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Anomalous pre-seismic behavior of the electromagnetic normalized functions related to the intermediate depth earthquakes occurred in Vrancea zone, Romania

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Abstract. In this paper the electromagnetic normalized functions (ENF), carried out in ULF band, have been analyzed in correlation with intermediate depth seismic events occurring in Vrancea zone. To confirm the relationship between anomalous, pre-seismic behavior and an imminent earthquake, a methodology based on the temporal invariability criterion of ENF for a 2-D structure, in non-geodynamic conditions, has been used. The electromagnetic data were collected at the Geodynamic Observatory Provita de Sus (GOPS), placed on the Carpathian electrical conductivity anomaly where the epicentral distance is about 100 km, and the National Geophysical Observatory Surlari (NGOS) taken as a reference and located 140 km from the Vrancea zone. The daily mean distributions of the ENF over a span of several months in 2009, carried out at GOPS, exhibit significant enhancements from the normal trend before all the earthquakes with magnitudes higher than 4. Two correlations between the magnitudes of seismic events and *Bzn* have to be highlighted: (i) an earthquake of $M \geq 4$ is expected to occur when $Bzn \geq 1.846$; (ii) meanwhile, the anomalous behaviour of $Bzn \geq 1.851$ may be use as pre- seismic value for an earthquake of $M \geq 5$. The lead time is closed on 7–15 days before earthquakes occurrence.

1 Introduction

In seismogenic studies, the volatile transport may be considered one of basic features of earthquake preparation and associated precursors. According to Gufeld et al. (1999), the degassing process of the Earth could be one of main factors controlling seismicity and energy transfer in the lithosphere. This process, based on laboratory experiments, includes the ascending diffusion effect of helium, hydrogen, and possible other gases belonging to the crystalline structure of rocks. Freund et al. (1999) have shown that most rocks composing the lithosphere can emanate molecular hydrogen as a result of the fracturing processes due to anhydrous minerals which contain some water as impurity of H^- in their crystalline structures. It was also suggested that in the Earth's lithosphere, some well conducting channels (deep faults with fluid flow) do exist and may generate continuous intersecting geotectonic systems (Park et al., 1993; Varotsos, 2005; Yen et al., 2004; Stanica et al., 2006; Stanica and Stanica, 2007). Under the acronym ENF (Stanica and Stanica, 2010) both the geomagnetic normalized function $Bzn(f)$ and normalized resistivity $\rho n(f)$ are known and their relationship with intermediate depth earthquakes will be presented in the next chapter. In this paper, only the correlation between anomalous behavior of $Bzn(f)$ and intermediate depth seismic events that occurred in Vrancea zone will be analyzed. In order to discriminate these effects, the regular observations at the Geodynamic Observatory Provita de Sus (GOPS) were carried out using a ground-based monitoring system with highly sensitive electromagnetic and geomagnetic sensors.

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2 Cause-effect relationship between earthquakes and ENF

For a given 2-D structure, the vertical geomagnetic component Bz is entirely secondary field and it is produced mainly by the horizontal geomagnetic component perpendicular to the strike direction ($B_\perp$). In this condition, the normalized function *Bzn* defined as

$$Bzn(f) = Bz(f)/B_\perp(f) \tag{1}$$

should be time invariant in non geodynamic conditions, but has become unstable due to the geodynamic processes and, therefore, could be used as a precursory parameter of the

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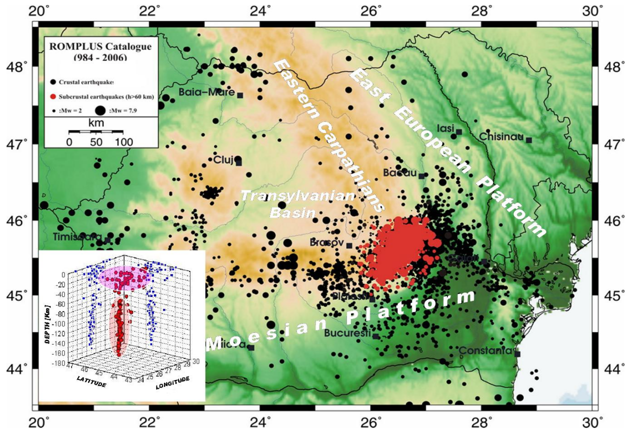

Fig. 1. Map of the seismic active Vrancea zone with crustal epicentres (black circles) and intermediate depth epicentres (red circles) earthquakes taken from ROMPLUS catalogue; the earthquakes foci for 2009 are shown in the lower left corner.

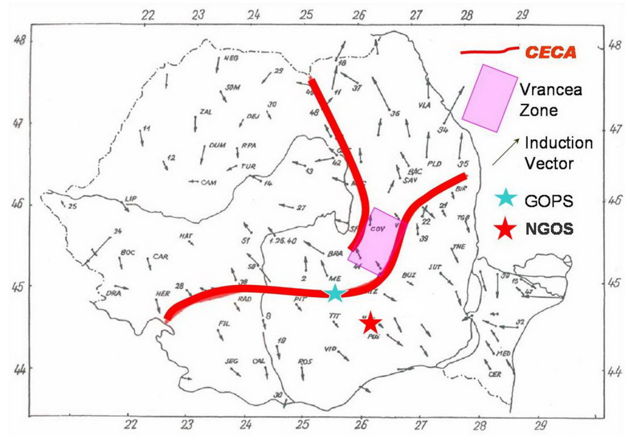

Fig. 2. Map of induction vectors with the Carpathian electrical conductivity anomaly (CECA) and monitoring sites (GOPS and NGOS).

intermediate depth seismic activity (Stanica et al., 2006; Stanica and Stanica, 2007, 2010). In order to explain cause (earthquake)-effect (ENF) relationship, we have to introduce the following magnetotelluric parameters

$$\rho z(f) = (0.2/f) \cdot |E_{||}(f)/Bz(f)|^2 \quad (2)$$

$$\rho_{||}(f) = (0.2/f) \cdot |E_{||}(f)/B_{\perp}(f)|^2, \quad (3)$$

where: ρz and $\rho_{||}$ are vertical and parallel resistivities, f is frequency (Hz), and $E_{||}$ is the electric field parallel to the geoelectrical strike direction. Having established $\rho z(f)$ and $\rho_{||}(f)$ from Eqs. (2) and (3), we may estimate the normalized function $Bzn(f)$ in terms of resistivities with the relation

$$|Bzn(f)| = [\rho_{||}(f)/\rho z(f)]^{1/2} \quad (4)$$

Relation (4) demonstrates the fact that *Bzn* could be linked to the resistivity/conductivity variation along the faults' systems (conductive path) through the Earth's lithosphere and its right part leads to the normalized resistivity which is expressed by the formula

$$\rho n(f) = \rho_{||}(f)/\rho z(f) \quad (5)$$

We consider that one of the realistic mechanisms for triggering earthquakes in the Vrancea seismogenic volume can be the dehydration of rocks which make fluid-assisted faulting possible (Stanica et al., 2004). Thus, the changes of resistivity occurred before an earthquake, as a sequence of geodynamic processes developed into and in the close vicinity of the seismogenic volume, could be detected by means of the anomalous behavior of the *Bzn* parameter taken throughout the frequency domain 10^{-2} Hz–2.10^{-4} Hz.

3 Seismic active Vrancea zone and Carpathian electrical conductivity anomaly

The earthquake-prone Vrancea zone (Fig. 1) is situated at the arcuate bend of the Eastern Carpathians and it is bounded to the north-east by the East European Platform, to the south by the Moesian Platform, and westwards by the Transylvanian Basin. The epicentres of intermediate depth (70 km–180 km) earthquakes are concentrated within a very small area having 80 km length and 40 km width, delimited by CECA (Fig. 2). According to the historical RomPlus catalogue (National Institute of the Earth Physics, Romania), the frequency-of-occurrence is about 2–10 seismic events per month with $3 < M < 4$, 1–3 events per month with $4 \leq M \geq 5$, an average return period of 2–5 yr for the events with $M > 5$ and about 3 strong earthquakes ($M \geq 7$) per century. The crustal activity is weak ($M < 5.5$), often occurring in clusters and mainly located in the depth interval of 10 km–40 km.

Stanica et al. (2004) suggested that one of the realistic mechanisms for triggering intermediate depth seismic events in the Vrancea zone might be the torsion process of the seismogenic volume, generated by descending astenospheric current, which, associated with distribution of the stress and the dehydration of rocks make fluid-assisted faulting possible. In this context, pre-seismic perturbation of the normalized function *Bzn* could be linked to the electrical conductivity/resistivity variation along the submerge path through the lithosphere. The enhanced electrical conductivities in the lithosphere are generally attributed to the presence of saline fluids (Jankovki et al., 1985), black shales and/or graphite (Pinna et al., 1992; Stanica and Stanica, 1993), and less commonly, in regions of recent tectonic activity, to the partial melting. On the Romanian territory, CECA (Fig. 2) has been delineated along the Carpathian region by a zone of about 10 km width, established mainly by the divergence of induction vectors (Wiese convention); it represents a conglomerate of sedimentary rocks, black shales and/or graphite formed only at the contact zone between two continental plates (East-European Plate with Intra-Alpine Plate, towards the north-east and Moesian Plate with Intra-Alpine plate, towards the south). It is also quite possible that its geoelectric parameters remain fairly constant throughout its entire length (Jankovki et al., 1985; Pinna et al., 1992).

4 Electromagnetic and geomagnetic methodologies

Because the signals related to the earthquakes are very weak, some methodologies have been developed for discriminating them from the natural and artificial signals: geomagnetic transfer functions analysis (Saraso et al., 2009); mono- and multi-fractal analyses (Hayakawa et al., 1999; Telesca et al., 2008); Spectrum density ratio analysis using the ratio of vertical to horizontal components (Hattori et al 2004); the statistical relationship between the magnitude of impending earthquakes and anomalous pre-seismic transmission of VHF-band radio waves (Moriya et al., 2010) and so on. Stanica and Stanica (2006, 2007 and 2010) demonstrated that for a 2-D structure, the normalised function *Bzn* is time invariant in non-seismic conditions and its pre-seismic perturbation/instability is considered as a sign of impending earthquake. In order to have information related to the type of geoelectrical structure beneath GOPS, we have used both the magnetotelluric equipment GMS-06 (Metronix-Germany), having 5 channels (two electric-Ex, Ey and three magnetic: Bx, By, Bz), 24 bit resolution, GPS, two frequency ranges (LF: 2.10^{-4} Hz–1 kH; HF = 0.5 kHz–10 kHz) and adequate "MAPROS" software packages. The "MAPROS" software is able to perform the following basic tasks:

- real time data acquisition and processing;
- robust estimation of the electromagnetic (EM) transfer functions;
- real time display of time series and all important parameters ($\rho_\perp$, $\rho_|$, skew and strike);

Using a single-site tensor-impedance decomposition technique (Bahr, 1998), by means of MAPROS software packages, it was possible to separate the local effects from the regional ones and to estimate the EM parameters: (i) skew; (ii) geoelectrical strike direction; (iii) resistivities perpendicular ($\rho_\perp$) and parallel ($\rho_|$) to the strike. On the frequency domain 10^{-2} Hz–2.10^{-4} Hz, a skewness distribution less than 0.3 (Fig. 3) emphasizes a 2-D type structure, having in the same interval a geoelectrical strike direction of about 95°–98° (Fig. 4).

These results confirm once more that the CECA's structure, placed under GOPS, is of a 2-D type, being orientated approximately east-west, and forms not only a tectonic boundary between two continental plates (Moesian Plate

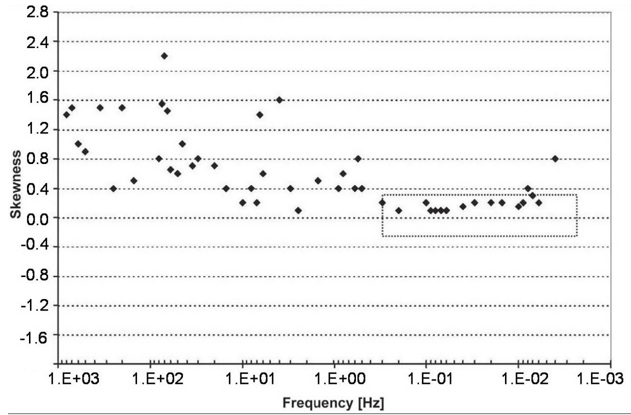

Fig. 3. Skew coefficient versus frequency; values less then 0.3 (in rectangle) indicate the frequency range where there is a 2-D structure.

with Intra-Alpine plate), but also represents a peculiar conducting channel extended to the seismic active Vrancea zone (Fig. 2). Having this information, a geomagnetic methodology able to assess the ENF precursors on the frequency range corresponding to the 2-D structure and intermediate depth interval has been applied. The next step in our study was to realise a continuous monitoring of the geomagnetic components Bz, $B_\perp$ and $B_|$ at the GOPS by the use of MAG03DAM recording system (Bartington–England), with 6 channel, 24 bit resolution for the collection of data from three axis magnetic field sensor MAG03 MSL (frequency range 1 kHz–DC). In order to carry out the $B_\perp$, one of the horizontal components of the three axis magnetic sensor has always been orientated perpendicular to the strike. The parameters of the data acquisition card are under software control and an additional program collects information every five seconds and stores it every 60 s, on the PC HDD. Using the wireless connection, all the data are transferred to the central unit placed at the Institute of Geodynamics-Bucharest for real-time data processing and analysis.

5 Results

All the intermediate depth earthquakes triggered in January–September 2009, with magnitude (M_w) higher than 3.0 (Richter scale), have been selected from the earthquake catalogue issued by the National Institute of the Earth Physics-Bucharest and analyzed in correlation with *Bzn* distribution. Daily averaged distribution of the normalized function *Bzn* and its standard deviation have been calculated for the frequency range less than 1.666E-2 Hz, where a 2-D structural condition is accomplished and its increasing values are expected to be obtained before an earthquake. To assess the robustness of the presented methodology, three examples of *Bzn* distribution acquired in a span of about nine months (January–September) in 2009 are shown. The first particular

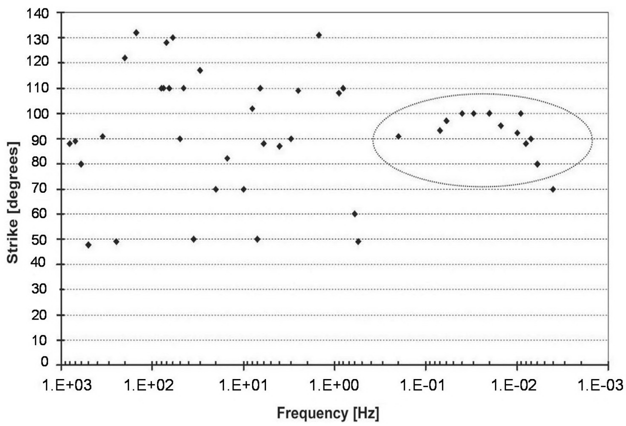

Fig. 4. Strike versus frequency; in ellipse is the frequency range where 2-D structures have a strike direction of about 95°–98°.

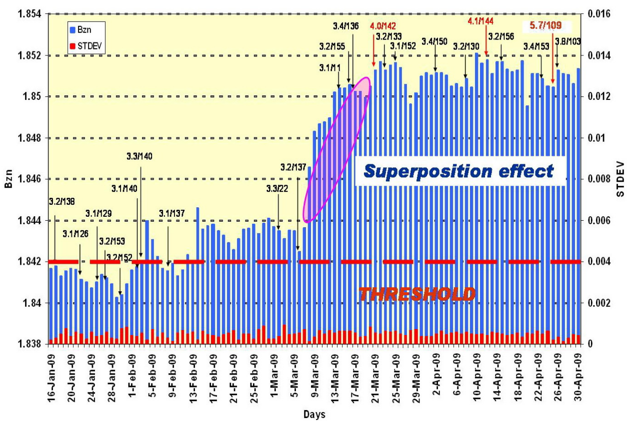

Fig. 5. *Bzn* and STDEV distributions at the GOPS, within the interval 16 January–30 April 2009; vertical arrows are earthquakes and ratio 5.7/109 is the magnitude/hypocentre depth of earthquake; dashed red line is threshold.

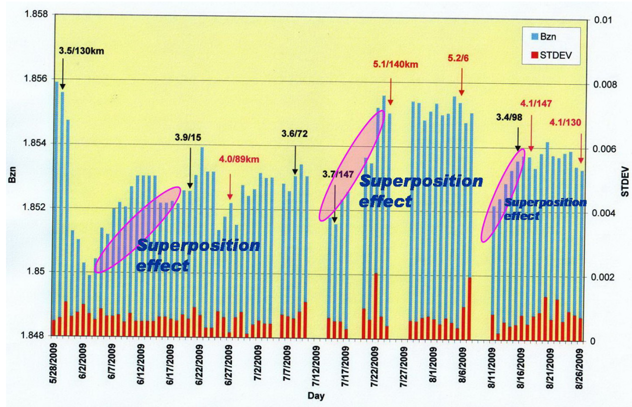

Fig. 6. *Bzn* and STDEV distributions at the GOPS, within the interval 28 May–26 August 2009; vertical arrows are earthquakes; ratio 5.1/140 is the magnitude/hypocentre depth of earthquake.

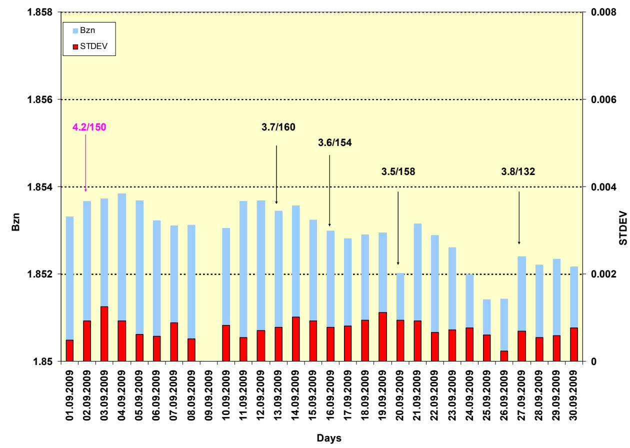

Fig. 7. *Bzn* and STDEV distributions at the GOPS, within the interval 1 September–30 September 2009; Vertical arrows are earthquakes; ratio 4.2/150 is magnitude/hypocentre depth of earthquake.

case of the *Bzn*'s distribution correlated with both standard deviation (STDEV) and intermediate depth seismic activity within a 105 day interval (January–April 2009) is shown in Fig. 5. This distribution emphasizes two very large instability domains with increased values of about 1.843 on 16 January–7 March interval and of about 1.851 on 8 March–30 April interval. The largest earthquakes occurred in the last interval are marked by vertical arrows, having values of magnitude oscillating between 4.0 and 5.7. All of them are in good correlation with the instability domain of the *Bzn* (highest values), which started on 9 March, being associated to a major changes of electrical conductivity bellow GOPS and along the submerged high sensitive path (CECA) deployed at lithospheric level, due most probably to fluid migration through faulting systems. An average value of 1.842 in Fig. 5, associated with earthquakes of $M < 3.3$ triggered in the period 16 January–7 March, represents the threshold limit between the so-called "normal trend" of *Bzn* and its second anomalous domain which started on 8 March, which may represent a superposition effect of the three earthquakes of magnitude 4.0, 4.1, and 5.7, that occurred on 21 March, 12 April, 25 April. The earthquake of magnitude 5.7 (Richter scale) was triggered in the Vrancea zone at 109 km depth on 25 April at 20:18:48 (local time), and was felt in Bucharest and over a large area extended from the epicentral zone towards NE and SW directions, corresponding with the fault plane orientation of the focal mechanism.

Figures 6 and 7 depict results of *Bzn* distribution observed at GOPS on the two intervals 28 May–26 August and the whole month of September. Figure 6 reveals three anomalous domains of *Bzn* which may be related to 5 earthquakes with magnitude larger than 4. The first domain, extended to the interval 4 June–10 July, is characterized by enhanced values of *Bzn* between 1.850 and 1.854, and may be related to an earthquake of magnitude 4, occurred on 27 June. It

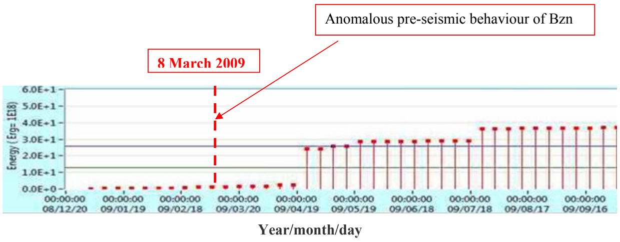

Fig. 8. Variation of earthquake energy in the interval 1 January–30 September 2009.

is also necessary to mention the existence of a superposition effect generated by all three earthquakes: $M = 3.9$ (on 20 June), $M = 4.0$ (on 27 June) and $M = 3.6$ (on 8 July). The second domain is expanded to the interval 14 July–7 August and reflects also superposition effects of the two earthquakes of magnitude 5.1 and 5.2, triggered on 24 July and 5 August, respectively. The anomalous values of *Bzn* are comprised between 1.854 and 1.855. The last domain (11 August–26 August) has an average value of about 1.853, which is probably associated with the two earthquakes of magnitude 4.1, occurring on 17 and 26 August.

Figure 7 illustrates the *Bzn* distribution for September 2009, where similar pre-seismic characteristics are observed. Thus, enhanced values of *Bzn* are correlated with the increased values of earthquake magnitudes and decreased foci depth.

The local variation of earthquakes' energy (Es) carried out for the analyzed interval in 2009 is shown in Fig. 8. The relationship between magnitude and energy is $\log E_S = 11.8 + 1.5\,M$, giving the energy E_S in ergs from the earthquake magnitude M. It is quite obvious that an increase in seismic activity initiated on 9 April in the Vrancea zone was responsible for the *Bzn* jump observed one month ago (on 8 March). This seismic activity supported the model of focal mechanism (Stanica et al., 2004) based on the stress generation due to the dehydration of rocks and fluid migration through the faulting system, which may have produced changes of electrical conductivity associated with increased values of *Bzn*.

The conclusive results are depicted in Fig. 9 where, for the Vrancea zone, it is most probable that an earthquake of $M \geq 4$ is expected to occur when $Bzn \geq 1.846$, while a $Bzn \geq 1.851$ may be used as a pre-seismic value for an earthquake of $M \geq 5$.

6 Conclusions

The *Bzn* parameter carried out at GOPS has been analyzed to detect its pre-seismic anomalous behaviour related to the intermediate depth earthquakes with $M \geq 4$. Before all the earthquakes of $M \geq 4$, the variation of normalized function *Bzn* exhibited significant enhancements from the normal trend. The average value of 1.842 (Fig. 5) associated with earthquakes of $M \leq 3.3$ occurred in the period 16 January–7 March; it represents the threshold limit between the normal trend and pre-seismic perturbation of *Bzn* considered as possible earthquake precursors. For the same interval, there are no significant changes at the reference station NGOS (Fig. 10), due to the fact that it is not placed on/near a conductive path. If anomalous behavior and normal trend domains are much closed, as a multitude of earthquakes of different magnitude occurred at short time intervals, then a superposition effect has been observed. For the Vrancea zone, two correlations between the magnitude of seismic events and *Bzn* have to be highlighted: (i) an earthquake of $M \geq 4$ is expected to occur when $Bzn \geq 1.846$; (ii) meanwhile anomalous behaviour of $Bzn \geq 1.851$ may be used as a pre-seismic value for an earthquake of $M \geq 5$. As this methodology allows us to know always the geotectonic changes after any seismic event, it becomes an interesting tool of studying the earthquakes and the associated geodynamic processes.

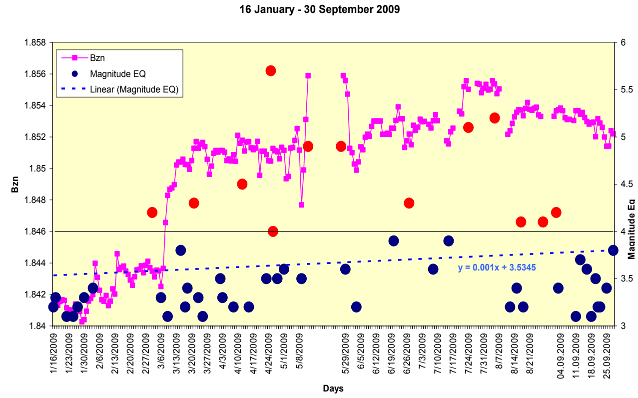

Fig. 9. Distributions of the *Bzn* and earthquake magnitude on the whole interval analysed; blue circles are earthquakes with $M < 4$ and red circles are earthquakes with $M \geq 4$.

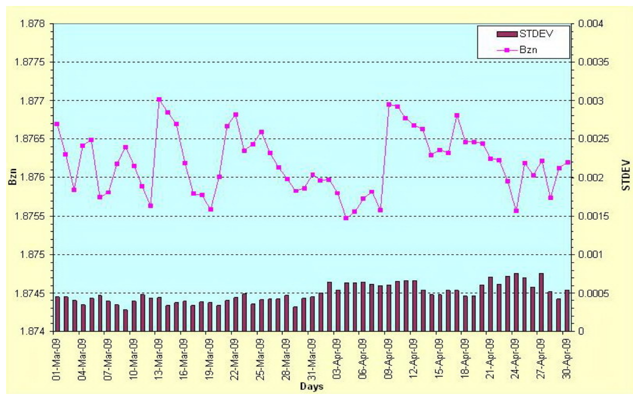

Fig. 10. Distribution of the *Bzn* and STDEV at NGOS on the interval 1 March–30 April 2009.

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