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The expert earthquake database (EEDB) for seismic-geodynamic research*

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Abstract. In this paper, a high-tech expert system EEDB for solving a wide range of seismological research tasks is proposed. The logical and functional structure as well as results of the algorithms usage for the analysis of seismic processes are considered. The algorithms allow us to calculate and to visualize maps and diagrams of seismic regime parameters such as parameters of a graph of repeatability, seismic activity quiescence, clusterization of earthquakes, concentration criterion. The analysis software provides a cartographic representation of a seismic characteristics change in space. Examples of the EEDB system application with the view of learning concrete seismic regime anomalies are given.

Keywords: Earthquake prediction, geoinformation approach, visual analysis, seismicity parameter

Introduction. The interactive computing system called the EEDB was developed by the authors for the research into the seismic-geodynamic regime. The construction of the system was a gradual transition from a usual geoinformation to a high-tech expert system due to a consecutive inclusion into it of various mathematical methods for the seismological data processing, introduction into research of new geophysical characteristics and because of the perfection of the means for a clear representation of results. The term "expert" in the name of the system reflects one of its basic features: providing the user with necessary information and modern scientific techniques for solving a given research task. Therefore the created information-expert system can be considered as automated workplace for the researcher of the seismic-geodynamic regime in different geographical areas.

The logic structure of the EEDB represents a set of programs blocks interacting with one another: a seismological database, a geographical subsystem and a subsystem of data analysis (Figure 1). Of a similar structure were systems prior to the EEDB as applied to other tasks, in particular, to the tsunami problem in the Pacific Ocean [1].

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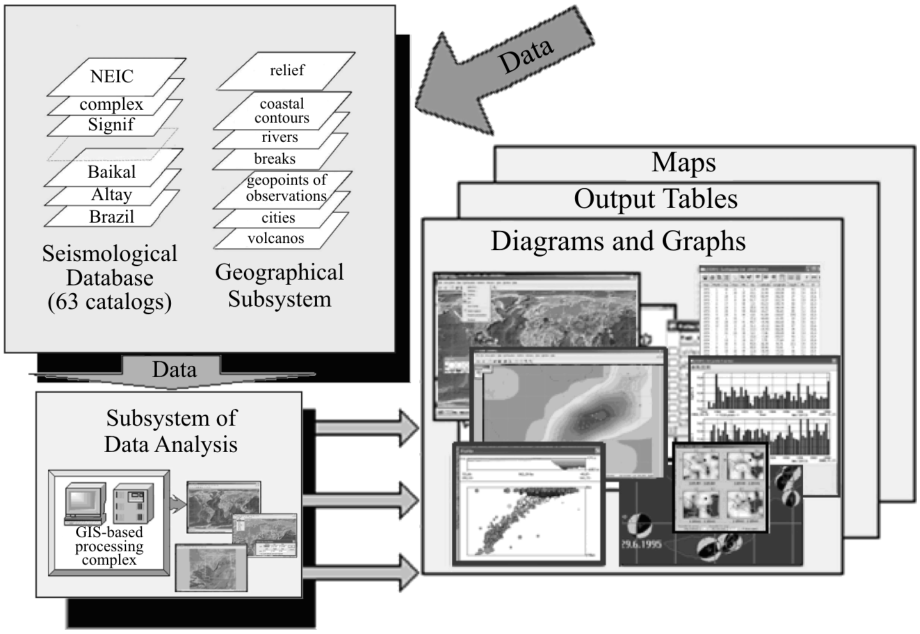

Figure 1. Functional structure of the EEDB software

The seismological DB underlying the basis of the system contains 63 catalogs of historical and modern earthquakes, among which are both catalogs from known agencies and geophysical services, and the authors' catalogs representing the incorporated and cleared data collected from various sources. Many catalogs are used from the following considerations. First, this allows both in the scale of the whole globe with the world catalogs and on local levels with the regional monitoring data. Second, the comparative analysis of completeness of various catalogs intersecting on the maps carried out with the help of the EEDB (using histograms of the average events number per time unit and the curve of dependence of the magnitudes registered in the events catalog on time) conditionally enables one to zone a geographical map into regions with indication to a preferable catalog (Figure 2).

In our studies, we most often use the world-scale catalogs, such as the global catalog NEIC (1973 till present) and SIGN (−2000 up to 1993) of the American Geophysical Service (USGS), and the regional-scale catalogs, such as the compiled Baikal catalog (BAIK in the sequel—a source for 87 % of its records were materials of the Baikal Branch of the Geophysical Service, SB RAS—URL: http://www.seis-bykl.ru), and the Altai catalog (Altai-Sayan Branch of GS SB RAS). As Figure 2 shows, the isolated by us mutually imposed boundaries of catalogs completeness are even wider in the case of the catalog BAIK, than was established by authors of GS catalogs [2, 3].

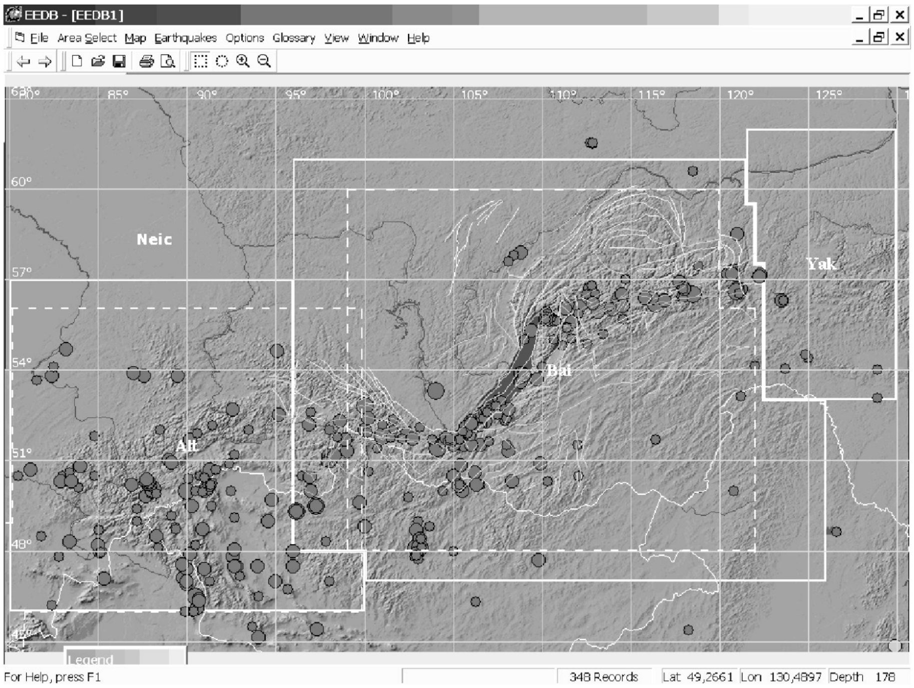

Figure 2. Regional zoning according to the earthquakes catalogs completeness data with the names of these catalogs. The geographical layers on a relief map are the following: earthquakes (Ms ≥ 5), boundaries, rivers and the fractures zones of various types. The dashed line denotes the boundaries of regions indicated by GS SB RAS [2, 3]

The format of the given earthquakes epicenters contains fields with the key parameters estimating the source of earthquakes: seismic energy, magnitude, geometrical size of the epicenter (Length), the moment of the earthquake occurrence, epicenter's coordinates and depth (Figure 3). The main seismic characteristic is seismic energy, which in different catalogs may be expressed by various power scales. For example, for many events of the NEIC catalog, only magnitudes determined with the body waves (mb) are known, but for events from other catalogs, in particular, for the Altai territory, there is only an energy class $K = \lg E$ (determined by T.G. Rautian's technique [4]). For reduction of all catalogs to the uniform magnitude scale Ms (surface-wave magnitude) we used a well-known Richter's formula for the global catalogs $K = 4.8 + 1.5$ Ms and other variants of this formula have been accepted by now for regional catalogs, in particular, $K = 4.0 + 1.8$ Ms for our investigation of territories of West and East Siberia. The formula Ms $=$ (mb $- 2.4)/0.5556$ that were empirically obtained from the ratio of known magnitudes pairs is used for recalculation of Ms from mb. The length of seismic dislocation L is calculated by the formula $\lg L = aK + c$, where a and c are some constants [5].

Year	Month	Day	Hour	Min	Sec	Latitude	Longitude	Depth	Ms	Kl	Book	Lengh
1968	6	17	2	55	13,5	55,96	110,58	0	4,2	11,5	11	3,66775
1968	7	2	1	49	50,0	53,18	107,62	0	4,1	11,0	11	3,27793
1968	7	3	3	17	21,7	53,18	107,62	0	3,6	10,5	11	1,97697
1968	7	14	7	11	29,2	53,16	107,64	0	3,9	11,0	1	2,61818
1968	7	30	21	22	23,6	51,89	105,92	0	4,2	11,5	1	3,66775
1968	8	17	6	46	49,9	50,52	108,85	0	3,9	11,0	1	2,61818
1968	9	10	7	54	52,5	55,86	110,01	0	3,9	11,0	11	2,61818
1968	10	19	21	15	37,5	53,02	106,91	0	3,7	11,5	11	2,21208
1968	10	30	1	33	37,0	52,22	106,37	0	4,4	10,5	11	4,34110
1968	11	11	22	54	55,7	54,93	110,28	0	3,6	11,5	11	1,97697
1968	11	13	13	21	6,3	52,82	107,35	0	3,6	11,0	11	1,97697
1968	11	24	15	21	26,0	53,60	109,00	12	4,4	12,5	10	4,34110
1968	11	25	20	46	38,4	53,40	108,14	0	3,6	10,5	11	1,97697

Figure 3. Catalog format of seismic events

The preprocessing of initial catalogs consisting in selection of an earthquakes subset according to the inquiry parameters is also included into the seismological block: the choice of a current catalog, the range of time, magnitudes, a spatial range, etc. Further, the dynamic separation of the earthquakes chosen from aftershocks is possible; an independent function realizing three algorithms of this operation at the user's is available. The first algorithm, conditionally named statistical, is based on parameters of a spatial-temporal difference between aftershock events and the main shock, which were obtained from the statistics of the available data on aftershock processes and are dependent on the main shock magnitude. However, a most frequently used method of aftershock filtration is the second algorithm (Figure 4) including the following stages:

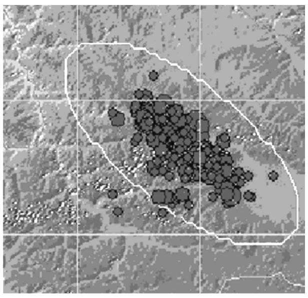

Figure 4

1. The first pass of the catalog aimed at finding the non-aftershock events density (aftershocks are eliminated according to the parameters found by the above-mentioned statistical method).
2. The second pass, when the preliminary aftershocks are determined on a rectangular cell, whose size is proportional to the main shock magnitude.
3. Calculation of the dispersion ellipse isolating the aftershock group by the maximum-likelihood method or the root-mean-square deviation from the center of sampling.
4. The subsequent passes of the catalog aimed at the level-by-level aftershocks separation in the elliptic metric.

At Stages 2 and 4, the aftershock process time is determined as ratio of the aftershocks number to the total density on a rectangle or on an ellipse according to Prozorov's method [6].

The geographical subsystem is an important part of any GIS, because an adequate visualization of the geophysical data is a necessary condition of its correct interpretation. Methods of the digital cartography and appropriate GIS-technologies make it possible to develop the seismological data visualization system on the cartographical basis meeting the user's requirements for the plotting not only of catalogs of earthquakes but, also, of other accompanying information.

The system of cartographical support of EEDB uses the "shaded-relief raster images" [7] for creating the digital geographic maps. The 3D-effect is provided by the consecutive triangulation method and calculation of each triangle's brightness according to the orientation of its plane with respect to the pitch angle of a light beam. Parameters of illumination and main colors are set by user. Then various shades of brightness can be obtained. To make the construction of maps of various scales possible starting with the all-world map and ending with maps of investigated regions, an appropriate data array with an optimum spatial resolution is automatically selected, and the quantity of triangular elements in each grid cell fitting the chosen scale of a map is defined.

Currently there are some global databanks representing a surface relief with various resolutions [8]. The most well-known among them are GTOPO-30 and SRTM-90, respectively, with 30 arc-second and 3 arc-second data grids in the proposed system. The GTOPO-30 and SRTM-90 databanks are freely distributed digital models of a relief developed by the U.S. Geological Survey (USGS). More detailed data on SRTM-90, that give 90 meters spatial resolution, are connected by our program at local level, when zooming maps of investigated areas (the Baikal and the Altai regions) are constructed. Then the vector and the dot layers and, also, explanatory texts are imposed onto a raster image.

The vector technology is applied to a level-by-level screen visualization of coastal lines, rivers, states borders, fault zones and fractures of the Earth's crust (with division into reverses, strike-slip, downthrows, downthrow-strike-slips, upthrows, upthrow-strike-slips). This technology is applied with the purpose to reduce the volume of the saved information due to the storage of linear objects coordinates as vectors. The thickness of lines of an image remains constant when objects are zoomed.

The dot information is kept in simple textual files and consists of such layers as points of geophysical observation, the volcanoes locations and settlements, and may be easily filled up with any other dot information.

A subsystem of the data analysis includes methodologies, methods and algorithms of a solution of geoinformation analysis tasks basing on the developments of authors and up-to-date leading researchers into the seismic-geodynamic processes using the earthquakes catalogs.

The first layer is the above-mentioned procedures of checking the completeness and the quality of the earthquakes catalogs using the temporal functions: $N(t)$ (number of events) and Ms(t) (their magnitudes) [9]. The following layer of the programs block is associated with the visual analysis of a seismic characteristics complex and consists of two sublayers: graphical and cartographical.

Graphical methods of research are construction of various profiles, diagrams, histograms, petal and azimuthal diagrams. For example, this is a histogram of the radiated seismic energy averaged over a chosen time step ($\lg E_{\text{avg}}(t)$, joules), the events magnitude-frequency relationship (an empirical histogram of the number of events in certain magnitude intervals with the use of linear regression), temporal behavior of a slope of magnitude-frequency relationship corner $b(t)$, etc. For construction of an empirical regression line of the magnitude-frequency relationship, the methods of maximum-likelihood and least squares are used. Also, there is a possibility to define b-values without calculation of the dependence $N(M)$ with Utsu's formula [10] resulting in less displaced estimations in comparison with the least squares method.

One of the last in the group of graphic methods the module of calculation of the environment damageability parameter or seismogenic dislocations density $K_{\text{avg}}(t)$ was developed (Figure 5). The research into the temporal parameter changes gives a representation about seismic stability as changes of physical environment characteristics. The stability is understood as a uniform increment of dislocations length and of the number of events.

The cartographical methods of research are the construction of various isolines maps, animation cartography (the earthquakes visualization as gradually fading flashes proportional to real time) and, also, the 3D graphics, in

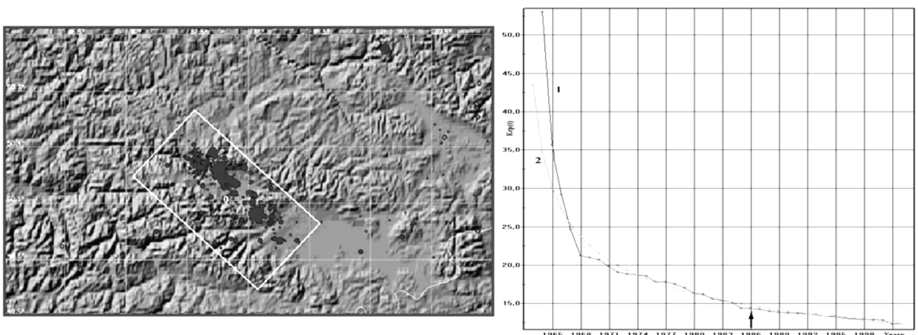

Figure 5. The temporal dependence of the parameter of seismogenic dislocations density K_{avg} [11] for the Chuya earthquake area, Ms $\geq$ 2.5: 1) the real profile, 2) the profile of a uniform increment of fractures. Since 1986, the smoothing out of profiles form, and since 2000, a falling jump of values on the real profile are observed

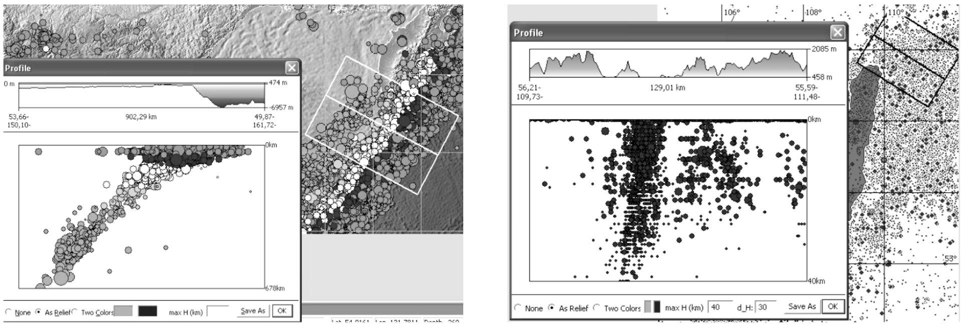

Figure 6. The vertical cross-sections of the relief and seismic process in the South Kamchatka (to the left) and North Baikal (to the right) regions

particular, the construction of vertical cross-sections with plotting of a relief and distribution of the seismic-events processes (Figure 6).

Also, the built-in subsystem programs block is the calculation of cartograms of the total energy distribution for revealing seismic quiescence areas before a strong earthquake, zones of spatial distribution of the slope of magnitude-frequency relationship value (b-value), maps of radiated energy stability (the parameter K_{avg}; the parameter σ as a root-mean-square deviation of radiated energy from the norm), seismic activity isolines (A_{10}, A_{15}, where A is an average of the earthquakes in a certain range of the energy class $K = 10$, 15).

The visualization technology of the listed zonal maps uses a mathematical method of linear interpolation by the 2D Bessel formula and contains the following stages realized by the program:

1. Partitioning of a considered area into elementary cells,
2. Calculation for each cell of an investigated parameter,
3. Construction of spatial distribution maps for this parameter (with the use of the linear interpolation method) on consecutive intervals of time before a strong earthquake shock.

An example of the given technology application can be the maps of distribution of the environment damageability parameter K_{avg} (Figure 7).

To the spatial analysis methods, it is also possible to refer the clusterization technique, i.e. grouping of all earthquakes on the basis of their interrelations. The latter are caused by a natural localization of existing seismicity in the active faults zones (for example, boundaries of plates or blocks). By revealing clusters, we establish the structure of seismicity, which then can be compared to geological structures. To find clusters, the parameters of a maximum spatial-temporal distance in all pairs (dT and dS) and, also, the type of clusterization (temporal or spatial) are set.

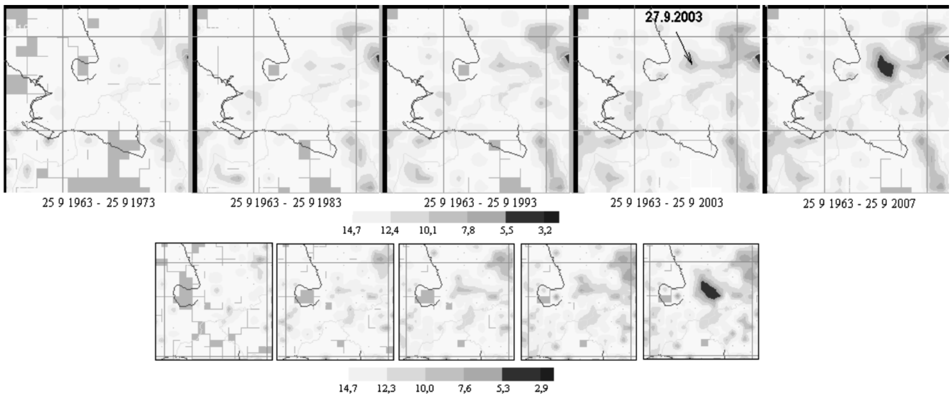

Figure 7. Spatial distribution of the seismogenic dislocations cumulative density K_{avg} for the earthquakes of 1964–2007, Ms = 2.0–4.5: for the Altai-Sayan area of latitude 82–91.35 and longitude 46–52 (at the top), the size of an averaging cell $0.3^\circ \times 0.5^\circ$ and for the Chuya (27.09.2003) earthquake area (at the bottom), the size of a cell $0.2^\circ \times 0.3^\circ$. The maps present the data for every 10 years

The clusters analysis programs are the construction of temporal graphs of the number of found connected events (with averaging and without it), distributions of the number of clusters vs. their events average, the conformity of distributions of the clustered events to Gauss's law $N(dt)$. It is possible to construct the rose diagrams of summed azimuths of clusters, too.

Discovering and analyzing the groups of connected events, we may find the structure of seismicity in the area under study, and by consideration of such a structure in different periods of time we may detect changes of seismic process in space.

In the system EEDB, several methods of clusters definition are used:

- Method of introduction of the spatial-temporal parameters dT and dS,
- Sobolev's method (dT and dS are automatically calculated, proceeding from the theory of space fractality and physical processes of the environment destruction) [12],
- Estimation of the "epicenters density" using Morishita's index [13].

The research technology of the clusters constructed by the first method includes both the geoinformation approach (methods of cartography) and graphic analysis elements, i.e. it is a case of complex research into geophysical data.

The analysis of a change of the activity of the fractures structure can be carried out with weak seismicity, using the following scheme:

1. Preliminary selection and clearing of the chosen catalog part from aftershocks and swarms. After separation of the above described procedure,

a lot of the connected events, concerning the swarm sequences, remain. The technology of clearing of catalogs from swarms is similar to the aftershocks separation procedure except for a condition about the magnitudes relationship between of the main and dependent events: in case of swarm separation, the dependent events may have both smaller and greater magnitudes in comparison with the initial event of the swarm process.

2. The main stages of the procedure of clusters separation with the connection parameters dT and dS. Values of introduced parameters can be defined, for example, using the profiles of dependence of the numbers of pairs of the nearest in time events on these parameters, revealing the intervals of appreciable excess of the number of pairs concerning the profile of exponential distributions (for dT) or of maxima of the number of events (for dS) (Figure 8 a).

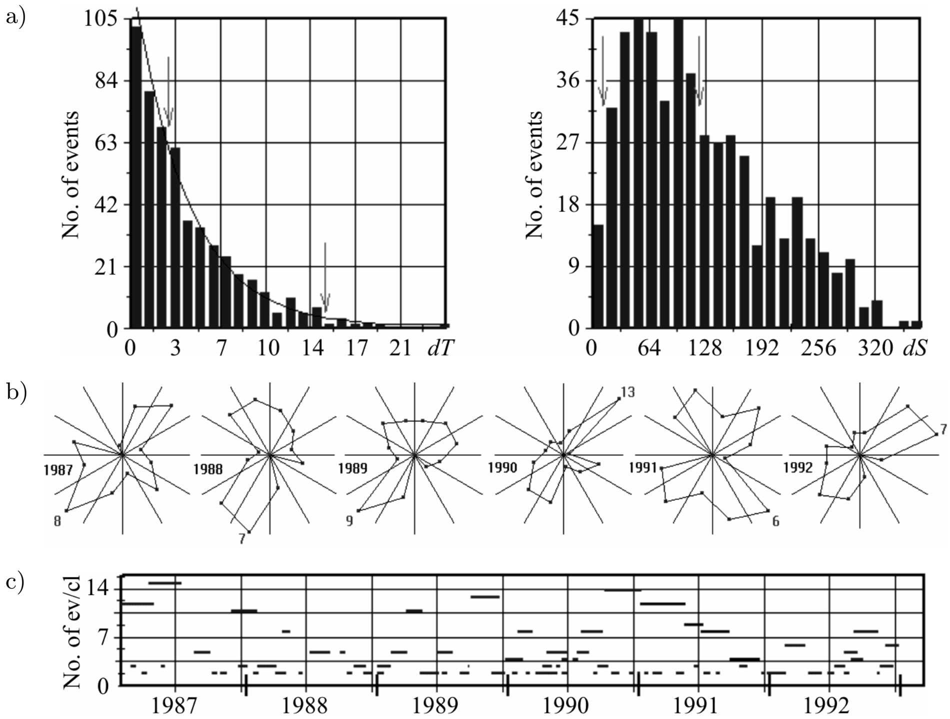

Figure 8. Stages of the cluster analysis of the selective data from BAIK Catalog for 1987–1992: a) profiles of dependence of the number of pairs of the nearest in time events on dT and dS with the marks of intervals used for further clusterization; b) rose diagrams showing the distribution in space of the clustered pairs azimuths (dT = 1–20, dS = 1–50), clearly revealing the SE–NW directions in 1991; c) the time extent of revealed clusters and the number of their earthquakes: the most extending clusters in 1991 form a continuous sequence containing 12, 9, 8 and 4 events

3. The visualization of the distribution of azimuthal directions of the segments, connecting the neighboring events (in terms of time or space) in a cluster, i.e. of clustered pairs. For the time analysis of seismic process, the considered period is divided into separate intervals: years, months, etc. that allows revealing clusters with an anomalous orientation of the connected pairs. In 1991, for example, a rose diagram of the clustered pairs azimuths on the BRZ appreciably differs from a customary picture because 55% of the connected pairs of that year have the Southeast–Northwest (SE-NW) direction, whereas the South–North (S-N) and the Southwest–Northeast (SW-NE) directions are usual for the BRZ (Figure 8 b).

4. Checking the participation of revealed clusters to the nearest in time aftershocks and swarms in case of the agreement of their primary azimuthal orientation (Figure 9 a–c).

5. Checking the presence in a sampling of overlooked aftershocks to assure that the considered clusters are not a residual part of aftershock sets (Figure 9 d, e).

6. Zooming separate fragments of a territory aimed at a more detailed consideration of the clusters of interest.

7. There is a possibility of the additional quality checking of separation of clusters using a synthetic catalog, which is built on the real catalog points by replacing the time moment of each event by a random value from a preset time range. This option is also realized in the system EEDB. As the spatial point positions of a synthetic catalog are not changed, the localization of resulted clusters is not changed as well, but their number should considerably

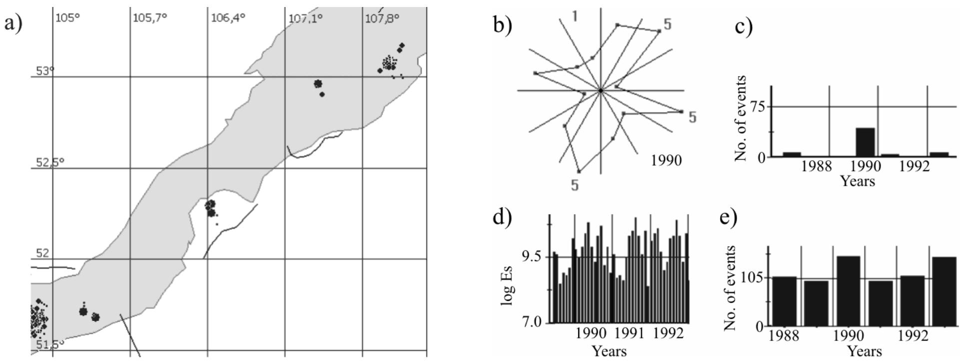

Figure 9. The nearest in time aftershocks: a) a map of the aftershocks sequences and swarms separated by the program for 1987–1992; b) a picture of azimuths distribution of the aftershocks pairs in 1990 when their number has appreciably increased; c) the number of events connected in aftershocks sequences. The histograms describing the 1988–1992 seismic process ($2 \leq M \leq 4$) after aftershocks separation: d) the total radiated energy per month and e) the number of events per year

decrease, thus indirectly confirming the validity of all previous interpretation conclusions, which have been made on the real data according to the results of program maps and graphics calculations.

So, the clustering method alongside with other ones can be related to methods of the seismic regime spatial analysis allowing us to reveal stage by stage real geological structures and processes. Also, the programs of construction of epicenters mechanisms diagrams, which change in space characterize the regularities of the stressed state change in the Earth's crust, and some other techniques concerning cartographical methods, but their description exceeds the scope of this paper.

The *b*-value method as an example of application of the built-in data analysis software. An application of the algorithm carrying out the visualization of zonal maps can be considered on an example of the *b*-value cartograms construction. A difficulty here is in non-regularity of seismic process in the elementary cells, and this may result in the case of *b*-definition using a small number of earthquakes that do not represent all the range of the magnitude-frequency relationship. In addition, the estimation accuracy depends not only on the number of events in a sliding window, but also on the statistical uniformity of this data sampling, i.e. the window should cover a spatial area of the same geodynamic type and correspond to such a temporal interval, where there are no essential changes of seismic flow parameters [14]. That is why the estimations obtained by this method should be made with great care, with investigation whenever possible of the character of seismicity distribution in each cell, with allowance for representativity of a data sampling and, respectively, avoiding excessive details of the introduced summation parameters (magnitude and time steps, the cell sizes).

The cartograms of *b*-value parameter (Figure 10) in the Baikal Rift Zone (BRZ) are constructed on a sufficiently detailed grid ($0.4° \times 0.6°$) and on 8-years intervals. Such a detailing is allowable due to the use of the catalog BAIK having a high representativity rate ($M = 1.5$ and higher) in comparison to other catalogs (for the interval of 1987–2003) and an acceptable dispersion of the graph points concerning the regression line: $\sigma = 0.08$ (see Figure 7 a).

The isolines maps in Figure 10 a show a small divergence of average values of *b* parameter between the first and the second temporal intervals within the range of one step accuracy set by the color scale (0.90–1.05 and 1.05–1.20). The boundary of a considerably lowered density of the data between the southwest and northeast areas of the BRZ passing along the longitude 109° is traced in these cartograms.

As Riznichenko has noticed [15] "for reliable definition of each separate value it is necessary to have about 100 and more representative earthquakes in a wide enough range of energy class K". For the statistically exact def-

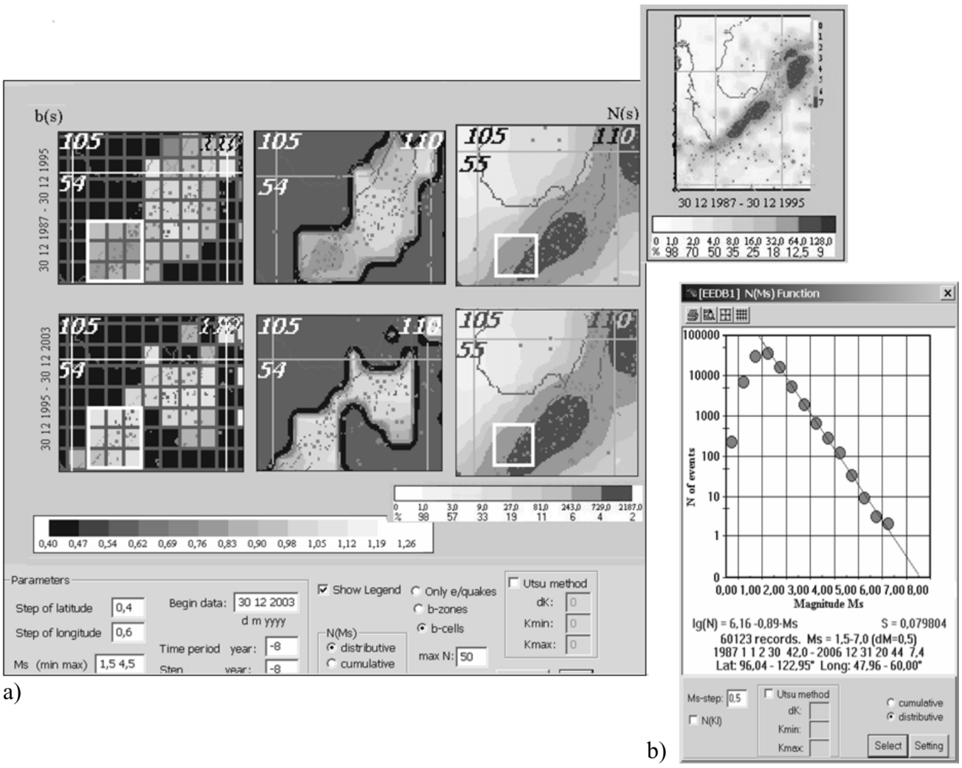

Figure 10. The magnitude-frequency relationship of the Baikal catalog earthquakes ($1.5 \leq \text{Ms} \leq 4.5$) on the temporal interval of 1987–2003 (b); a change in the parameter of a slope of the magnitude-frequency relationship value $b(s)$ in the BRZ as a grid of values, i.e. b-cells (a, on the left) and zonal maps, i.e. b-zones (a, in the center) for a $0.4° \times 0.6°$ grid with double overlapping, appropriate maps of the earthquakes number in the chosen grid cells with double overlapping (a, on the right). The legend shows the b estimation error values calculated by the number of earthquakes. In the right-top part of the figure (a), a map of the earthquakes number in cells without double overlapping is given for comparison, showing an error of b definition exceeding 6 % over the whole BRZ area

inition of a necessary volume of data sampling and for taking account of its influence on an estimations error of a considered parameter, we use the concept of confidential interval.

In practical tasks, exact enough confidential intervals for a selective estimation (in this case for $\bar{b}$) can be constructed, basing on the Muavr-Laplas theorem [16] that is well-known in the probability theory, according to which the accuracy of 3 % can be provided with the data sampling volume (n) such, that

$$\frac{|u|}{2\sqrt{n}} \leq 0.03. \qquad (1)$$

Thus, if confidential probability equals 0.95 (such a statistical reliability of a conclusion is considered to be moderate), the quintile $|u|_{0.95} = u_{0.975}$ has the value 1.96. Based on the given formula, we may determine the accuracy of $\bar{b}$ parameter estimations obtained. For this purpose in the program EEDB, there is a possibility to construct the quantitative isolines of the earthquakes inside the cells, i.e. of the data sampling volume (see Figure 10 a). So, for $0.4^\circ \times 0.6^\circ$ averaging grid in the axial BRZ area the parameter estimations error is 6–18 % ($32 \leq n < 256$) reaching a level of 35 % ($n = 8$) outside of the lake contour. Because of such a low accuracy and wishing to keep the cell detailing, the parameter calculation is made with the use of an averaging window with double overlapping of a cell. The error of thus obtained estimations decreases to 4–6 % ($243 \leq n \leq 729$) in the whole BRZ area (filled with a dark gray color) falling to 2 % ($n > 729$) on some sites (filled with a black color).

An advantage of interpreting the b-value cartograms method is its possible connection with processes of the elastic energy accumulation in the Earth's crust (sources of stress). In the case of the complete release of potential elastic energy of the earthquake sources $\bar{b} = 1.8$ ($\gamma = 0.5$), and in the case of its moderate release $\bar{b} = 0.9$ ($\gamma = 0.5$). Thus, by observing b-value it is possible to judge about a relative amount of elastic energy, released by epicenters [17]. In other words, temporal changes of parameter γ values correspond to reorganization of stages of stress-deformed lithosphere conditions [18]. Proceeding from these assumptions, it is possible to conclude that an increase in the value b observed, for example, in the central area of the BRZ on the latest interval (1996–2003), specifies changes in geodynamics of the given site as unloading. The growth of average b-values in the central part of the BRZ is proved by the data of the temporal graph (Figure 11).

Conclusion. In the given paper the system EEDB is considered, on the one hand, as software representing a category of GIS-systems since a demand for the use of a geographical base for the solution to spatial seismic-geodynamic tasks appeared to be the key stimulus for the given system development in the conditions of absence or inaccessibility of such systems for the moment of the beginning of research.

The basic modules, of which the software of a geographical environment consists, are considered. As the program shell is also a control system of the seismological database, the content and format of all included earthquakes catalogs are described. This part of our research was registered in the State Register of Databases as "Expert Earthquakes Database". The geographical shell as well as seismological DB is constantly in "alive" modifying condition, the geographical information being constantly actualized in view of the new available detailed geographical data and the seismological information being enriched with new operative data.

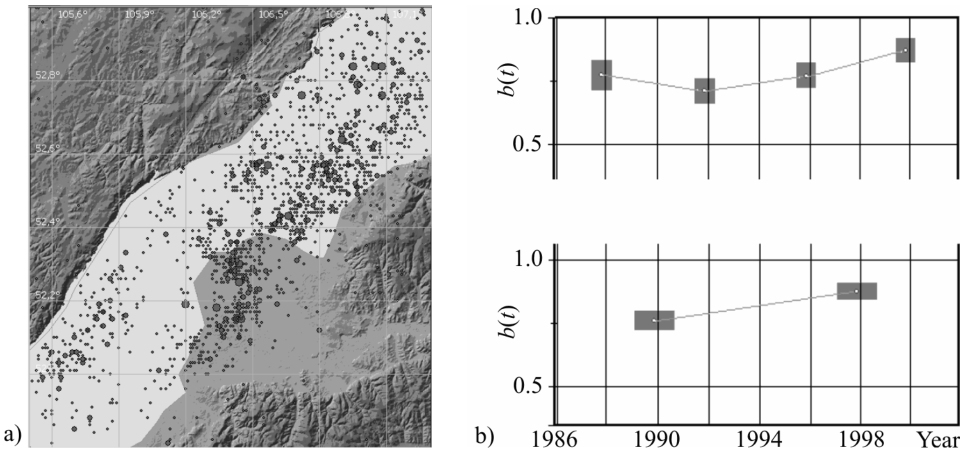

Figure 11. The BRZ area (a) shown in the frame in Figure 10 and changes in the profile of *b*-value parameter on 4-years (b, above) and 8-years intervals (b, below). The error of *b* definition is shown by segments and calculated by formula (1). The average *b* value grows from 0.75 up to 0.9

On the other hand, the EEDB program system in the process of its development was gradually transformed from an information system of geographical visualization of the earthquakes database to a high-tech expert system. As a result, the EEDB in addition to the historical catalogs and the graphic shell of the Earth has begun to represent the whole complex of research techniques. In examples of the data analysis, the use of a geoinformation approach principle [14] in the research into a seismic-geodynamic regime is shown. The techniques of a multistage analysis using the concentration criterions, clustering of earthquakes, and parameters of a graph of repeatability are discussed. They all use the most complete, reliable and complex information provided by the system about seismicity state and its dynamic changes. At the same time, synthesis and generalization ("expertise") of this information are being carried out with attraction of experience, intuition and knowledge of the researcher. A clear advantage of the given development is the possibility of its constant actualization associated with improvements of the techniques of the given type of research at present and in the near future.

To conclude, we would like to note that the graphic shell EEDB, whose prototype was first developed in the languages FORTRAN and Pascal within the operational system DOS, in the proposed realization is written in Visual C++ and maintained with operational systems Windows (NT, XP, Home). It operates as friendly interface allowing the users of different computer experience to quickly and effectively carry out reviewing, visualization and data analysis. The program system has been successfully introduced, is used for the investigations and currently installed on a number of computers. As a result of the use of the proposed software for the Altai region research, it is possible to mention the investigations of seismic regime of strong earthquake preparation areas, published in [19, 20].

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