CORRELATIONS BETWEEN GEOMAGNETIC ANOMALIES RECORDED AT MUNTELE ROSU SEISMIC OBSERVATORY (ROMANIA) AND SEISMICITY OF VRANCEA ZONE

A. MIHAI1,2, I.A. MOLDOVAN1, V.E. TOADER1, M. RADULIAN1, A.O. PLACINTA1

1 National Institute for Earth Physics, RO-077825, Calugareni st, no 12, Magurele, Ilfov, Romania
2 Faculty of Physics, University of Bucharest, Atomistilor 405, POB MG-11, RO-077125, Bucharest-Magurele, Romania
E-mail: mihai.a.andrei@gmail.com

Received October 4, 2018

Abstract. In the present paper, a relationship between geomagnetic anomalies recorded at one magnetometer located inside Vrancea seismogenic zone and the occurrence of intermediate earthquakes is examined. To better distinguish the regional anomalies from global geomagnetic storms, the datasets were correlated with the geomagnetic indices taken from NOAA/Space Weather Prediction Center. During five years of investigations (2013–2018), three intermediate depth earthquakes with a moment magnitude $M_w$ larger than 5.0 occurred in the Vrancea zone and were accompanied by significant anomalies on the E-W component of the local geomagnetic field ($B_y$) measured at Muntele Rosu (MLR) Observatory. The anomalies recorded at MLR were also analyzed along with the seismic energy distribution, providing good opportunity to distinguish the anomaly morphology, and were correlated with the radon emissions and temperature variations, during the detector operating time, in 2016.

Key words: geomagnetic anomalies, intermediate earthquakes, Vrancea zone.

1. INTRODUCTION

The Vrancea region is one of the most active seismic zones in Europe and it is known for its strong intermediate-depth earthquakes. This area is a complex seismic region situated at the convergence of three major tectonic units: (i) East European Craton to the Northeast, (ii) Moesian plate to the South and (iii) the younger Intra-Alpine plates (Tisza-Dacia blocks) to the West.

The Vrancea seismogenic zone is characterized by both crustal and intermediate earthquakes. Crustal activity (0–40 km) in Vrancea zone is weak, with an activity rate of 0.514, for the earthquake with $M_w > 3$ [1], while the intermediate activity is high, with an activity rate of 100.1 events per year for earthquakes with $M_w > 3$.

The present paper comes to complete the study of [2] with the radon emissions data and in correlation with intermediate depth Vrancea seismicity (Table 1) and
the geomagnetic anomalies recorded on MLR observatory, during a five years period 1.01.2013–1.01.2018. More than that, the released seismic energy was computed during the geomagnetic anomalies in order to see if there exists a quantitative link between anomaly drop and seismic activity. If in the previous study were used the geomagnetic data sets to demonstrate a relation between the drop of E-W horizontal magnetic ($B_y$) component and the seismic activity, now will be used extra-data and to obtain a more reliable earthquake forecasting.

Table 1

<table>
<thead>
<tr>
<th>No</th>
<th>Data/hour</th>
<th>Lat (N)</th>
<th>Long (E)</th>
<th>$H$ (km)</th>
<th>$M_w$</th>
<th>$D_{MLR}$ (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eq. 1</td>
<td>06.10.2013/01:37</td>
<td>45.67</td>
<td>26.58</td>
<td>135.1</td>
<td>5.2</td>
<td>50</td>
</tr>
<tr>
<td>Eq. 2</td>
<td>23.09.2016/23:11</td>
<td>45.71</td>
<td>26.61</td>
<td>92</td>
<td>5.5</td>
<td>56</td>
</tr>
<tr>
<td>Eq. 3</td>
<td>27.12.2016/23:20</td>
<td>45.71</td>
<td>26.60</td>
<td>96.9</td>
<td>5.6</td>
<td>55</td>
</tr>
</tbody>
</table>

Anomalous geomagnetic anomalies were observed prior to earthquakes occurrences [3, 4, 5, 6, 7]. A pair of magnetometers station located in Peru recorded some unipolar pulses prior to earthquakes [8], but these unipolar pulses looks similar to pulses created by lightning phenomena. One proposed source for these pulses is the break-up of peroxy defects as result of an increase of tectonic stress. Silicate minerals can form peroxy defects that are typically introduced through the incorporation of H$_2$O into anhydrous minerals, and these peroxy defects act like a source of electron and positive holes, generates currents that can disturb the local magnetic field. Piezomagnetic phenomena could also create anomalous signals as a response of crustal deformation applied to ferromagnetic minerals [9]. A long-term anomaly variation was detected before and during the Molise Earthquakes at L’Aquila station situated 140 km away from epicenter [5]. This anomaly shows a decrease of ~ 40 nT only on $H$ component (North-South component) and looks very similar to the anomalies recorded in Vrancea [2, 10]. There are two similarities and two differences regarding these two types of anomalies, both of them present a drop of one magnetic horizontal component and also the morphology of anomalies looks similar. The main difference between two cases is represented by the depth of earthquakes that accompanied the anomalies. The L’Aquila anomaly occurs prior to crustal events and for Vrancea zone, only the intermediate earthquakes are accompanied by anomalies [2]. The last difference is represented by the distance between magnetic observatories and seismic zones, which is significantly smaller for Vrancea case.

Other papers [11] demonstrated that rocks with significant amounts of mafic/ultramafic composition may account for some magnetic anomalies. To see the magnetic susceptibility variance with temperature the unweathered samples were heated and then cooled in a normal atmosphere (oxygenated atmosphere) but also in an argon atmosphere to simulate the deep earth conditions. It was noticed that
susceptibility decrease drastically when the Currie temperature was reached. During the cooling process, the samples take back their magnetic properties but not at the same values.

Most rocks contain a small concentration of radon, and there are reports of spikes in radon concentrations prior to major earthquakes due to pre-seismic stress and rocks fracturing which releases it. Radon concentration was monitored by [12] in five stations and noticed some variations in radon concentration before three moderate earthquakes, but the cause of this variations may be related to weather changes: rainfall, atmospheric pressure, temperature, humidity, wind, groundwater.

2. DATA AND EQUIPMENT

Starting with 1996, the Romanian Seismic Network was improved and extended with a Multidisciplinary Network designed for geophysical/geochemical and atmospheric field parameter monitoring and event detection, network that includes recordings of magneto-telluric and electric-electrostatic field, ULF waves, air ionization, radon and CO, infrasound, etc. [6, 7].

The Muntele Rosu (MLR) observatory location, near to Western wedge of Vrancea seismogenic zone provides a good opportunity to study the local geomagnetic anomalies for the 2013–2018 period. All five years of data were taken from Muntele Rosu (MLR) observatory and compared with geomagnetic data from Surlari (SUA) to distinguish the local geomagnetic data. The magnetometer from MLR was installed inside a tunnel to avoid the temperature variations of the instruments. The location also provides a good sealing properties for others anthropic effects like railways, roads, buildings etc. Throughout 2016 year, a radon detector was installed in the tunnel and gives us the opportunity to compare the radon readings with geomagnetic anomalies associated to two of the largest earthquakes occurred during the study period (Eq. 2 and Eq. 3 from Table 1).

In this study were used the following data:

(i) The geomagnetic data from 2013–2018 were taken from Surlari (SUA) part of international network INTERMAGNET, and from Muntele Rosu (MLR) part of National Institute for Earth Physics;

(ii) The seismic bulletins used in this study were taken from “Romplus” seismic catalog developed by National Institute for Earth Physics;

(iii) The planetary K-index used to characterize the magnitude of geomagnetic storms were taken from the National Oceanic and Atmospheric Administration (NOAA)/ Space Weather Prediction Center;

(iv) Temperature and radon measurements used in this study cover a year period length and provide to the present paper only one anomaly associated with the largest earthquakes (Eq. 2 and Eq. 3 from Table 1) recorded during 2016.

The MLR magnetometer is a three-axis fluxgate type developed by Bartington Instruments with a measuring range of +/− 70µT. The magnetic field sensor is
sensitivity to small variations with a band larger than 2 kHz but up to 3 kHz and 15 pT rms/Hz\(^{1/2}\) noise. Same company designed the data-logger acquisition which have six channels and a resolution of 24-bits. The sampling of Data-logger acquisition is controlled by a software program and displays the average of 12 samples recorded in one minute. For radon measurements were used Radon Scout produced by Sarad company, with a measurements range 0–10 Mbq/m\(^3\) and a sensitivity of 5.52 cph/ (kB/m\(^3\)). The instrument uses the X-ray spectroscopy with PIN diodes and has an integration interval of 1 hour or to 3 hours.

Seismic energy calculation was made by using a software tool called “Report energy” [13] (LabVIEW program) which calculate the cumulative energy (Fig. 1) using the bulletins generated by Antelope software (http://ds.iris.edu/ds/nodes/dmc/software/downloads/Antelope/) as input parameters.

Firstly, it is necessary to set parameters like: (a) seismic area, (b) time interval, (c) depth interval, (d) magnitude interval and (e) the location path of seismic

![Fig. 1 – Cumulative seismic energy evolution for Vrancea zone from 29.11.2012 to 02.05.2018.](image)

Firstly, it is necessary to set parameters like: (a) seismic area, (b) time interval, (c) depth interval, (d) magnitude interval and (e) the location path of seismic
bulletins. Each earthquake located inside the seismic area is converted in energy using Equation (1) and cumulated with the seismic energy of all previous days from the time interval. Equation (2) is necessary to obtain $M_s$ (Surface magnitude) using the $M_l$ (Local magnitude) magnitudes generated by Antelope program. This program was previously used by [13] to separate the regional/local seismic areas and the precursor situations using the earthquake energy. The cumulative energy graphs are used to compare the geomagnetic anomalies decrease with the earthquake energy release. Thus, alongside cumulative seismic energy we also plot the graphs with daily energy release using the Eq. (3)

\[
\log (E) = 11.8 + 1.5 \cdot M_s \\
M_l = -2.14 + 1.43 \cdot M_l - 0.018 \cdot M_l^2 \\
\log (E) = 11.8 + 1.5 \cdot M_l
\]

The global magnetic variations represent the main phenomena that disturb the magnetic measurements on sites. These variations are represented by the solar storms which creates an increase in amplitude and frequency of geomagnetic representation. To avoid the false identification of these solar storms as seismo-magnetic anomalies, the representation of geomagnetic field was represented alongside the daily sum of $K_p$ indices. For graphical reasons, the $K_p$ indices measured at every 3 hours were represented as daily sum, so the solar storms were well defined when the sum of $K_p$ indices exceed the value 20. The quantity of solar radiation increases during summer time and decrease during winter, these phenomena make the diurnal variation uneven. Creating a lunar representation of geomagnetic field on MLR observatory was helpful to note that big diurnal variation can influence the detection of small anomalies.

The missing data sets recorded at MLR observatory were corrected automatically using a LabVIEW program which replaces the missing data with the last good value. Missing data sets recorded at SUA (INTERMAGNET Observatory) were replaced with the number “99999” to highlight the malfunction time of instruments. For graphical reasons, this value was also replaced with the last good recorded value.

Personnel visits or maintenance operations at the location could also generate false variations in geomagnetic filed. This kind of anomalies lasts only a short time and are visible on all magnetic components and bring with them a significant increase of magnetic field. These anthropic anomalies were removed using a LabVIEW program.

3. RESULTS AND DISCUSSION

To highlight the local geomagnetic anomalies recorded at MLR observatory, the data from Surlari Observatory (SUA) were also plotted, as reference data. During the studied 5 years period, [2] has centralized 8 anomalies in Table 2,
together with seismic sequences that accompanied these anomalies, seismological parameters, $K_p$ indices, magnetic component affected, shape and $B_y$ component drop evolution. The daily sum of $K_p$ indices was plotted alongside geomagnetic data, to avoid the false identification of solar storms as seismo-magnetic anomalies. As shown in Fig. 2, the presence of solar storms is pointed when the sum of $K_p$ indices reach the redline. On geomagnetic representations, the solar storms are accompanied by an increase in frequency and amplitude.

![Graph](image)

**Fig. 2** – (Color online). Anomaly number VI (Table 2) on MLR $B_y$ component and the earthquakes that occurred during this anomaly and the daily representation of $K_p$ indices.

Figure 2 presents the shortest anomaly (VI from Table 2), where the magnetic field on horizontal component $B_x$ and on the vertical component $B_z$, looks similar for both observatories MLR and SUA. The only one notable variation is on horizontal component, $B_y$. Associated with geomagnetic anomalies number I, II, III, VI and VII from Table 2, in Figs. 2, 3 and 4 it is also illustrated the seismicity, represented by colored bullets, with the same color as in Table 2. With green bullets are represented the earthquakes that occurred on the fall of the $B_y$ magnetic component and are called generic “head-earthquakes”. After the $B_y$ component drop, inside geomagnetic morphology, it could be recognized a period of stagnation of $B_y$ component. This period could also be accompanied by earthquakes, named “middle-earthquakes (red bullets). The “tail-earthquakes” are the last earthquakes and are associated with a return of $B_y$ magnetic field component. As can be seen in Table 2, the anomalies could be short period (I, III, IV, V, VI anomalies) and long period (II, VII anomalies).
The seismic sequences (I–VII) with seismological parameters and $K_p$ indices of all Vrancea earthquakes of magnitude $M_w > 3$ that occurred alongside the geomagnetic anomalies [2]
During the five years of observation, four earthquakes with \(M_w\) larger than 5 occurred in Vrancea zone. Three of them were intermediate earthquakes (Eq. 1–Eq. 3, in Table 1) and were accompanied by \(B_y\) component drop. The crustal earthquake with \(M_w = 5.4\) occurred on November 22, 2014, was not accompanied by a geomagnetic anomaly. So, the anomalies related to MLR, \(B_y\) horizontal component are related to deep processes that occurred at high depths [2]. The cumulative energy represented in Fig. 1 shows an increase in steps when a major earthquake occurs. Four major jumps are visible from 2013 till the 2018 year. The main reason for these jumps are the occurrence of earthquakes with \(M_w > 5\), and the jumps are missing for the 2015 and 2017 years, years with a low seismic activity.

![Figure 3](image)

**Fig. 3 – (Color online).** Representation of two short-period geomagnetic anomalies (anomaly number I and III) recorded on \(B_y\) component alongside the daily seismic energy (green histograms), and \(K_p\) indices (pink histograms).

Figure 3 illustrates the seismicity (colored dots), the daily sum of \(K_p\) indices and daily energy release for 2 short period anomalies taken from Table 2. Anomalies I and III show the same decrease on \(B_y\) component at around 40 nT, but the seismic activity highlighted by daily energy representation look different. In anomaly number I, the energy was released mostly through a single larger earthquake (Eq. 1, \(M_w = 5.2\)), surrounded by gaps in seismicity. Instead, the anomaly number III shows a more homogeneous seismicity, with no significant gaps and a large number of smaller earthquakes.

The same situation is also noticeable for long-term anomalies (Fig. 4). Anomaly number II shows a decrease of ~40 Nt recorded on \(B_y\) component and the
anomaly number VII shows a greater drop of $B_y$ component (90 nT). Also, the seismicity and the energy release during these anomalies look different, with greater seismic activity for the anomaly number 7. Studying the seismic energy, the drop on $B_y$ component is proportional with the seismic activity. Using the daily seismic energy and the cumulative seismic energy alongside geomagnetic data during anomalies presence could help to make an approximative idea about how earthquakes grow.

![Fig. 4 – Representation of two long-period geomagnetic anomalies (anomaly number II and VII) recorded on $B_y$ component alongside with the $K_p$ indices (pink histograms) and the daily seismic energy (green histograms).](image)

Radon emissions recorded at MLR observatory show no clear relation with medium size ($M_w < 6.0$) earthquake occurrence (Fig. 5). Radon emissions look to be related more to other factors like humidity, raining periods and groundwater circulation through the tunnel. It is known that radon ascends to the surface mainly through cracks and faults, on short distances by diffusion and long distances by advection (dissolved in water or carrier gases) [14]. The main uncertainty for Vrancea zone, remains the migration time and the migration paths from the earthquake focus to the surface. The anomalies presence only on $B_y$ component can be explained due to instrument setup, which gives low readings on $B_y$ component (1600 nT) and makes the anomaly visible. For example, an anomaly with 40 nT drop on $B_y$ gives on the total horizontal field a comparative anomaly of 2–3 nT, which make impossible to see a variance on total horizontal field. The anomalies recorded on MLR observatory...
could be explained probably by a magnetic signature of serpentinization reactions or partial melts of rocks bodies from deep depth (intermediate depth) [2].

**4. CONCLUSION**

The main propose of this study was to correlate the geomagnetic anomalies recorded at MLR observatory in the last 5 years with seismicity, seismic energy, and radon readings. The three major intermediate earthquakes occurred in this interval provided a good opportunity to investigate the link between seismicity in Vrancea zone and the presence of anomalies recorded at MLR observatory, the seismic energy distribution, and radon emissions.
The radon emissions couldn’t be related to the seismic activity, the main peaks in radon measurements were probably triggered by weather phenomena which change the humidity and groundwater circulation. The degree of $B_y$ component drop is directly proportional with the released seismic energy. Big drops on $B_y$ components can be followed by big earthquakes but also small and short anomalies can be followed by a significant event/s. For a better forecasting, the futures earthquakes that will be accompanied an anomaly needs the study of seismic energy. The results of this paper could be used as a benchmark for the future anomalies, and the future anomalies will reshape these results. The crustal earthquakes that occur on November 22, 2014, was not accompanied by a geomagnetic anomaly, placing the disruptive processes at high depth. Intermediate earthquakes occurrences seem to be related to partial melts of rocks at the contact with Vrancea slab which create a magnetic signature readable on $B_y$ horizontal component.

Acknowledgments. This paper was supported from Nucleu Program PN 19 080102/2019. The results presented in this paper rely on the data collected at Surlari (SUA). We thank Geological Institute of Romania, for supporting its operation and INTERMAGNET for promoting high standards of magnetic observatory practice.

REFERENCES


