Bull. Nov. Comp. Center, Math. Model. in Geoph., 12 (2008), 55–64

Research into harbingers of earthquakes with wavelet analysis of data monitoring*

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Abstract. This study deals with technique of interpretation of harbingers of strong earthquakes aimed at operative forecast of seismic danger. Geomonitoring data of a natural impulse of the Earth's electromagnetic field (NIEEMF) together with seismic monitoring data are analyzed. As an instrument for the analysis of a non-homogenous structure, the wavelet transformation of a time series in question is used. Using a hypothesis about forming the "power wedge" on a "magnitude–time" diagram for allocated strong earthquake fault areas, the possibility of the data NIEEMF monitoring for the preparation process control in a fault area is shown.

1. Introduction

This paper deals with studying precursors in a fault area of a strong earthquake with application of the wavelet-analysis of the monitoring data. The analysis of seismic data about the preparation of a strong earthquake for an allocated fault area and variations of a natural pulse electromagnetic field of the Earth (NIEEMF) is made.

The data for 2007, obtained in the course of seismic and electromagnetic monitoring of the Altai–Sayansk seismic-prone area, are analyzed. A basis for investigations is the data of a seismic network for geophysical and gas-hydrochemical monitoring in the Altai–Sayansk region (on the territory of the river Altai, the river Khakassia, the river of Tuva, the Altay and the Krasnoyarsk territories) as a part of 12 key points for seismic, electromagnetic and gas-hydrochemical monitoring.

Let us note that the possibility of the earthquakes prediction with their pulse electromagnetic precursors is considered a long period of time [1]. It is known that most impulses that are continuously recorded at any point of the Earth's surface, have the lithospheric origin [2]. On the basis of the analysis of the long-term monitoring in seismic-prone areas of Northern Tjan-Shanja, and Baikal it is discovered that there is a connection between electromagnetic emission and seismic processes in the Earth's crust [3]. In 2005, in the Krasnoyarsk region, based on electromagnetic records from two stations NIEEMF ("Orie", "Shira"), there was revealed a connection between seismic events on an extensive territory. The daily average variations

*Supported by FASI, Contract 02.740.11.0031.

of NIEEMF obtained by the stations “Krasnoyarsk” and “Orie” have also common features with those obtained in the Baikal area.

The algorithm of fast wavelet transformation [4] that allows one to reduce the processing time for a big geomonitoring data file without loss in quality is used. Various wavelets: Gauss, Haara and MHAT were used for the data analysis. This attempt allows to carry out the data analysis on various wavelet scales. The result of processing are wavelet spectra of the EMI data which enable us to trace regularities of daily average and mid-annual NIEEMF variations, and, consequently the occurrence of electromagnetic earthquakes precursors.

Several large earthquakes which occurred in 2007, were studied. A comparison of wave spectra to the initial NIEEMF data, which reflect moments of the behavior of an electromagnetic field is made.

2. Methods of data analysis

For recording the NIEEMF, the equipment for the real-time tracing changes in variations of electromagnetic impulses (EMI) is used. The given equipment as a stationary regional station of monitoring is intended for solving a problem of the operative earthquake forecast, or as a field routing equipment for recognition of structural heterogeneities of the Earth’s crust deposits prospecting. The above-stated problems can be solved both by measurement and analysis of the NIEEMF parameters, and by measurement of the field arising at artificial activation of the Earth’s surface with a blow or an explosion. The equipment can be used for carrying out the basic research in seismology, geophysics, monitoring of a impulse electromagnetic field of the Earth, working out new methods for minerals search and for diagnostics of technical conditions of artificial constructions and estimation of their residual resource.

The equipment consists of a microcontroller, two recording channels for a NIEEMF magnetic component (H-component), the channel of an electric component (E-component) and the acoustic or seismic channel. There is a possibility of inclusion of four additional measuring channels. The NIEEMF intensity is measured by the method of calculation of impulses exceeding a set threshold on intensity of a field. The unit of measurement used is imp/second. On the basis of the long-term recording impulses of an electromagnetic field, average values of intraday variations of intensity of a stream of electromagnetic impulses are obtained. Earlier, the averaged daily NIEEMF variations recorded at the station “Shira” were studied.

The daily average variations received at the stations “Krasnoyarsk” and “Orie” have also common features with those obtained in the Baikal region. The following features in the change of the NIEEMF before earthquakes with $K > 4.0$ have occurred are marked: an abnormal course of a field is observed

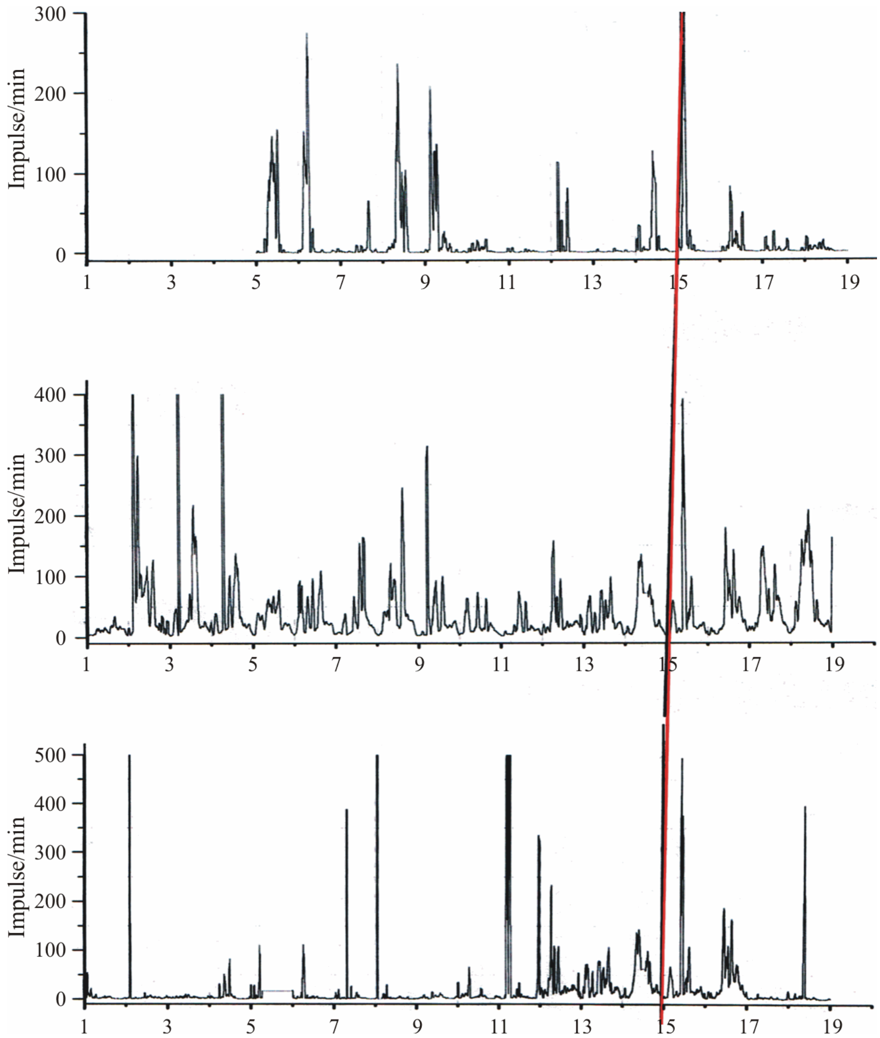

Figure 1. NIEEMF data from Shagonar, Tabat, and Orie stations (from top to bottom) on May 2006

three or less days before the earthquake occurrence; an intensity maximum is needed 8–40 hours before an earthquake; an earthquake always occurs when an anomaly is decreasing; the NIEEMF intensity in an abnormal course maximum 4–5 times exceeds the intensity of regular variations.

In addition, the NIEEMF data obtained from three stations (Figure 1), on the basis of 600 km (Shagonar-Tabat-Orie) testifies that seismic electric processes in the Earth's crust ASCR move with a certain velocity about 100–200 km/h that allows us to solve the problem of localization of the electromagnetic emission source using a network of the NIEEMF stations.

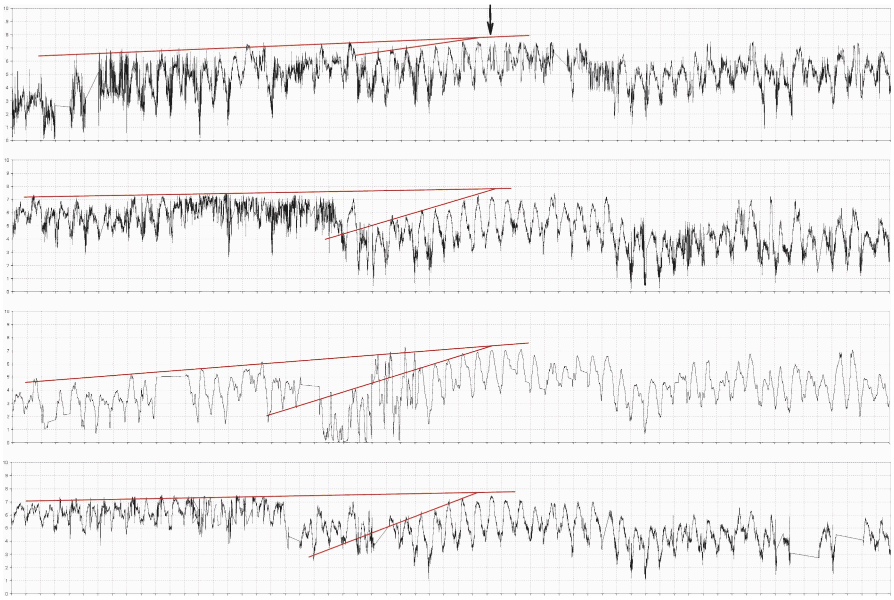

Figure 2. Representation of the number of recorder EMI impulses in the logarithmic scale and a "power wedge" detection

Research into NIEEMF data was carried out in several stages: transformation of the initial data from the equipment for further processing; processing of the transformed data (filtration); construction of diagrams of the dependence of the number of NIEEMF impulses on time and allocation "wedge areas"; construction of wavelet-diagrams according to NIEEMF; a comparative analysis of the processed data.

For transformation of the NIEEMF primary records (the number of recorded impulses per time) to the "power" form, it is necessary to transform the NIEEMF time series to a logarithmic scale with the following interpretation within the limits of the above described model, because the number of impulses per time represents an analogue to the released energy. In Figure 2 an example of representation of a number of recorded EMI impulses per time in the logarithmic scale $F = \ln N(t)$ is given.

The method of fast data wavelet transformation was used for analyzing the EMI. We write down the integrated wavelet transformation of the function $f(x)$ in the form

$$\widetilde{W}_{a,b} = \widetilde{W}_{\varphi} f(a,b) = |a|^{-0.5} \int\limits_{-\infty}^{\infty} f(x)\varphi\left(\frac{x-a}{b}\right) dx = |a|^{-0.5} \int\limits_{-\infty}^{\infty} f(x)\varphi_{a,b}(x)\, dx.$$

Function $\varphi_{a,b}(x)$ determines the basic wavelet for obtaining a wavelet diagram of the function $f(x)$ on the interval $[x_0, x_1]$ (the shift parameter b

changes in this range). The borders of the range of values of the scaling factor a are selected according to requirements of a certain task. The following calculation scheme of wavelet transformation of a signal under study is proposed:

$$a_i, \quad i = 1, 2, \ldots, M;$$
$$b_j = j \cdot \Delta x, \quad \Delta x = \frac{(x_1 - x_0)}{N} = \text{const}, \quad j = 0, 1, \ldots, N;$$

where N is the number of discrete readouts on the interval, M is the size of a sample of scales.

Let us introduce a function $L(a_i)$, characterizing a window of convergence of the basic wavelet:

$$L(a_i) \in \{1, 2, \ldots, \infty\}; \qquad \left| \varphi\left(\frac{\pm j \cdot \Delta x}{a_i}\right) \right| < \delta, \quad \forall j > L(a_i),$$

where δ is a convergence threshold, that is a positive constant whose values is "close" to zero. For $j > L(a_i)$, we assume that

$$\varphi\left(\frac{\pm j \cdot \Delta x}{a_i}\right) \equiv 0.$$

The basic wavelet matrices and the matrices $F_{l,j}$ are defined as:

$$l = 0, 1, \ldots, 2L(a_M);$$
$$\varphi_{i,l} = \varphi\left(\frac{(l - L(a_M)) \cdot \Delta x}{a_i}\right);$$
$$F_{l,j} = f\big(x_0 + (j - l + L(a_M)) \cdot \Delta x\big).$$

The wavelet transformation can be rewritten in the form of the integrated sum:

$$W_{a_i,b_j} = W_\varphi f(i,j) = \frac{\Delta x}{2\sqrt{a_i}} \sum_{n=L(a_M)-L(a_i)+1}^{L(a_M)+L(a_i)} \big(F_{n-1,j}\, \varphi_{i,n-1} + F_{n,j}\, \varphi_{i,n}\big).$$

As components of both matrices and of the function $L(a_i)$ are constants, the wavelet-transformation procedure is reduced to multiplication and addition of some set of constants. Thus, matrices are arranged so that the number of operations to calculate of factors of their entries be minimal. This essentially decreases the computer costs, necessary for calculations.

For numerical experiments with real data, the passage of programs [4], written in the language Borland C++ in the object-oriented programming environment "Builder 5.0" is used. The input and output data in numerical experiments are described by means of this software (Figure 3).

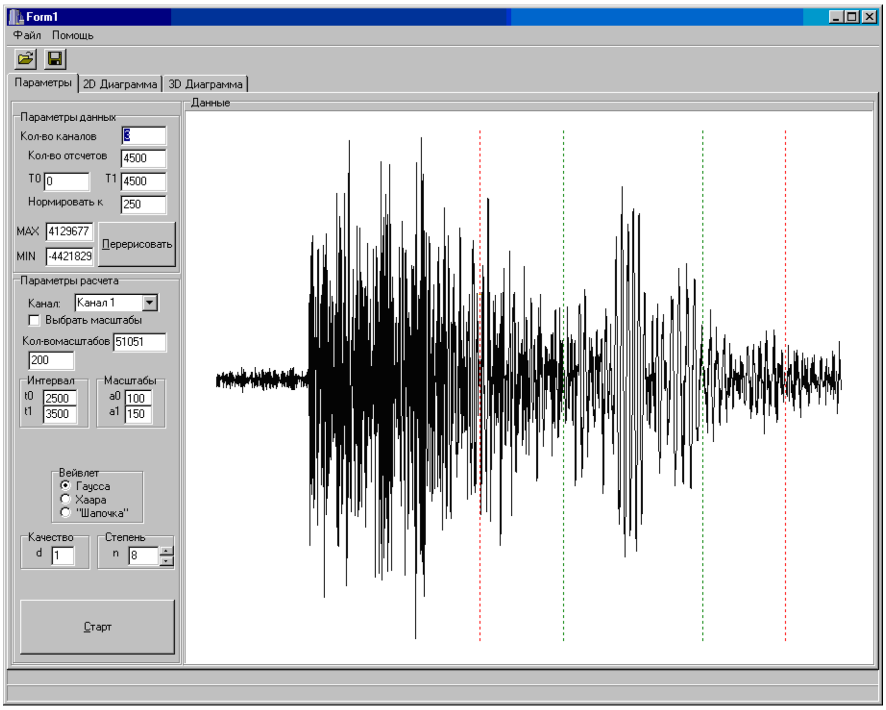

Figure 3. The program interface of fast calculation of a wavelet spectrum of the 1D signal

Input data:

- text file `*.txt` with a set of readouts of a signal;
- an interval of a signal and the number of channels (up to 256), which are to be read from a file;
- the channel number to be displayed;
- the start and the end of a processed interval of a signal;
- the start and the end of the parent-wavelet scale range, or a separate set of scales;
- a parent-wavelet type.

Output data:

- visualization of an initial signal (drawing can be saved as a graphic file if necessary);
- two-dimensional (3D in the future) visualization of a wavelet spectrum of the chosen channel of a signal;
- text file `WWW.txt`, containing specially organized values of spectra on all chosen channels.

After pressing the button "Draw again", the display window becomes more active and the input signal is visualized with allowance for the parameters chosen. In addition, the signal segment to be processed and the necessary additional intervals for excluding the boundary effects is displayed. By pressing the "Start" button, the wavelet-spectra calculation procedure is triggered.

3. Results of the data analysis

A detailed study of seismic data and electromagnetic precursors of the Baikal earthquake of 04.07.2007, which occurred in the North Baikal area with magnitude $M = 5.6$ has been carried out. The given event was recorded by a network of geomonitoring stations (Figure 4).

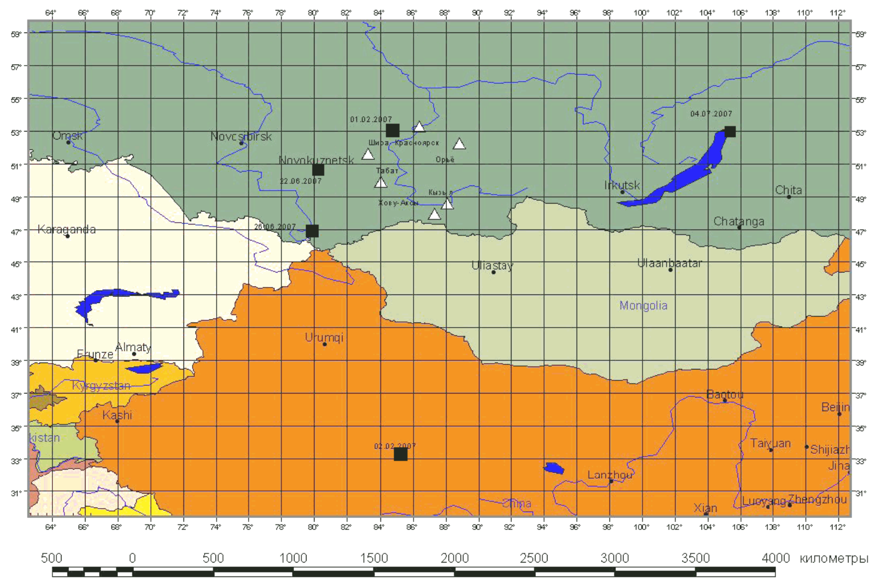

Figure 4. The geomonitoring stations network (white triangles) and notable earthquakes of the first half of 2007 (black squares)

By analysis of seismic process the seismic-prone fault area with a radius of 400 km is allocated. In this seismic system, the earthquakes with magnitudes of the range $3.7 < M < 5.6$ are detected within two-years period (Figures 5–7).

For carrying out of a comparative analysis of precursors, monitoring data the united diagram of wavelet, seismicity and EMI is made (Figure 8).

In Figures 8, a and b, moments of the Baikal earthquake are designated by an arrow. It is seen that the behavior of the NIEEMF in EMI diagrams and the behavior of frequencies in wavelet diagrams are interdependent. In particular, the moment of the Baikal earthquake of 04.07.2007 in diagrams of

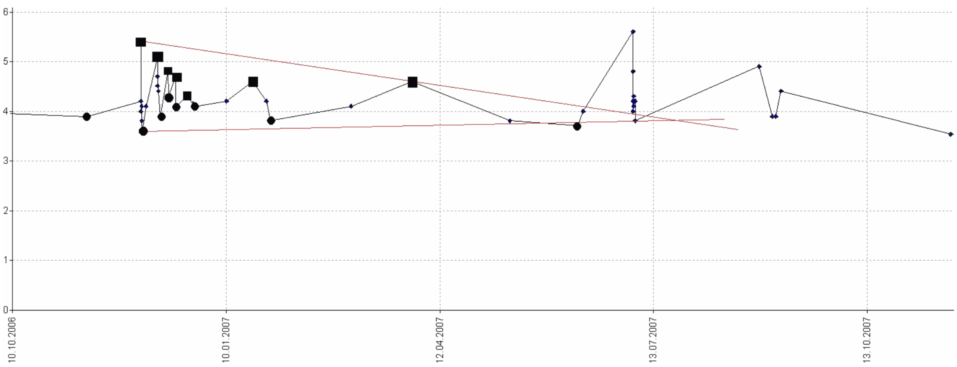

Figure 5. Allocation of the preparation area of the Baikal earthquake. Squares designate the top border of “a power wedge” and circles—the bottom border

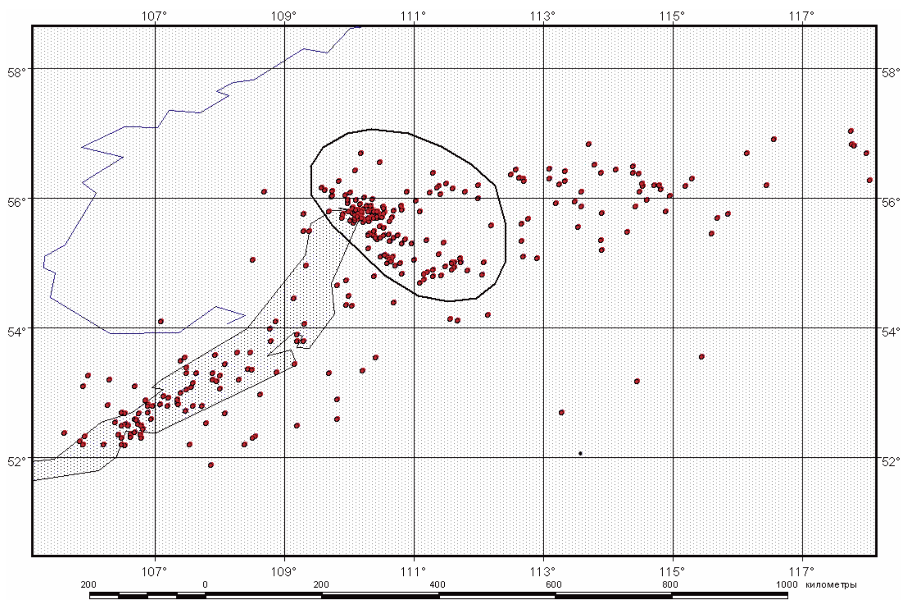

Figure 6. A fault area of the Baikal earthquake of 04.07.2007 with magnitude $M = 5.6$

the Gauss wavelet transformation is allocated as a sharp change of frequency structure on “wedge” areas. The developed technique of the analysis of precursors using the wavelet analysis is effective and suitable for analysis of the process of preparation of significant earthquakes. By the form of wavelet spectra it is possible to judge about the character of preparation of an expected earthquake.

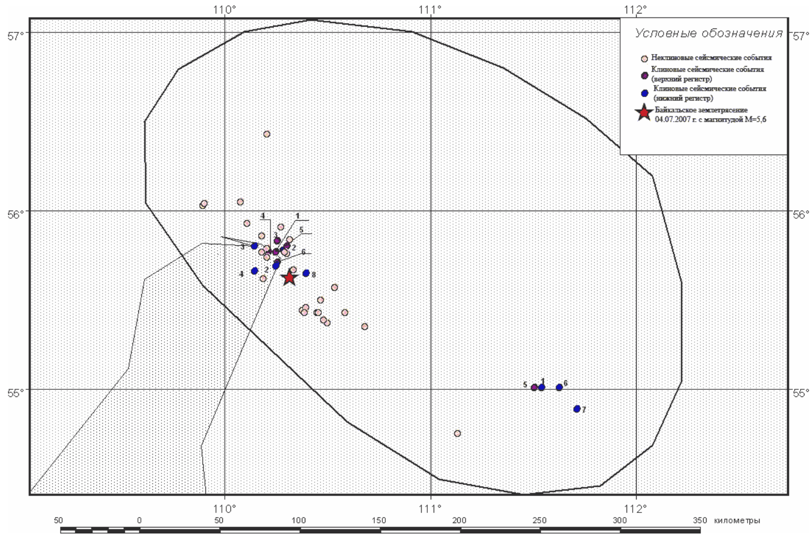

Figure 7. The spatial distribution of seismic precursors of the Baikal earthquake

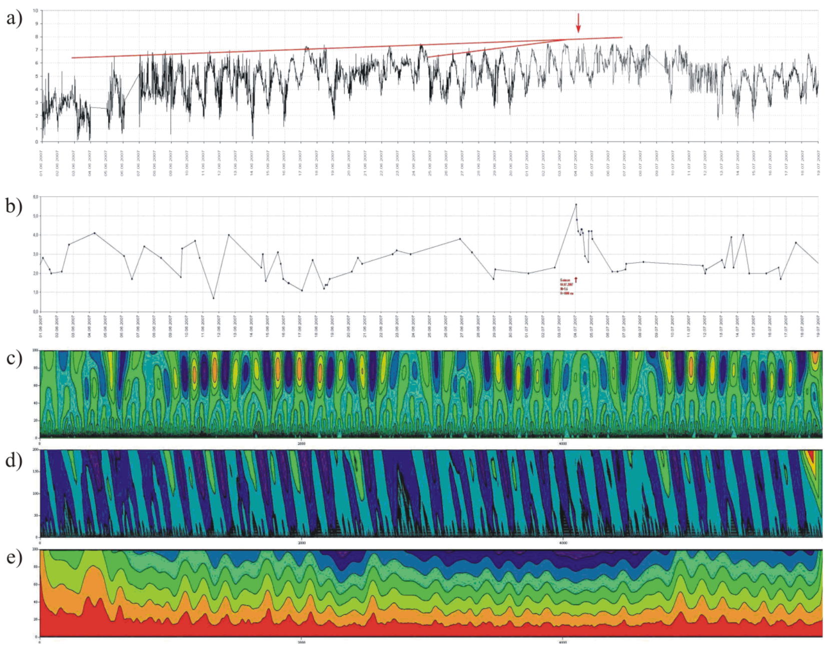

Figure 8. Comparative diagrams of wavelet spectra with the geomonitoring data from the station Orie for the period of 01.06.2007–19.07.2007: a) NIEEMF data for the station Orie for the period of 01.06.2007–19.07.2007; b) seismic monitoring data for the station Orie for the period of 01.06.2007–19.07.2007; c) wavelet spectrum of the Gauss transformation for NIEEMF; d) wave spectrum of the Haara transformation for NIEEMF; e) wave spectrum of MHAT transformation for NIEEMF

Conclusion

The analysis of the NIEEMF variations for revealing the seismic events precursors on the basis of the geomonitoring data is carried out. The technique for the NIEEMF data analysis using the wavelet transformation to describe the earthquakes precursors has been developed. Based on the results of the research, it is possible to conclude that the wavelet analysis is an effective tool for the description of the data structure as it obviously reflects the NIEEMF behavior in seismic-prone zones.

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