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ELECTROMAGNETIC MONITORING IN GEODYNAMIC ACTIVE AREAS

Dumitru STANICA* and Maria STANICA

Institute of Geodynamics of the Romanian Academy, 19-21 J- L. Calderon St., Ro-020032
tel: 40-21-3172127; Fax: 40-21-3172120
**Corresponding author's e-mail*: dstanica@geodin.ro

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ABSTRACT
This paper represents the Romanian contribution in the frame of the European Co-operation "COST ACTION 625" and it is centered on an electromagnetic methodology for the natural hazard assessment due to both the seismic events and associated active faults which are considered to be sources of the most significant landslides in the Subcarpathian area (Romania). This methodology was established according to the geotectonic features of the seismic-active Vrancea zone and Provita de Sus landslide area. Subsequently, a specific approach regarding the electromagnetic precursory parameters, selected according to the temporal invariability criterion for a 2D geoelectric structure in non-seismic condition, taking into consideration their daily mean distribution versus intermediate depth seismic events recorded simultaneously, was elaborated. A similar electromagnetic technique conveying to additional parameters and models concerning the evolution in time of the landslide phenomena was also imposed, so that a disaster forecasting become possible.

KEYWORDS: electromagnetic short–term precursory parameters, seismic-active Vrancea zone, active faults, landslide assessment, Provita de Sus test site

INTRODUCTION

The assessment of natural hazard and risk generally aims at analyzing potential impacts of specific processes to a rather well balanced system, in order to emphasize to what extent it might be affected in the future. In this paper two distinct problems are tackled: **short–term precursory parameters associated with intermediate depth earthquakes** and **landslides assessment.**

As the seismic-active Vrancea zone is one of the "hot" subjects, we focused on a specific approach to emphasize the **short–term precursory parameters** associated to intermediate depth earthquakes (EQs), by using electromagnetic (EM) data. It means that a specific EM methodology centered on the pattern recognition and on the anomalous behaviour of the **Bzn and ρn parameters** (Stanica et al., 2002; 2003) linked to seismic events is to be taken into consideration by respecting some compulsory conditions:

- The establishment of the optimum placement of the monitoring site and its EM pattern (a two-dimensional structure, strike orientation and the normal distribution of the Bzn and ρn parameters in non-seismic condition);
- The installation of the specific geophysical system for continuous monitoring of the EM field;
- The accomplishment of the daily mean variations of the Bzn and ρn parameters on certain frequency ranges, in order to highlight their connection with seismic events.

A similar methodology, but more comprehensive owing to its additional parameters (electrical anisotropy, skewness – dimensionality information and strike) for investigating the structure changes (slope angle, new micro-fractures, sliding surfaces, conductivity increase, etc.) was applied for studying the Provita de Sus landslide assessment. It is known that, generally, the landslides occur with the other natural disasters (earthquakes or floods) and because each landslide is rather different, it was necessary to choose an adequate monitoring system on the basis of the preliminary analysis of phenomena and geological conditions (Stanica et al., 2005). Therefore, another goal of the paper is to present a specific ground-base monitoring system (SGMS), to better understand its efficiency for broad application in landslide studies and hazard mitigation. Additionally, by combining different data sets and analysis techniques, and also by merging electromagnetic parameters with tomographic images and with low frequency electric signals occurred prior the stress to reach a critical value, a compelling dynamical paradigm, in which is emphasized a correlation between electromagnetic parameters and the earthquakes' magnitude, was carried out. In consequence, by analyzing the data from the Provita de Sus test-site, it was possible to assign the increase of the landslide activity to the local fault which has been reactivated by the earthquakes (EQ) occurred in the Vrancea zone. In the end, this paper illustrates the stage of the SGMS implementation and to what extent the results carried out in the Provita de Sus test site may contribute on understanding such kind of phenomena.

SHORT–TERM PRECURSORY PARAMETERS ASSOCIATED WITH THE INTERMEDIATE DEPTH EARTHQUAKES

METHODOLOGY AND RESULTS

Unlike the other type of information (electric or seismic), the electromagnetic data seem to be more acceptable for tackling the short-term precursory parameters, because they are restricted neither to narrow high conducting paths – as the electric data, nor to a short time before the earthquakes – as the seismic ones.

It is well known that at the Earth surface the vertical geomagnetic component Bz is entirely secondary field and its existence is an immediate indicator of lateral inhomogeneity. For two-dimensional structure, Bz is produced essentially by $B_\perp$ (horizontal geomagnetic component perpendicular to the geological strike) and consequently a normalized function Bz defined as:

$$Bzn = Bz/B_\perp, \tag{1}$$

hould be time invariant for a given 2D structure (Word et al, 1970).

Furthermore, in terms of resistivity, we may compute:

$$\rho_z = 0.2\, T \left| E_\parallel / Bz \right|^2 \tag{2}$$

and

$$\rho_\parallel = 0.2\, T \left| E_\parallel / B_\perp \right|^2, \tag{3}$$

where: T is period (sec.), ρ_z is the vertical resistivity, $E_\parallel$ and $\rho_\parallel$ are the electric field and the resistivity parallel to the strike.

Thus, the normalized function Bzn may be estimated as:

$$\left| Bzn \right| = (\rho_\parallel / \rho_z)^{1/2}, \tag{4}$$

Relation (4) demonstrates that Bzn could be linked to variation of the electric conductivity into the Earth and, its right part lead to the normalized resistivity (Stanica and Stanica, 2003) defined as:

$$\rho n = \rho_\parallel / \rho_z \tag{5}$$

As a first step, it is important to point out the EM pattern (skewness, strike and specific distribution of the Bzn and ρn parameters in non-seismic condition) for the monitoring site - National Geophysical Observatory Surlari (NGOS - Fig. 1) and to extract the anomalous behaviour of the Bzn and ρn parameters, the most probably due to the resistivity changes appeared at the intermediate depth level.

In order to determine the EM pattern at the NGOS 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: 4096sec.-1kH; HF=0.5kH - 10kH) and an adequate software packages “MAPROS” able to perform the following basic tasks:

- Real time data acquisition and processing;
- Robust estimation of transfer functions;
- Real time display of time series and all important electromagnetic parameters ($\rho_\perp$, $\rho_\parallel$, skewness and strike, etc).

Using magnetotelluric tensor impedance de-composition technique (Bahr, 1998), it was possible to separate the local effects from the regional ones and to identify the MT parameters: (i) skewness; (ii) strike orientation; (iii) resistivities perpendicular ($\rho_\perp$) and parallel ($\rho_\parallel$) to the strike. Having this information, a specific methodology using frequencies (10^{-2} - 4.10^{-3} Hz) which correspond to the 2D structure and intermediate depth interval has been applied.

The continuous monitoring of the geomagnetic data was accomplished by using the recording system MAG-03 DAM (Bartington, England), with 6 channels, 24 bit resolution, able to collect the data from the three axis magnetic field sensor MAG-03 MSL (frequency range: DC- 1kHz) and a laptop for real time data storage and processing. One of the horizontal components of the three axis magnetic sensor has always been orientated perpendicular to the geological strike. Subsequently, the changes of electrical conductivity inside of the Vrancea’s seismogenic volume and its surroundings, before an earthquake occurred, as a sequence of the lithospheric conductivity changes produced by the dehydration of the rocks associated with rupturing processes and fluid migration through faulting system inside the Vrancea’s seismic active volume and its surrounding areas, have to be reflected by the Bzn and ρn parameters.

To have a comprehensive view on the applied methodology, the daily mean distribution of the parameter Bzn in correlation with Vrancea’s deep seismic events occurred simultaneously is shown in Fig. 2, within a span of about three months (01 February 2003- 30 April 2003). It is easily visible that there are some domains characterized by increased Bzn values versus its normal distribution (1.870 ± 0.0004), in non seismic conditions, as a direct consequence of the thermo-mechanical processes occurred at crustal and subcrustal level before and during of the earthquakes. Vertical lines mark the earthquakes’ magnitude with values oscillating between 2.8 and 4.3. According to this information, it is admitted that major changes of electrical conductivity are produced.

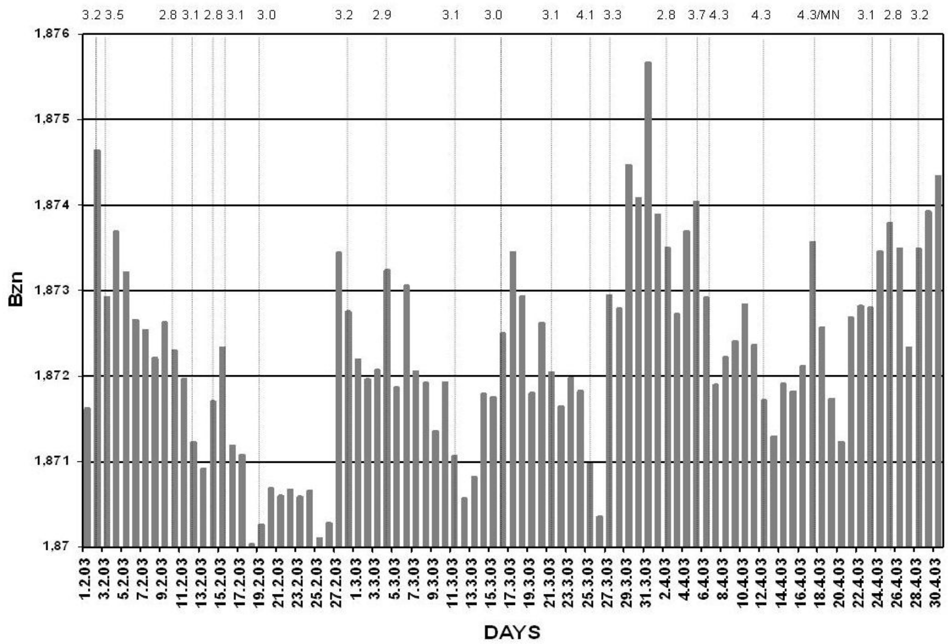

Fig. 2 Daily mean variation of the Bzn parameter represented simultaneously with seismic events (vertical line) having marked their magnitude; the line of 1.870 (± 0.0004) is normal distribution in non seismic condition; the errors bars of the Bzn varying between ± 0.0002 and ± 0.0004.

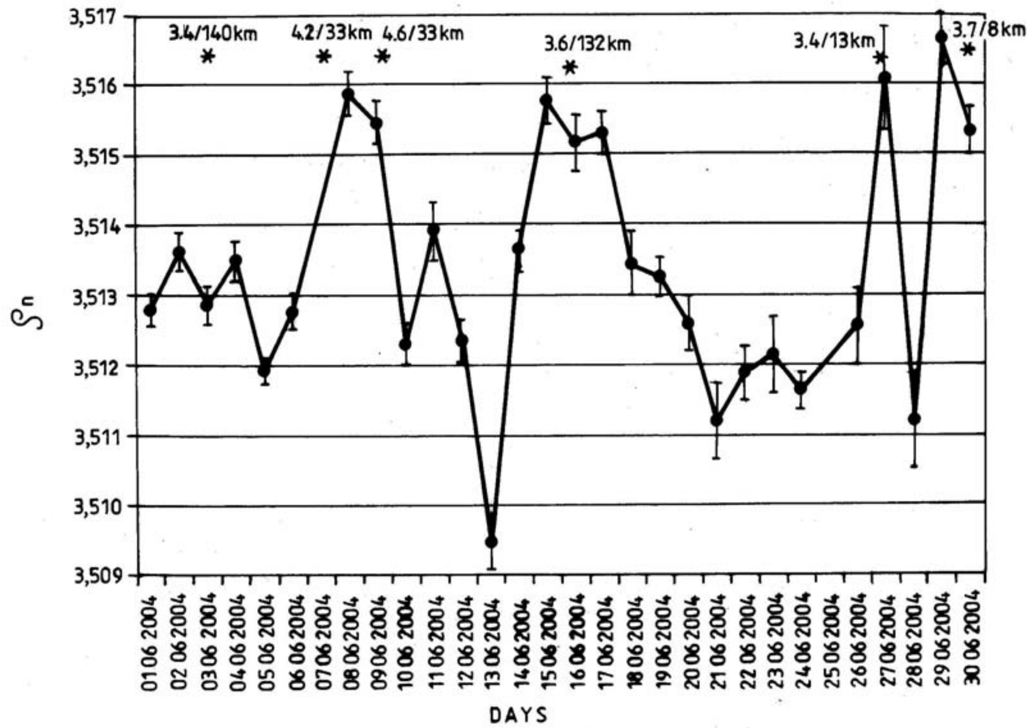

Fig. 3 Daily mean variation of the ρn parameter (with error bars) represented simultaneously with seismic events (star) having marked their magnitude/depth; the line of 3.512 (± 0.0002) is normal distribution in non seismic condition.

For a better understanding of this methodology, it is also presented Fig. 3 that contains the daily distribution of the parameter ρn, correlated with the simultaneous seismic events, for a month interval (01.06-30.06.2004).

This figure emphasizes increasing values of the ρn parameter by comparing with its normal distribution (3.512 ± 0.0002) in non seismic conditions, due to the same geodynamic processes and consequences mentioned above.

LANDSLIDES ASSESSMENT

The Provita Fault (PF) has been developing in the flyshoid domain of the Subcarpathians and it was reactivated by the intermediate depth earthquakes (M=6) occurred in the Vrancea zone, on 27th November 2004 (Fig.1). For this reason the Provita de Sus landslide zone, cross-cut by this active fault orientated NE-SW, was chosen as a monitoring test site. This landslide has the following characteristics (Tatu et al., 2005):

- both the rear and front limits of the slide deposits are at about 670 m and at 410 m altitude, respectively;
- the maximum thickness of the slide deposits is of about 35 m;
- the angle of rupture surface is about 30° (rear) and 10° (front);
- the landslide area is about 1.25 km^2

SPECIFIC GROUND-BASE MONITORING SYSTEM (SGMS)

One of the main objectives of this paper was to implement a complex monitoring system that may provide early-warning against the risk arising from landslide triggered by the EQ occurred in the Vrancea zone, in this particular case concerning the Provita de Sus locality. In this respect, a methodology able to investigate the electromagnetic and electric parameters induced by the crustal and subcrustal geodynamic processes (landslides triggered by earthquakes) will be presented (Stanica et al., 2005). For getting this goal, the following activities have been accomplished:

(i) Adaptation of the monitoring system at the peculiar conditions of the Provita de Sus (test site) for pattern recognition;

(ii) Acquisition of specific data to produce 2D tomographic images as a first step for the risk assessment;

(iii) Assessment of the electromagnetic parameters related to both the earthquakes (EQ) occurred at the intermediate depth, characteristic to the seismic-active Vrancea zone, and the landslides associated to the Provita active fault (PF).

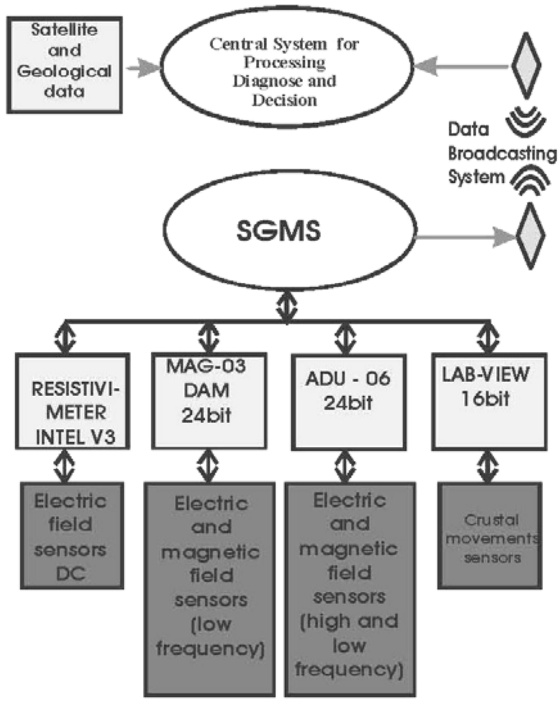

Fig. 4 Specific ground-base monitoring system (only the electric and EM components have been presented in this paper).

The SGMS (Fig. 4) consists of three separate equipments able to carry out discrete observation and/or continuous monitoring (Stanica et al, 2006) of:

(a) HF and LF electromagnetic field (Geophysical Electromagnetic Measurement System - GMS 06, Metronix-Germany);

(b) Geomagnetic field (MAG 03 DAM, Bartington-England);

(c) Geoelectric field (Resistivimeter INTEL V3, INTEL 92-Romaia);

All the three measurement equipments include specific sensors, data acquisition modules and adequate software. The MAPROS software packages (Metronix- Germany) used for the electromagnetic system runs under Windows 95 or Windows NT operating systems, on a laptop connected to a single ADU or an ADU network and has the following tasks:

- In-field system calibration and automatic offset compensation;
- Real time data acquisition and processing;
- Robust estimation of transfer functions;
- Real time display of time series and all the important EM-parameters;

Also, in order to draw up geoelectrical cross-sections, 1D and 2D inversion and modeling of the data have been used.

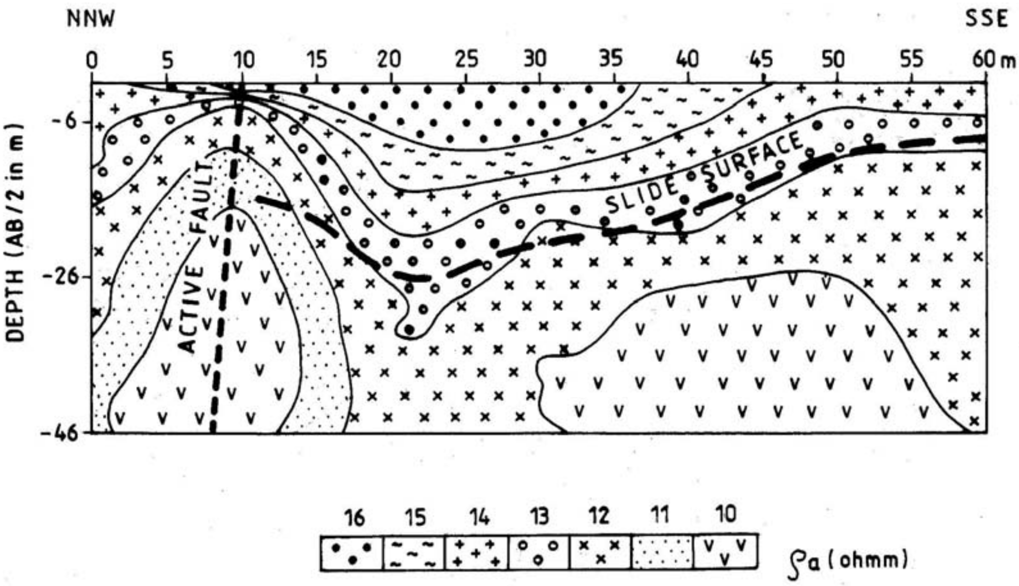

Fig. 5 Geoelectric tomography along the VES profile perpendicular to the Provita active fault (PF).

METHODOLOGY AND RESULTS

The objectives are to be focused on the recognition of the electromagnetic parameters which could be correlated with active faults and associated landslides. The studies had to be involved in a multi-parameters context and, therefore, in the Provita de Sus - test site we installed the discreet and continuous monitoring systems of the electric, magnetic and EM fields.

The main condition for a specific approach of this problem was to use long time continuous electromagnetic data, on the hand, and appropriate algorithms to point out and extract possible anomalous variations, on the other hand, so that we could make an analysis of the electromagnetic results during the landslides processes. Thus, the specific methodology and MAPROS software packages have been applied for obtaining, in real time, all the important electromagnetic parameters and to extract their anomalous behaviour versus the specific pattern pre-established in non active-tectonic conditions.

As a first stage in getting to this aim, it is important to mention the specific equipment used for real-time monitoring of the electromagnetic field and the methodology applied to calculate the time evolution of the electromagnetic parameters. As in previous part (A), by using magnetotelluric (MT) tensor impedance decomposition procedure (Bahr, 1989) it was possible to identify the type of geological structures and to emphasize the strike orientation of the possible new micro-fractures occurred at shallow depths interval. In this respect, the specific methodology has consisted in extracting of the peculiar changes in time of the resistivity - parallel and perpendicular to the geological strike, electrical anisotropy, skewness and strike, and to point out the low frequency electric signals, that "arrive" before the time derivative of the magnetic field, emitted prior the stress reached a critical value.

By analyzing EM data carried out at Provita de Sus test site, it was possible to link the increased activity of landslide with the PF reactivation due to the intermediate depth earthquake of M=6 occurred in the Vrancea zone, on November 27th, 2004. This earthquake has also been remarked by the anomalous behaviour of the electromagnetic parameter Bzn (Stanica et al., 2006) recorded at National Geophysical Observatory Surlari.

The EM field results, which will be presented, reflect the following two activities:

1. EXPERIMENTAL STUDIES TO ESTABLISH GEOELECTRIC/ ELECTROMAGNETIC PATTERN OF THE TEST SITE IN „PRE-CRITICAL" CONDITIONS

In this context, all the electromagnetic data, obtained during the experimental studies (Stanica et al., 2006), conveyed to:

- Specific tomographic images carried out by using both the vertical electrical soundings (Fig. 5) and magnetotelluric soundings methods (Fig. 6);
- Estimation of the skewness parameter;
- Estimation of the geological strike;
- Assessment of the electrical anisotropy. In terms of resistivity the anisotropy may be defined as:

  $A = \left| \rho_{\perp}/\rho_{\parallel} \right|$,

where: $\rho_{\perp}$ and $\rho_{\parallel}$ are the perpendicular and parallel resistivities to geological strike.

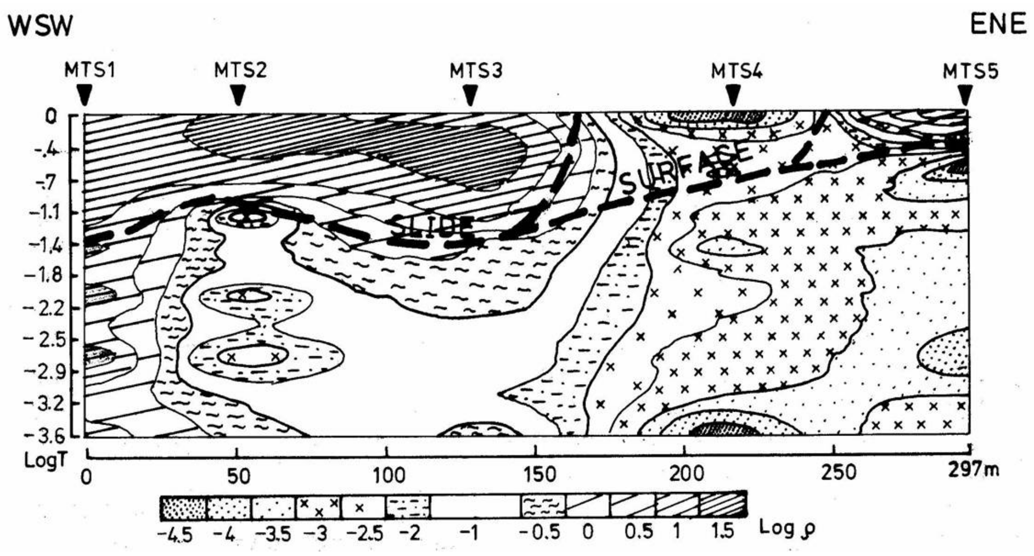

Fig. 6 Magnetotelluric tomography (B-polarized mode) along the MTS profile perpendicular to the landslide.

2. MONITORING OF THE EM PARAMETERS /PHENOMENA RELATED TO THE LANDSLIDE ACTIVITY.

In order to determine the time evolution of the slide activity occurred in the Provita de Sus test site, we made the measurements in the same point on landslide (electric and magnetic sensors in unchangeable position), with a sampling rate of 7 days, of both the EM parameters (skewness, strike and anisotropy) and the low frequency electric signals, that "arrive" before the time derivative of the magnetic field emitted prior the stress reached a critical value. Further on, some examples regarding this activity are set off:

- Skewness parameter recorded on 30th September, 2005 and 07th October, 2005;
- Strike parameter recorded on 30th September, 2005 and 07th October, 2005;
- Electrical anisotropy recorded on 30th September, 2005 and 07th October, 2005;

The obtained results reveal the significant changes of the EM parameters as follows:

- In the frequency range 2.10^3- 4.10^3 Hz, specific to the sliding activity occurred in the depth interval 0-30m, skewness parameter being higher than 0.3 reveals a 3D structure (for 30th September), while the same structure becomes 2D on 07th October (when the skewness is smaller than 0.3);
- For the both records, the strike parameter has deviations of about 12^0 versus its mean value ($92^0 \pm 2^0$), which may be assigned to the main rupturing process of the landslide which could be associated with the sliced blocks having complex array of micro-faults with different orientation;
- In the same frequency ranges 2.10^3- 4.10^3 Hz, the electrical anisotropy is of about 1.8 on 30th September and becomes of about 2.0 - 2.5 on 07th October .

As regards the low frequency electric signals emitted prior the stress reached a critical value, we used a special array of electrical sensors having the interval (D) between two pairs of 8m. Such an experiment has success if the interval between the sensors is chosen so that the electric spike to be not masked by natural electric variations (for D= 8m the spike is well represented, while for D=16m this is partially masked by the natural electric field variation- Fig. 7).

CONCLUSIONS

* According to all the electromagnetic information correlated with seismic events, it is relieved that the earthquakes are triggered during the instability period of the EM parameters, generated by the resistivity changes occurred at intermediate depth. When the stability and instability periods are very closed, then the suitable domains are superimposed and maximum amplitude value of the analyzed electromagnetic parameters may correspond or not with the maximum magnitude of the earthquakes;

* Some days before an EQ occurred, the daily mean variation of the Bzn and ρn parameters have had an anomalous behaviour marked by a significant increase versus their normal distribution identified in non seismic conditions, as a result of the lithospheric conductivity changes produced by the dehydration of the rocks, associated with rupturing processes and fluid migration through faulting systems developed inside the Vrancea seismogenic volume and its surrounding areas.

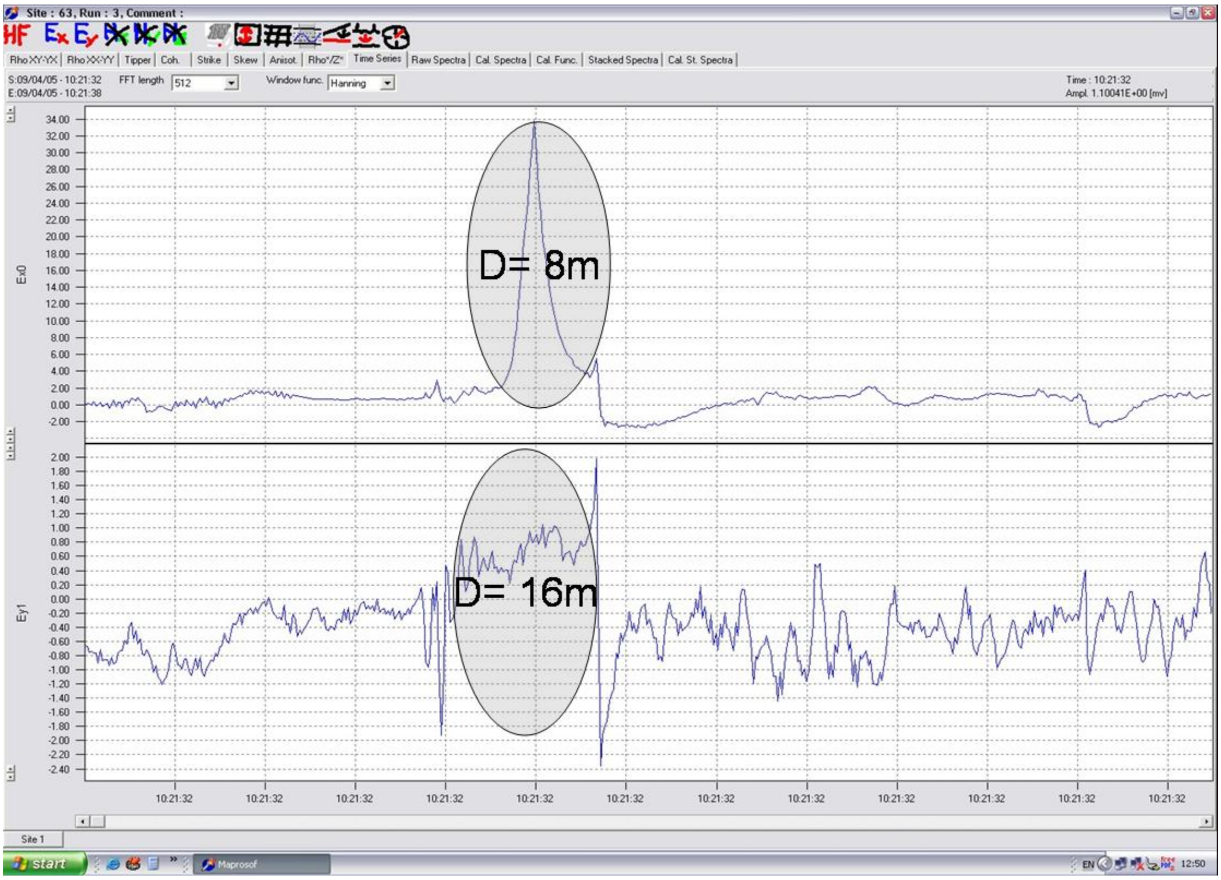

Fig. 7 Low frequency electric signal emitted prior the stress reached a critical value recorded by a special array of electrical sensors having the interval (D) between two pairs of 8m and 16m; the ellipses mark the low frequency electric signal.

* Even if at present it is not possible, yet, to make any predictable correlation between the magnitude of seismic event and the amplitude/shape of the Bzn and ρn parameters, for lack of sufficient data concerning extreme events (M>6), there is a chance to make a step forward on this way;

* As this methodology allows us to know always the structure changes after any seismic event, what permit to use further on the most adequate techniques, it becomes an interesting subject of studying the earthquakes and the associated geodynamic processes.

The described SGMS and methodology proved an effective way of monitoring the EM parameters and phenomena in order to detect their significant changes associated to Provita de Sus landslide. According to these results, the following general conclusions can be drawn from this test site:

* In 2005 year, on the Provita de Sus landslide the active fault (PF), reactivated by intermediate depth Vrancea's earthquakes and strong rainfalls, the major forces generating the slide activity there were. Significant morphological-geoelectrical changes on the landslide surface and its shallow depth (0-20m) had a local character only and were developed mainly between the middle and front part of the landslide. This process deforms the small sliced blocks and produces a complex array of reverse micro-faults, strike-slip micro-faults and folds;

* The accuracy of the EM parameters' changes versus the geodynamic characteristics of the Provita de Sus landslide allowed us to consider the SGMS as powerful tool to investigate any landslide areas characterized by very complex geology;

* The related study demonstrates the rich potential of using this new methodology for landslide monitoring. In particular, the SGMS can play an important role in monitoring of landslide-prone areas to signal the current movements, and provide near real-time warnings about motions on slides that can be a danger to the life and property of the people;

* High-resolution of the EM parameters and tomographic images can lead to an improved understanding of landslide mechanism and hazard assessment due to the seismic activity.

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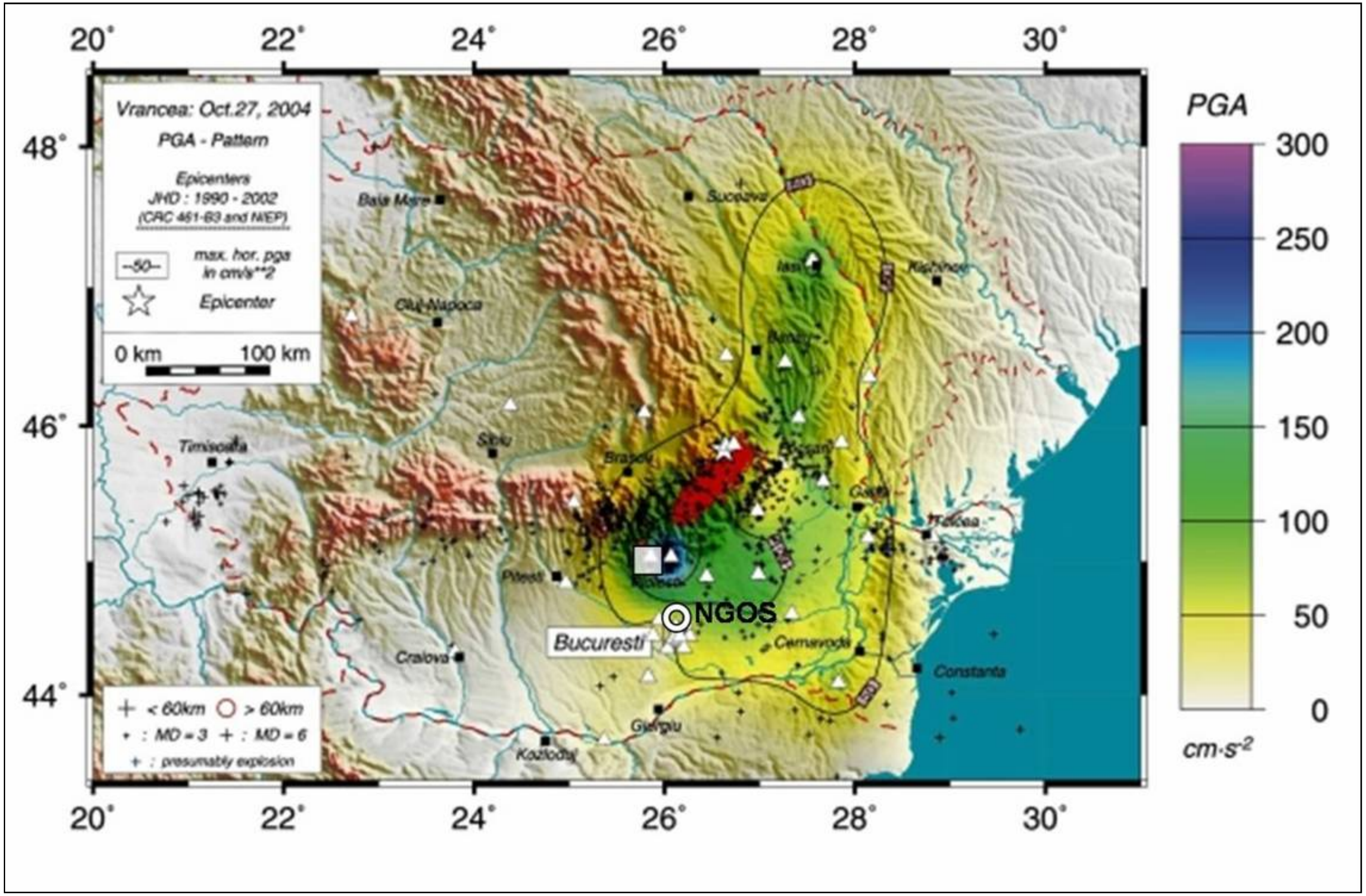

Fig. 1 The Romania's map showing the next elements: 1. the intermediate depth seismic-activite Vrancea zone (red area); 2. the epicenter of the earthquake occurred on 27 October 2004 (white star) and its horizontal acceleration (black isolines); 3. the location of the landslide test site (white rectangle); 4. NGOS - National Geophysical Observatory Surlari.