seismic activity.

I) From September 2008 to May 2009 (I), the horizontal component B_y of magnetic field variates with about 110 nT (Fig. 4). During this period, a moderate earthquake ($M_w = 5.4$) occurred on April 25 2009 at 109 km depth and this is the biggest event in the study period (big dots). Usually, this type of anomaly is visible only on B_y component, but in this anomaly, it was observed that the vertical component B_z is also affected by a small increase which lasts approximatively 120 days (Fig. 4). This behaviour of B_z component which not follow the pattern could be an indicator for earthquakes with M_w greater than 5 but must be proved with more examples.

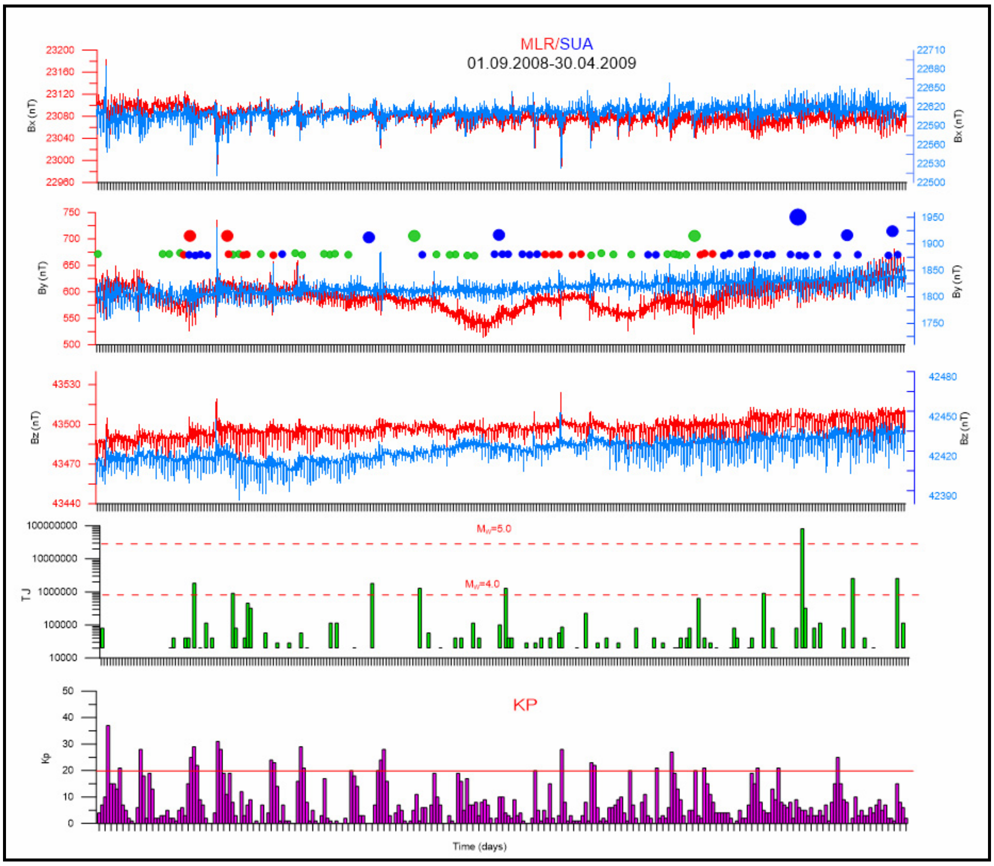

Fig. 4 – Representation of anomaly I (2008–2009) recorded at MLR (red magnetogram) relative to SUA recording (blue line) alongside with the K_p indices (pink histograms), the seismicity (colored dots), and the daily released seismic energy (green histogram) (Color online).

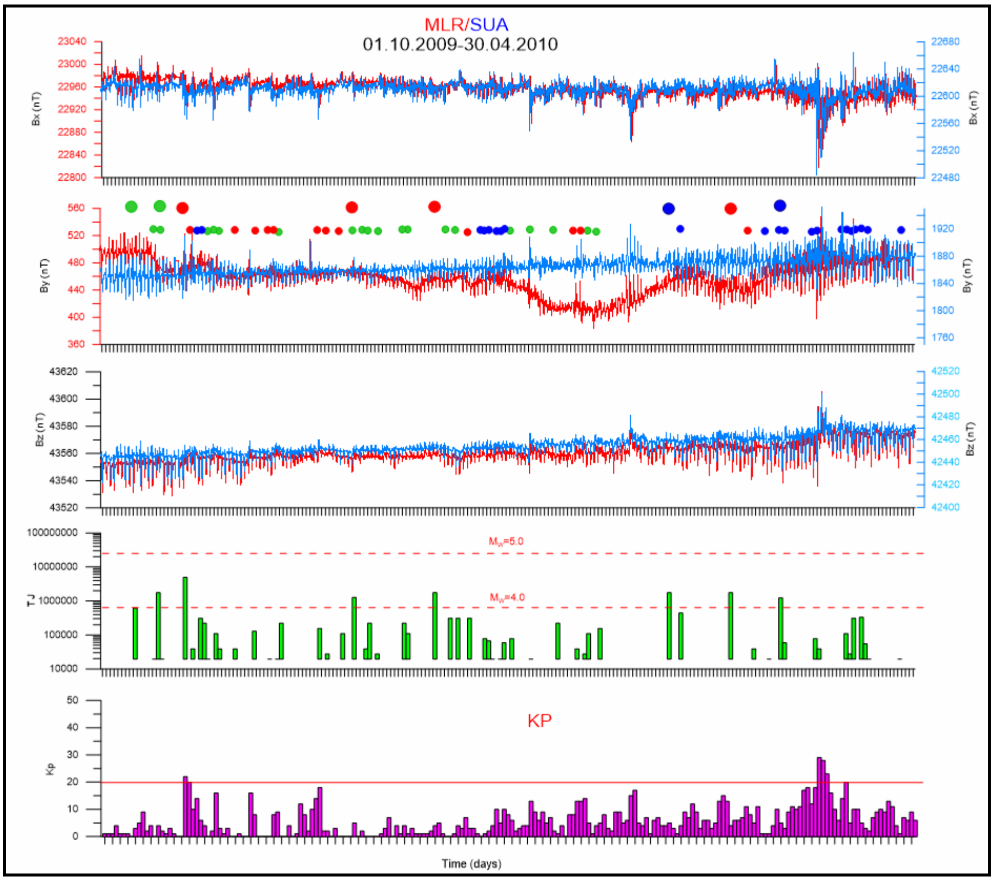

Fig. 5 – Representation of anomaly II (2009–2010) recorded at MLR (red magnetogram) relative to SUA recording (blue line) alongside with the K_p indices (pink histograms), the seismicity (colored dots), and the daily released seismic energy (green histogram) (Color online).

II) The anomaly II (Fig. 5) ilustrates almost the same decrease (100 nT) recorded on B_y component as anomaly I. Seismicity distribution looks similar except the lack of earthquakes with $M_w > 5$. The representations of magnetic components (B_z and B_z) recorded at MLR (red) look similar to SUA (blue).

III) The anomaly which last from October 2010 and March 2011 (Fig. 6) was plotted after major correction of the induced pulses that affected all three axes of the magnetic field (Fig. 3). In this period, the seismic activity was the lowest and were recorded only three events with $M_w > 4$. The decrease recorded on B_y component was direct proportional with the seismic energy release around 50 nT.

IV) Figure 7 illustrates the anomaly number IV that looks very similar to anomaly II, having the same decrease recorded on B_y component (100 nT). The energy released over these two anomalies were pretty similar, with 8 earthquakes with M_w greater or equal than 4 for anomaly II (medium size dots) and 7 earthquakes for the anomaly IV.

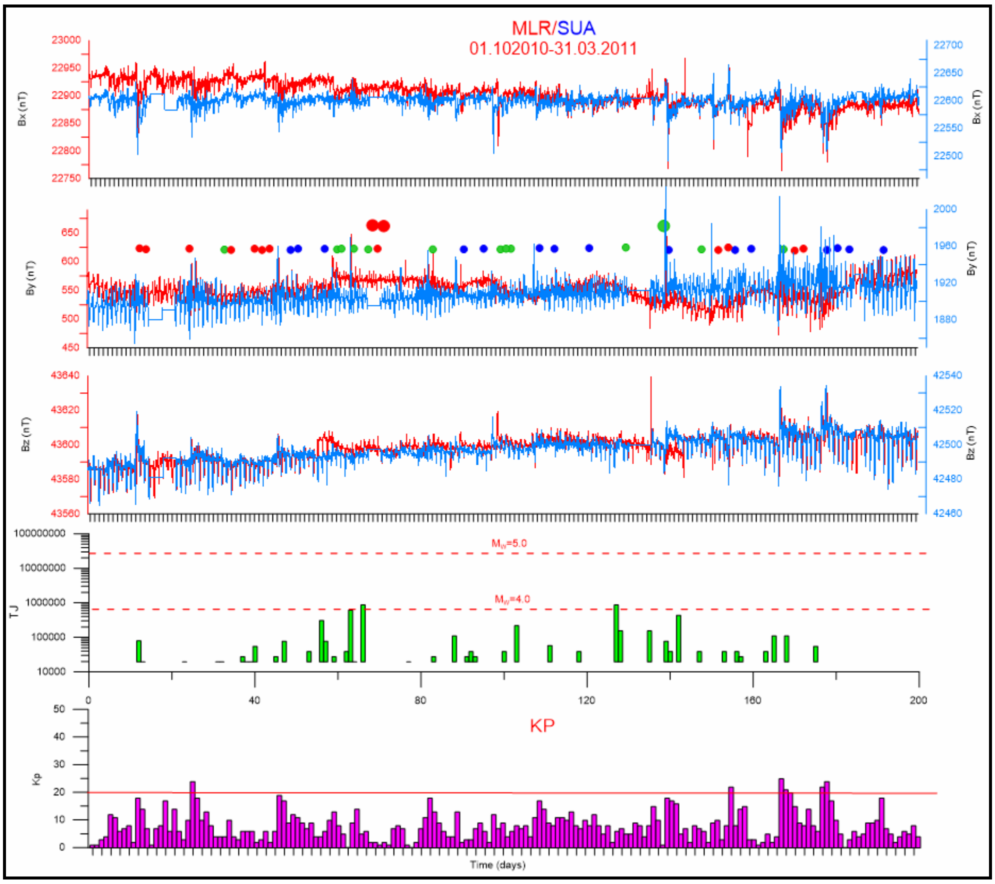

Fig. 6 – Representation of anomaly III (2010–2011) recorded at MLR (red magnetogram) alongside with the K_p indices (pink histograms), the seismicity (colored dots), and the daily released seismic energy (green histogram) (Color online).

V) The last anomaly present in this study is represented by the anomaly V (Fig. 8). This anomaly has a decrease recorded on B_y component of nT and it is the second smallest anomaly after anomaly III. The seismic energy released during this anomaly is similar to anomaly III with 4 earthquakes with M_w greater or equal with 4.

To demonstrate the proportionality between the decrease recorded on B_y component and the seismic energy released, the total energy release was calculated for each anomaly (Fig. 9). The anomalies presented in this study have different periods which may vary between 182 and 273 days. So, between the longest and shortest anomaly exist more than 100 days, days which count in total seismic energy calculation. The small anomalies could show obvious less energy released than long anomalies. To avoid that, an energy release-to-time ratio was done.

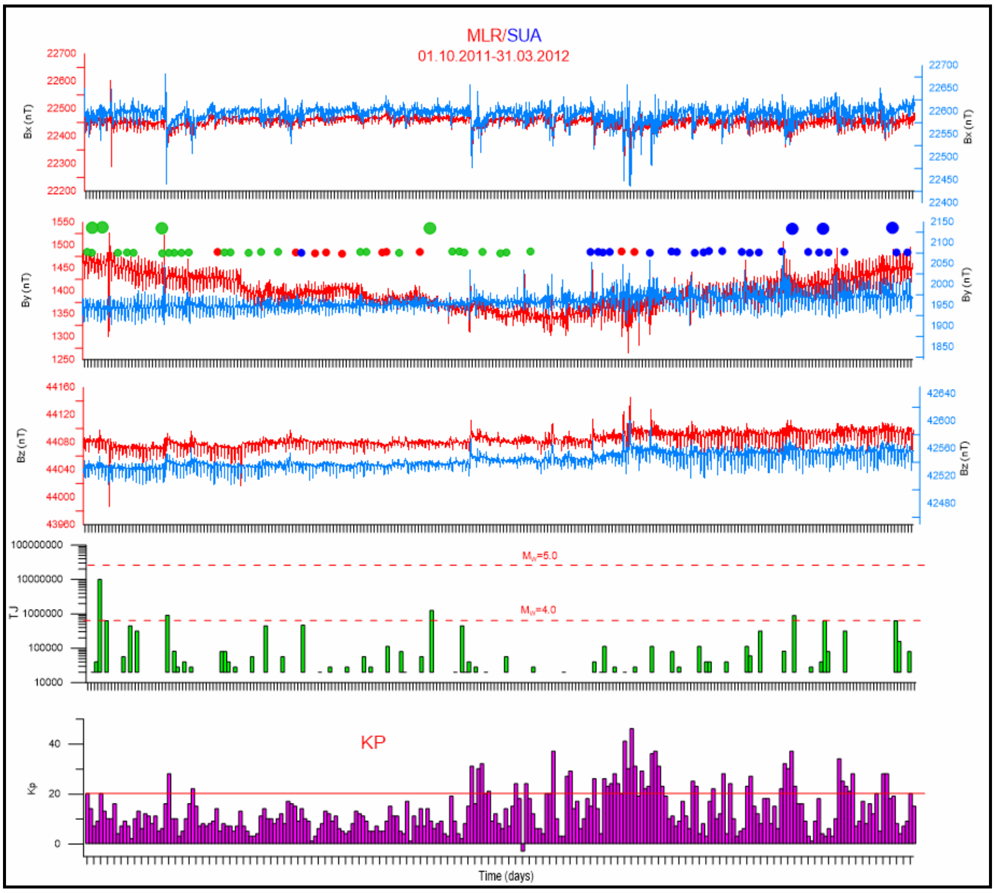

Fig. 7 – Representation of anomaly IV (2011–2012) recorded at MLR (red magnetogram) relative to SUA recording (blue line) alongside with the K_p indices (pink histograms), the seismicity (colored dots), and the daily released seismic energy (green histogram) (Color online).

As we can see in Fig. 9, the decrease recorded on B_y component for anomaly III and V is low as the total seismic energy released. Unfortunately for the anomalies I, II, and IV, the decrease recorded on B_y component were similar, 100 nT for II and IV, and 110 nT for anomaly I. The energy released during anomaly I was significantly bigger and was released during $M_w = 5.4$ earthquake. Until now, big decreases on B_y are accompanied by 7–8 earthquakes with magnitude greater or equal than 4 but smaller than 5. The small anomalies (III and V) are accompanied by 3–4 earthquakes with a magnitude greater or equal than 4 but smaller than 5.

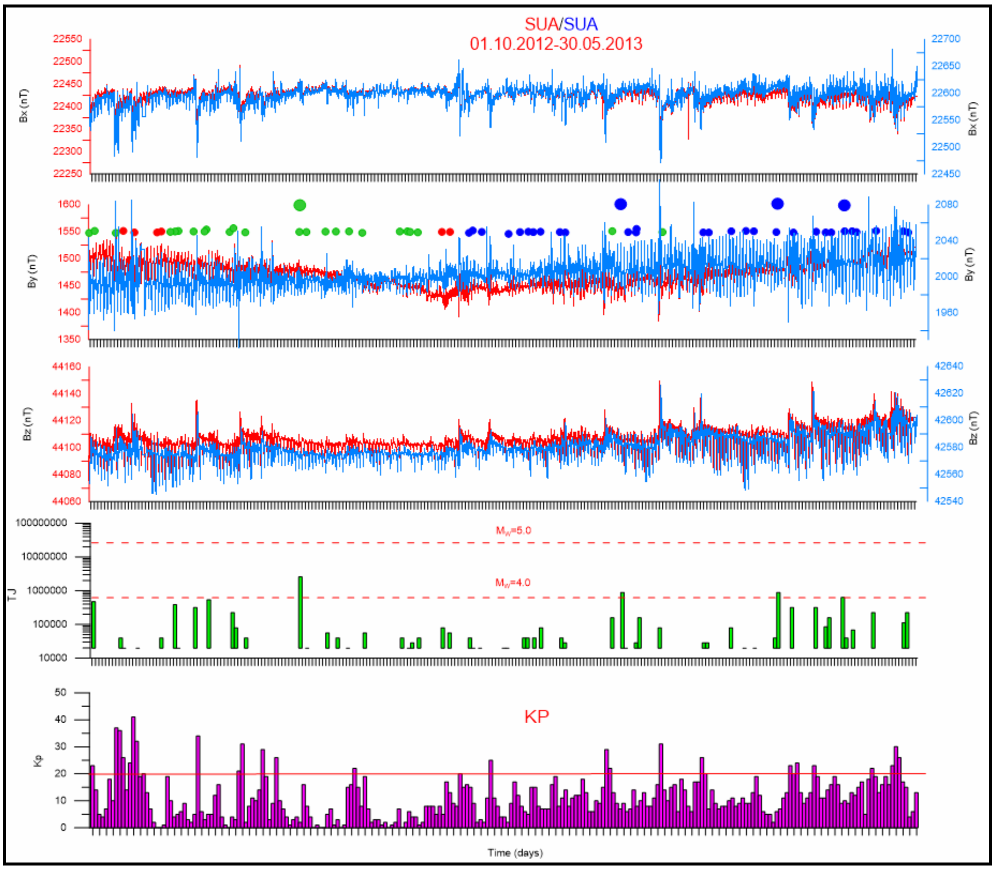

Fig. 8 – Representation of anomaly V (2012–2013) recorded at MLR (red magnetogram) relative to SUA recording (blue line) alongside with the K_p indices (pink histograms), the seismicity (colored dots), and the daily released seismic energy (green histogram) (Color online).

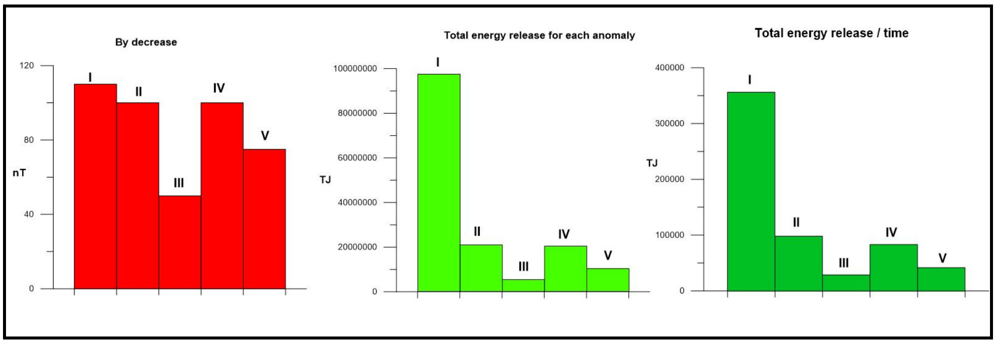

Fig. 9 – Anomalous decrease on B_y component recorded on every anomaly (red histogram), total seismic energy release (light green histogram) and the average of seismic energy (total energy release/time, dark green histogram).

4. CONCLUSION AND DISCUSSION

The main goal of this study is to investigate the geomagnetic behavior recorded in the Vrancea seismic area and its correlation with the seismic energy release. Even if the period during which the study was conducted was not a seismically active one, the seismic energy release for each anomaly reveals an interesting link between geomagnetic variations and Vrancea seismicity.

Big drops on the horizontal magnetic component are directly proportional to the released energy. Anomalies I, II, and IV which present a high decrease of B_y has big energy released, and anomalies III and V with low B_y decrease have less energy released.

The moderate earthquake ($M_w = 5.4$) that occurred on April 25 2009 was accompanied by a decrease of 110 nT recorded on horizontal B_y component but more than that, it was observed that the vertical component B_z is also affected by a small increase which lasts approximatively 120 days (Fig. 2).

Compared to the previous article, this study brings new statistical representations of the degree of B_y component decrease, the total energy release, and the energy release-to-time ratio for each anomaly.

Anomalous geomagnetic variations seem to precede earthquakes occurrences, but the interconnection between geomagnetic and seismicity changes is not simple to interpret and the nature of these variations is strongly debated. Also, the generation mechanism of the observed anomalous variation is not fully understood. Yen *et al.* [15] interpreted these anomalies as a result of stress accumulation which will lead to an enhancement of the conductivity structure of the lithosphere. This variation could be also related to underground electric currents generated along the fault plane [16, 17]. Another mechanism involves changes in magnetic susceptibility, conductivity, remnant and induced magnetization due to the piezomagnetic effect [18]. The GPS observations are used to determine the areas affected by stress, but also how these areas have evolved due to stress accumulation [19]. Additionally, like infrasound equipment, GPS stations can measure coseismic signals of earthquakes [20]. A tri-axial magnetometer is very sensitive to any type of displacement and the increase or decrease recorded on B_y component could be related to stress accumulation.

The intermediate-depth seismicity of the Vrancea zone occurs in two active segments, located at different depths and the seismic energy released during the geomagnetic anomaly depends on which segment is more active. Even if the anomalies are similar, the seismic activity could be different and depend on which seismic segment the major events occur. A higher seismicity increase in the upper segment is correlated with a given geomagnetic anomaly, while a significant lower seismicity increase in the deeper segment is associated to a similar geomagnetic anomaly [21].

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