Bull. Nov. Comp. Center, Num. Anal., 16 (2013), 65–79

Studying a spatial-temporal distribution of seismicity in the area around Fukushima Prefecture by GIS-EEDB program tools

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Abstract. In this paper, a modification of the high-tech expert system GIS-EEDB (Expert Earthquakes Database) intended for solving a wide range of seismological research tasks, called "Fukushima-EEDB" is proposed. For the first time the system was developed on the platform of Windows 8. The basic logical and functional structure as well as results of the using mathematical algorithms for the seismicity visualization and analysis of seismic regime is considered. The analysis algorithms allow us to calculate maps and diagrams of changing seismic process parameters such as parameters of a magnitude-frequency graph (A and b), seismic activation and quiescence, clusterization of earthquakes, concentration criterion and so on. The geographical and analytical software provides a cartographic representation of a seismic characteristics change on maps and on cross-sections. Examples of the system usage are presented for studying a seismic regime of circumjacent areas of the Fukushima Prefecture, Japan.

Keywords: Catalog data analysis, seismic database, geocomputing, graphic and cartographic representation, parameters of seismic regime.

1. The high-tech system GIS-EEDB and its modification

The interactive computing system EEDB was developed to support investigations of the seismic-geodynamic regime in different geographical areas [1]. It can be considered as automated workplace for the researcher of seismology area. The GIS-EEDB logic structure represents a set of program blocks interacting with one another [1, 2]: a seismological database, a geographical subsystem and a subsystem of data analysis. These subsystems can be denoted on the functional scheme of the study sequence (Figure 1).

The term "expert" in the name of the system reflects one of its basic features: providing the user with the whole necessary information and modern scientific techniques for solving (in unified environment) different research tasks such as seismological data processing, the perfection of the means for a clear representation of results and introduction into the consideration of new seismological characteristics.

There exists a variety of physical and mathematical tools used for analyzing seismicity. These tools can be ranged from empirical relationships

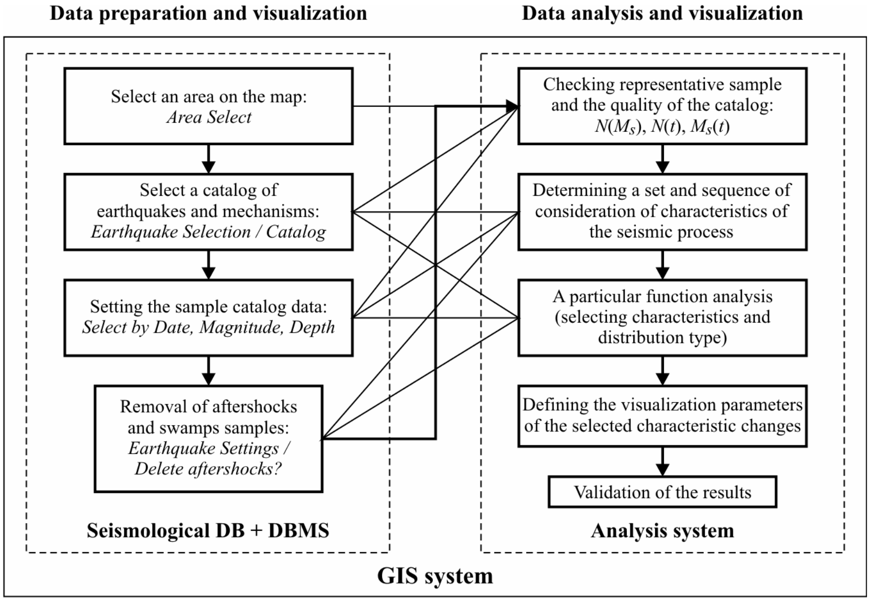


Figure 1. A sequence of seismicity study and the logic-functional structure of the EEDB system

obtained from the long-term observations of the behavior of global seismicity (the similarity law [3], the law of aftershocks intensity decay [4]) to the apparatus of mathematical statistics. The latter is applied to both:

- Research into a more local level within which the spatial distribution of events can be randomly considered.
- Study of time series because of a relatively short period of qualitative recordings of earthquakes.

In other words, the ultimate goal of developing the geo-information-expert system GIS-EEDB is not only the qualitative visualization on maps and charts, but also the expert analysis of the seismic process dynamics at different levels of scale: from global to local. At present, it seems to be very important to apply these possibilities to investigations of seismic activity in the Fukushima Prefecture affected on 11.03.2011 by 'the Great East Japanese Earthquake', $M_w = 9.0$ (the alternative name given by JMA is 'The 2011 off the Pacific Coast Tohoku Earthquake' or in short **Tohoku**-oki earthquake). We have bounded the scope of our research by the framework 36–39°N, 138–146°E. The adaptation and modification of the GIS-EEDB system to features of this geographical area consist of:

1. Creation of an optimal database using the Fukushima seismological data. Adaption of instrumental programs for processing and convert-

ing the Fukushima earthquakes data for the "Fukushima-EEDB" seismological subsystem format;

2. Development of a geographical system of the "Fukushima-EEDB" for the qualitative visualization and analysis of seismic data of the prefecture Fukushima. Filling a geographical subsystem of the "Fukushima-EEDB" with detailed geographical data of the prefecture using the ASTER GDEM data (for a shady relief model realized in the EEDB) and the Natural Earth (for detailed cultural and physical layers in vector and point format);
3. Adaptation of methods and algorithms to statistical processing seismic data in terms of a local geodynamics. Application of complex geoinformation analysis to learn regularities and anomalies of seismicity in Japan.

The above-listed preparatory works have been carried out in an environment of supporting applications expressly developed to supplement the system EEDB resources, and a subsequent preliminary analysis of seismic activity in thus adapted system Fukushima-EEDB. At the same time, the development environment of the GIS-EEDB was adapted to Windows 8 platform that consists of the translating codes of the main program and of supporting applications to the standards of the latest versions of Visual Studio and Firefox, and to adopting new versions of utilities: Global Mapper and FireFox.

For the seismological base, the Japan JMA catalog was chosen as the most complete one to date. When choosing, the following Japanese catalogs were compared: JUNEC (Japan University Network Earthquake Catalog, 1985/07/01–1998/12/31), NIED (National Research Institute for Earth Science and Disaster Prevention Earthquake Catalog, 1979/07/01–2003/06/30) and JMA (Japan Meteorological Agency Earthquake Catalog, 1926/01/01–2013/05/31).

2. The earthquakes distribution features visualized by means of the system Fukushima-EEDB

A simple **visualization** on the map with **sorting** by magnitude and the **selection** (by bolting small events) show some geologically active structures in the area adjacent to the Fukushima Prefecture. First, they are seismic lineaments and super-lineaments. It was assumed that seismicity of this area is a part of the trans-regional Japan-Sea lineament [5] (black lines boundaries in Figure 2), which extends from the Arctic Ocean to the Philippine Sea, including the underwater Lomonosov Ridge, New Siberian Islands, Sakhalin Island, Hokkaido and the north-eastern part of Honshu Island. The Japan-Sea lineament, in turn, is a composite element of the

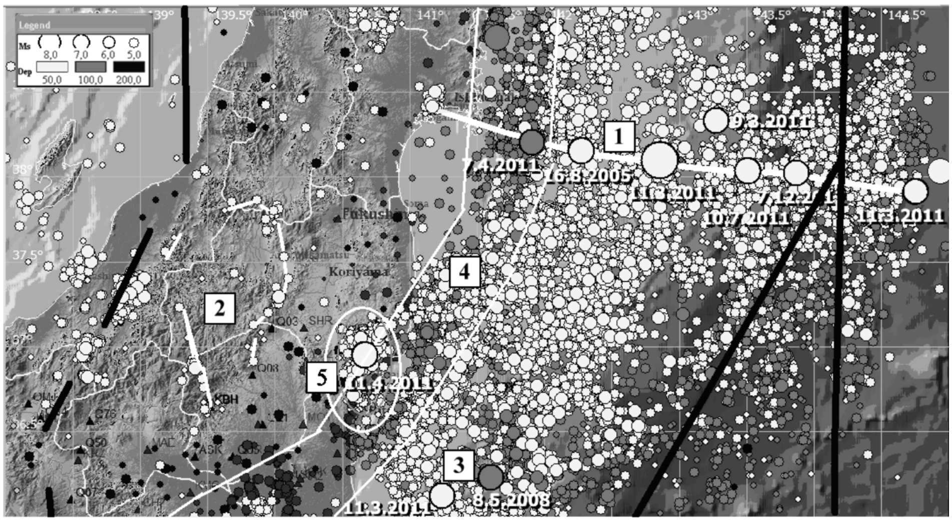


Figure 2. The seismicity of $M_s \geq 3.5$ (13,742 events) near the Fukushima coast, since 2003

Antarctic super-lineament being a planetary meridian seam [5]. In addition, the Fukushima map contains more local seismic structures in a linear distribution of the biggest events during the last 10 years (No. 1 in Figure 2); the response of 200 km to the south (No. 3 in Figure 2); a weakly-active intra-zone of volcanic activity in the form of a ring within including location of Aizu-Wakamatsu (No. 2 in Figure 2); a deep active zone (No. 4 in Figure 2); and a swarm (No. 5 in Figure 2) near the Pacific coast on the Ibaraki-Fukushima prefectural border (that is a shallow normal-faulting earthquake sequence [6]) including the $M_s = 7.0$ earthquake on April 11, 2011. This is an example of conducted visualize analysis of the primary information of the selected seismicity, using the visualization procedures of "Fukushima-EEDB" (see Figure 2).

The revealed linear distribution of the major events of $M_s \geq 7$ including the disastrous Tohoku-event can be considered to be the most interesting result (No. 1 in Figure 2; Figure 3a). The map of Takashi NAKATA et al. [7] marks in this region the tectonic elements of the northeastern and northern directions in line with global structures. But the trending of some tectonic structures: the stepwise displacement of eroded anticlinal ridge as well as the angled bend in the direction of the main Japanese trench (Figure 3a) and of other parallel faults, allow us to assume an ancient lately inactive fault along 38 parallel or another special structure, which manifested itself as a lineament with a high seismic potential in the last decade.

Substituting this tectonic map into the GIS-EEDB-system as a **background map** and visualizing major earthquakes (in the mode of **focal mechanisms drawing**) (see Figure 3), we see that the events of this chain

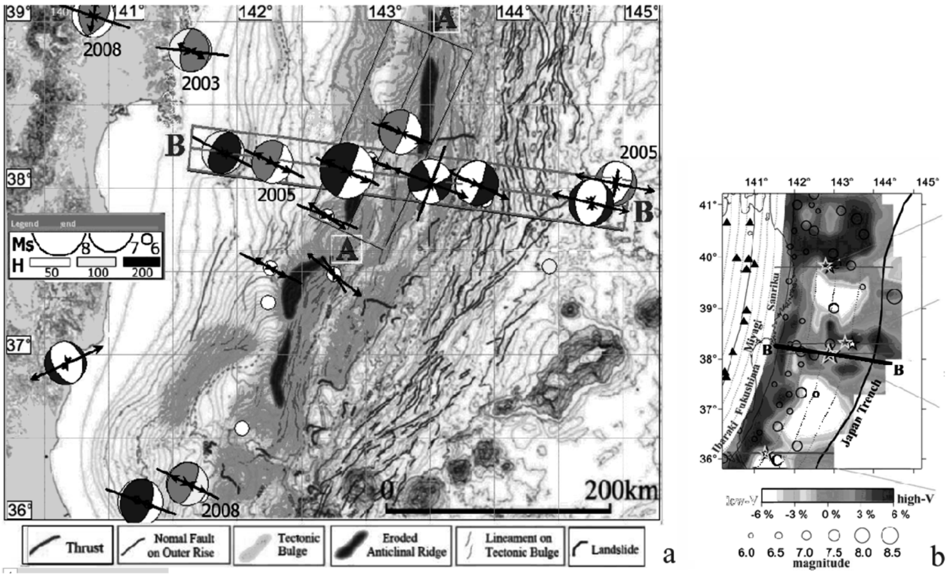


Figure 3. The rigid linear structure (BB): a) the tectonic geomorphologic map [7] (thin rings shows the events before the Tokoku-event, fatty— after that); b) the P-wave tomography image [9]

are localized in the gap between extended tectonic bulges and belong to different seismotectonic segments: reverse, strike-slip and normal:

1. The first left three events of the chain have the so-called reverse dip-slip mechanism of compression including, also, a shallower foreshock of the Tohoku-event located just to the north (Miyagi-oki event of 9.03.11), and the remote response in the southern part of the region.
2. The average event has a shift slide mechanism.
3. The right three events have normal mechanisms of stretching.

A frequent change in geodynamic regimes is characteristic of the inter-plate boundary separating the North American, Eurasian, Pacific and Okhotsk plates [8] and corresponds to a change in directions of the major tectonic deformations in this region.

The cross-section profile (AA in Figure 3a) directed along the strike of the main tectonic zones shows that although the center of seismicity after the Tohoku-earthquake had shifted to the right of the main event, however the area between the Tohoku-oki event and its foreshock was still weakly active (Figure 4a), especially on the zone of about 15 km wide marked in Figure 4a. This also suggests the presence of a rigid linear structure, aimed across the main direction of the linear tectonic zones. The shift of plates

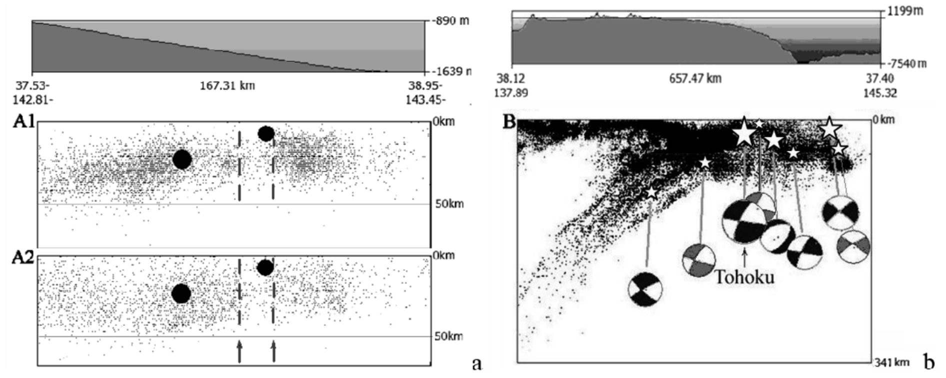


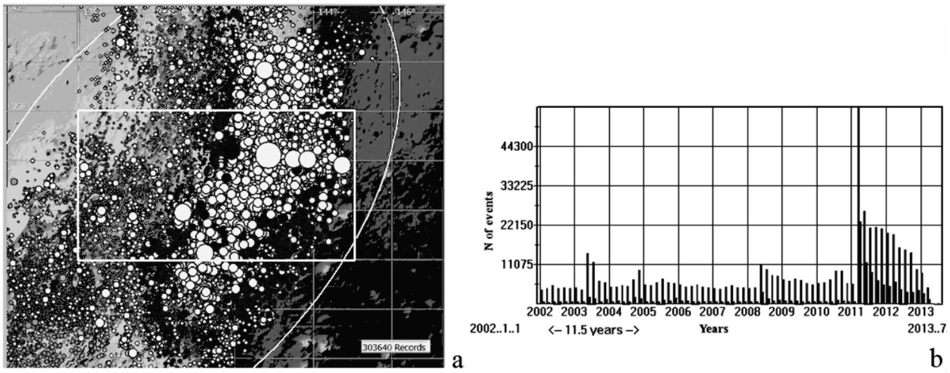
Figure 4. The cross-section profiles built by the GIS-EEDB: a) AA in Figure 3a for the whole seismicity before the Tohoku-event (A1) and after that (A2), b) BB in Figure 3a for the Tohoku-event aftershocks. The major events ($M_s \geq 7$) and the vertical projection of their mechanisms are shown by stars and stereograms in the figure b

along this structure could result in a cascade of destructive events at the edges.

Another evidence confirmed the fact of existing rigid inhomogeneity along the 38th parallel, for example, by the presence here of P-wave high-velocity areas [9, 10] (Figure 3b): "The high-V patches in the megathrust zone may result from subducted oceanic ridges, seamounts and other topographic heights on the seafloor of the Pacific plate that become asperities, where the subducting Pacific plate and the overriding continental plate are strongly coupled" [11]. Furthermore, some authors basing on the lateral slip distribution of the Tohoku-event [12] and on the other evidence assume here "a landward extending oceanic fracture zone controlling the slab morphology change around 38°N" [12, 13].

As a cross-section profile (BB in Figure 3a) that is perpendicular to the linear structure of the region and directed along the 38th parallel shows (Figure 4b), the location of earthquakes of the studied chain by the shape follows the junction zone of the Pacific and continental plates. We see that the compression mechanism of events corresponds to a zone of the Pacific plate dipping and its interaction with the continental plate, but the normal mechanisms — to the area, where the oceanic plate is stretched because of subduction. It is seen that the strongest event is located in the lowest depth of the active surface interacting plates and at the extreme bend point of oceanic plate.

Thus, we have considered an example of the primary information analysis of seismicity by means of the GIS-EEDB system using selection, sorting, and visualization. We use such procedures of visualization as: the procedure of mechanisms stereograms drawing on the map and profile (with calculat-



a b

Figure 5. The aftershock process of the Tohoku-event with respect to space (a) and time (b). Here the elliptic algorithm based on the Prosorov method [14] is used (*a*). Rectangle marks the area under study. The graph (*b*) shows that the aftershock process is not over yet (blue bars indicate to the number of all events, red bars— to events of $M_s \geq 2$)

ing the vertical projection of stereograms), in which a multi-layer fill (in the XOR-mode) of asymmetrical ovals calculated by the parameters of mechanisms catalog are used; the procedure of mechanisms drawing in the vectoral mode; the procedure of profile selection and drawing with building a relief profile and a vertical section of seismicity in a selected visualization mode; the procedure of loading to the EEDB environment whatever external raster map as a background; the recognition algorithm of linear structures by a set of points distributed in space; and so on. All the examples were shown using the functions of the first column of the functional scheme (see Figure 1), including the aftershocks detecting.

The functions of **aftershocks detecting** implemented in the EEDB are a set of different methods (empirical, elliptic, and interactive) and various modifications of the elliptic method [1, 2]. The efficiency of different algorithms for detecting aftershocks was evaluated by estimating the statistical properties remaining after the purification sets, and comparing them with a random Poisson exponential distribution. The application procedure of detecting aftershocks to seismicity of studied region remains only 14 % of the initial earthquakes. We have obtained using a temporal graph (Figure 5b) that the number of aftershocks is a few hundred thousand (303,640 events) and the aftershock process is not over yet: the seismic background has not reached the average level observed before the event. Thus, we can make an important conclusion that the bigger part of the studied region seismicity does not have an independent nature, and these are the sequences of events that are triggered, partially, by the Tohoku-earthquake. Moreover, a spatial distribution of the Tohoku-event aftershocks (Figure 5a) can help us to estimate the size of its activity zone, and consider the area adjacent to the Fukushima Prefecture as a part of the Tohoku-event preparation area applicable to retrospective search prediction characteristics. The application of the procedure of excepting the swarms and aftershocks to study the seismic regime characteristics significantly improves parameters of the process, bringing them to a stationary seismic process.

3. The research into seismicity parameters using analysis subsystem of Fukushima-EEDB

The study of seismic regime anomalies can be carried out for different seismic and geodynamic tasks. In this paper, we show the usage of the analysis subsystem of the Fukushima-EEDB for a retrospective study of various anomalies before a major earthquake, for example, the Tohoku-event. In addition to selection of the preparation zone of the analyzed earthquake, it is initially important to estimate the quality of the catalog used for the correct performance of data selection according to the upper bar of the second column of a functional scheme (see Figure 1). First, the selected catalog JMA allows finding out how the recording characteristics of the seismic network changed in time and in the energy range by means of the following graphs building in the EEDB:

1. The dependence $M_s(t)$ allows one to identify the following features:
   - The qualitative leaps of the recording system in 1977 (for $M_s < 3$) and 1987 (for $M_s < 1.5$), that are reflected in the steady growth of the number of recorded earthquakes—on average 3 times each year,
   - Stabilization at the end of 1997 (for the full range of magnitudes).
2. The $N(t)$ graph: In the more detailed range starting from mid-90s, another leap (in 2002 and 2003) may be noted followed by stabilization in recording quality.
3. The **Gutenberg-Richter dependence** of $N(M_s)$: A linear part of the graph in the magnitudes interval of 3.5–6.5 (by a least squares method) is revealed, corresponding to the Utshu method [15] (a maximum likelihood method) to the energy class interval of 10–16.

Based on this analysis, we can conclude that the seismic regime characteristics will mostly be reliable with the following parameters for selection: by 2002–2013 for the catalog completeness, and by magnitude 3.5–6.5 for the magnitude representativeness.

The magnitude-frequency dependence: $\lg N = \lg A - b(M_s - M_0)$, is not only interesting as a way to determine a statistically significant range of the magnitude. It also contains parameters which are the characteristics of the seismic process such as: A — a seismic activity reduced to a certain magnitude M_s (calculated from the energy class K) and b — the slope of the frequency.

Seismic activity A [16] is the first characteristic of seismic process explored by the *cartographic method* implying a calculation of contour lines for the averaged values of the parameter on a regular spatial grid. The resulting map of the parameter A_{15} shows the distribution of the mean long-term trend of reduced to 15 class ($M_s \simeq 5.5$) seismic activity, to obtain which the statistical homogeneity of averaged seismicity is required. We can see on the map (Figure 6) that the peaks of the long-term seismic activity for the last 20 years in the area of Fukushima are directly adjacent to the coastal line of the Fukushima Prefecture with a maximum in the area of Hitachi city.

To visualize of the spatial distribution of the **parameter *b***, another cartographic method: maps calculating according to the uniform time intervals is used. In the fill mode of contour lines visualization, the program to shade using a two-dimensional Bessel functions performs the spatial interpolation. This map (Figure 7) shows on the central zone of the Tohoku-event the formation of a poorly defined concentration center of negative anomalies, which stretched along the 38th parallel before the shock in 2007–2011. The temporal range is selected to have a sufficient number of events to obtain an acceptable error of estimation. The calculation of the estimate error uses

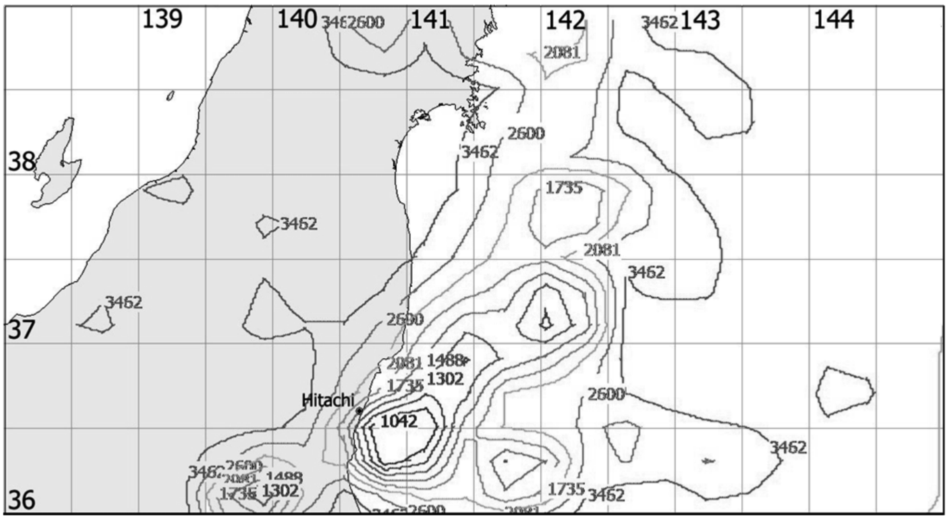


Figure 6. Seismicity activity in 1994–2013, $M_s = 3.5$–7, aftershocks are removed. The isolines (without shading) are displayed in the mode of calculating the value of frequency of events occurrence for each level in terms of years

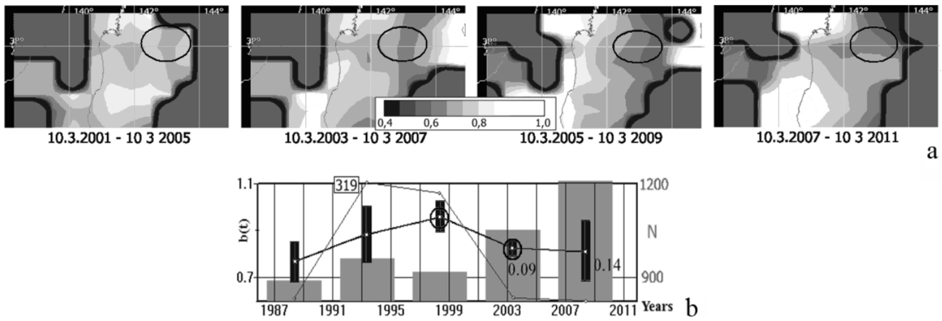


Figure 7. Fluctuations of b-value: a) the spatial anomalies averaged over 4 years (the cell size $0.4 \times 0.6°$, $3.5 \leq M \leq 7$, the root-mean-square deviation $\sigma \leq 0.3$, aftershocks are removed, the oval marks a focal zone of the Tohoku-event formation); b) a temporal graph with averaging over 5 years (the vertical green lines denote the deviation σ, the oval marks points of $\sigma \leq 0.09$; blue bars indicate to the number of events; a black line denotes the ratio of the numbers of weak to strong earthquakes)

the concept of representativeness of a sample: $\epsilon = |u|/(2\sqrt{n})$, where n signs the data sampling volume and the quintile value is $|u|_{0.95} = u_{0.975} \cong 1.96$ [2].

A decrease in the mean parameter b during the last 10 years amounts the value 0.15 (from 0.95 to 0.8 according to Figure 7b) with the error of estimation $\epsilon = 3.3$–2.9 %. Additional control of the values stability is done by a standard deviation having amounts to 0.09–0.1 at the most significant points (Figure 7b). As is known [17], b-values decrease indicates to a violation the uniformity of environment, its self-organization in rigid structures with increasing stress that may designate the preparation of a strong earthquake.

Relative total energy released by earthquakes per unit of time, which normalized to the background value of the mean seismic energy and presented in the form: $\log(E_{\text{sum}}/E_{\text{norm}})$, is the next parameter of the seismic regime under consideration.

This parameter is offered by P.G. Dyadkov [18] and has an advantage due to its greater independence of the character of the seismicity distribution in space (the results interpretation is not required to take into account the density of seismic locations in each cell). There is visible (Figure 8) a structure and dynamics of quiescence, formed in the last 2 years before the Tohoku-earthquake. The quiescence began to form in 2008–2009 years to the north part of the center of a future event. It was replaced by a weak foreshock activation for one year before the main shock. At the same time, the explicit quiescence is formed to the west and to the south of the shock in 2010.

This indicates to the fact, that the mechanism of seismic gap was loaded in this case. This effect was described in literature including those in Japan

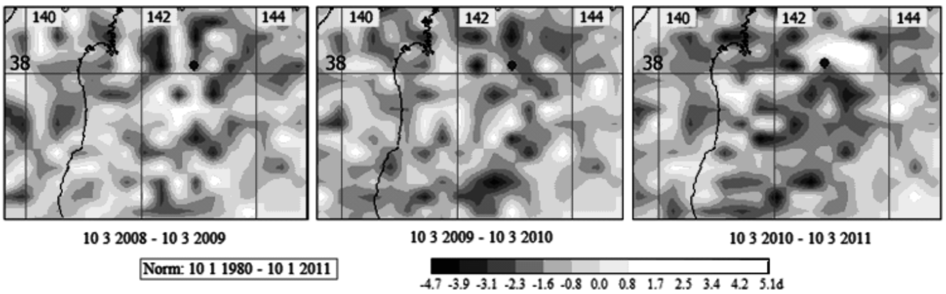


Figure 8. The relative seismic activations (yellow) and quiescence (blue) over one year time intervals before the Tohoku-event (the cell size $0.2 \times 0.3°$, $3.5 \leq M \leq 6.5$). The future Tohoku-earthquake epicenter is shown by the circle

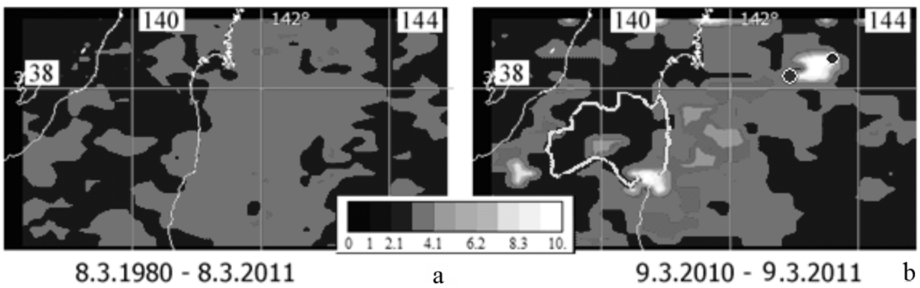


Figure 9. The gradients map: a) for the background seismicity; b) for the seismic activity over one year prior to the Tohoku-event (the cell size $0.1 \times 0.2°$, $3.5 \leq M \leq 6.5$, aftershocks are removed). The future Tohoku-event and its Miyagi-oki foreshock are shown by circles

as a basic model predicting many large earthquakes [19]. Moreover, we see that the shock center falls on the border area of the quiescence, into the point of the largest gradient values between areas of high and low relative total energy. This confirms the conclusions of our studies in 2004 [20] for the data of the Baikal rift zone that the largest earthquakes occur on the border areas of an anomalous seismic deficit at its points of a maximum gradient. The gradients map clearly shows the concise positive anomalies on the areas between the future Tohoku-event and its foreshock, as well as on the areas of a future earthquake of April 11, 2011 on the Ibaraki-Fukushima oceanic shores (Figure 9b). The procedure for the gradient calculating search for a maximum difference in the value of a relative energy of the current cell in comparison with the neighboring ones.

Parameter of density of seismogenic fractures or the concentration criteria K_{avg} is the most physical parameter as uses the theory of strength and the concentration criterion of the solids fracture to describe processes in the earthquake. This theory was developed in the papers by Akad. S.N. Zhurkov [21] and then A.D. Zavjalov proposed to use it

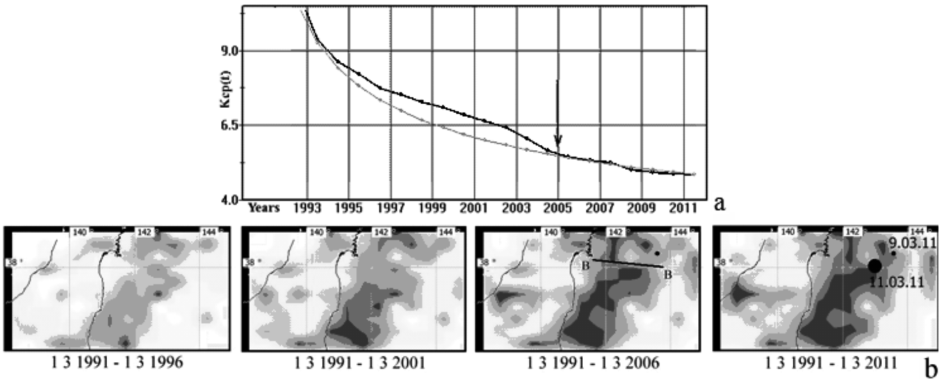


Figure 10. A change in the concentration criteria of the parameter K_{avg}: a) with respect to time (blue—real data, red—the data of a uniform increment of cracks); b) with respect to space (the cell size $0.3 \times 0.5°$, $3.5 \le M_s \le 9$, $H_{\max} = 50$ km)

for the prediction problems in seismology identifying a threshold value of this parameter for the Kamchatka region [22]. P.G. Dyadkov proposed another usage of this parameter for characterizing the seismic regime [2]. In particular, for the Chuya earthquake in the Altai region, on the temporal flattening of the cumulative graph K_{avg} in comparison with the idealized graph of uniform increments of fractures it appeared possible to identify the duration of the stability of the seismic process before a strong shock [2].

On the example of the Tohoku-earthquake, we also observe the flattening of the graphics in the last 6 years before the shock on the whole area of the shock preparation (Figure 10a). On the distribution map of the reviewed cumulative parameter (Figure 10b), we see the manifestation of the above described rigid structure BB (see Figures 2 and 3), as well as the expansion process of the fractures concentration to the area of the future Tohoku-oki shock (Tohoku-event) and its foreshock foci.

4. Conclusion

The Analysis system of the EEDB allows us to carry out a complex study of various characteristics of seismic processes. The functioning of the Analysis system is provided by two other systems: the Seismic database and Geographic information system of visualization; as well as by mathematical tools of computing characteristic and flexible methods of carrying out the study on the basis of the experience gained, knowledge and intuition of the researcher. Adaptation and application of the EEDB tools for studying seismicity of the territory adjacent to the Fukushima Prefecture have revealed the following results:

1. The presence of a rigid linear structure along the 38th parallel, directed across the strike of the Japan Trench and other linear tectonic structures of the region, was spatially revealed,
2. The assumption that the shifting of this structure inside the 09.03.11 due to moving plates, could bring about a cascade of destructive events of 11.03.11 at its edges was justified.
3. The JMA catalog was investigated in terms of the magnitudes representativeness and periods of the qualitative changes in the recording characteristics of the stations network.
4. The long-term seismic activity map reduced to the 15-th energy class shows that the greatest activity occurs on the area of the Japan-Sea trans-regional lineament in the Fukushima area over the past 20 years. It is directly adjacent to the Fukushima Prefecture coastal area with its maximum near to the Hitachi city.
5. The middle-range and long-range anomalies were detected from characteristics of the seismic process happened before the Tohoku-event including: 1) A poorly-distinct reduction of the parameter b for the last 10 years prior to the event; 2) the graph flattering of a parameter of the seismic fractures density on the studied area for the last 6 years; 3) the formation of quiescence zones for the last 2 years; 4) bright positive anomalies of relative energy gradient for the last 1 year prior to the shock.

All of these signs may indicate to the spatial and temporal features of the environment stabilization and consolidation in front of the Tohoku strong shock.

Acknowledgements. The author is grateful to Prof. Kenji Satake (The Earthquake Research Institute, The University of Tokyo, Japan) for the access to the JMA-catalog and to Dr. An.G. Marchuk for preparing the data from Natural Earth site; as well as to Prof. A.P. Vazhenin (University of Aizu, Japan) for helping in formulation of the task and its realization.

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