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The GIS-EEDB computing system, lineaments, and the earthquake prediction problem*

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Abstract. The main object of the study in Geophysics is multi-dimensional nonlinear systems, varying over a wide time range from a split second to geological epochs. The present-day mathematics does not allow a sufficiently strict description of such systems, so the problem of reliable long-term earthquake prediction is still unsolvable. The reliability of prediction increases with a decrease of the time range, reducing the size of the system and the growth of its structuring. The problem is in the absence of a formal definition of the nature of structuring and allowable reducing size without loss of information content. It is generally accepted that the geophysical environment is a union of self-similar partings, according to whose borders the environment is destroyed. The least action principle prescribes the destruction of a homogeneous medium by a spherical or a plane surface (or by a circle or a straight line in the 2D case) for a point or a flat load, respectively. The algorithm of lineaments construction implemented in the GIS-EEBD allows one to formally design and minimize a system of such straight lines and circular structures, integrating the whole set of structure-forming earthquakes. When minimizing a lineaments system, the overall field splits to disconnected subsets of geometrically related events. The authors believe that the analysis of multilevel processes inside and outside the structure of each such subset will allow one to approach to a reliable short-term earthquake prediction.

Keywords: earthquake prediction, natural disasters databases, seismic lineaments, gravity.

1. Geophysics and earthquake prediction

The focus of geophysical problems is all the processes taking place in the Earth, on the Earth, and, partially, in the external environment (if their effects on the Earth's phenomena are scientifically established). Probably, it is impossible to name a field of the natural history, which was not involved into the study of the Earth. This involvement is determined by a highly complex system of linkages of all the processes, including the ones affecting natural disasters and their generating (see, e.g., a chart in [1]).

In 2003, one of the International Geophysical companies published the mnemogramma, with which one can select a preferred set of parameters for measuring in a specific applied research, in particular, for the tasks

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of seismological prediction (Seismic Hazard Determination: http://www.enviroscan.com/html/seismic_hazard_determination.html). As is shown, the dimension of the system, i.e., the number of parameters required to describe the behavior and properties of the entire system or even any of its cells, is far beyond the classical six-degrees-of-freedom of a rigid body. In addition to such a many-parametric property, the characteristics of the mathematical description of geophysical systems are the nonlinearity of the proceeding processes and a wide time range (from fractions of a second in crushing rocks to the geological eras of Geodynamics).

For the past century, advances in instrumentation and computer technologies, as well as in numerical mathematics, have been accompanied by considerable achievements in static and statistical descriptions of geophysical systems, fields and objects, in the analysis of seismic waves, and in building geoinformation systems (GIS) for various fields. The success is so essential that even the geologists, who still do not have a mathematical device, for example, tektonicists and paleo-seismologists, have begun to actively mathematize their sections in the hope of having a device of a dynamic description of "tectonic issues" [2].

In order to include a variety of new, continuously evolving options as branches of knowledge, when creating Geoinformation Systems (GIS) it is necessary to form a detailed databases that cover centuries and thousands of kilometers, in terms of time starting from days and observational steps starting from tens of meters. Such database will be, in principle, generated, but it is a time-consuming process. A big variety of the scale of measurements results in the inevitable loss of stationarity of an ensemble of observed processes [3] and such a mathematical apparatus of the GIS for stationary processes has still to be established, so the hope for the rapid progress in mathematization of Geology [4] and, in particular, of Tectonophysics, is yet illusory, despite an obvious success.

Currently, there is a statement that "many, if not most, of geodynamic systems, whose behavior was supposed predictable, behave in principle unpredictable. Namely, this fact but not the lack of observational data is the main cause of unreliability, such as of seismic forecasting" [5] and "... it's not the preparing mechanism of seismic events that has not been studied; but the mechanism is such that it generates an unpredictable, chaotic dynamics" [6].

Geophysics is gradually evolving as, for example, relative to the geological aspects. There are proposed certain laws, whose physical genesis is not clear yet, but the mathematical apparatus of their support is booming. Within the theme in question, to such laws, we can refer the following:

1. The magnitude-frequency relation [7],
2. The hierarchical structural self-organization [8–13] and the fractal sep-

arability of the geophysical environment [14–17] (law of self-similarity),

3. The geophysical system entering the state of self-organized hierarchical criticality, i.e., a logical transition of the source to the irreversible gaining momentum phase [18–20].

The studies conducted have shown that the total separability of all geophysical processes carries the information about the degree of their self-similarity, but there is almost nothing said about the nature, direction and place of their development. Moreover, the value of the fractal dimension depends on its type (a cell type, information kinds and correlation types, etc.), on the way of its calculation, a sample size, the size of the territory, a magnitude range, duration and the time of beginning observations [21–24]. At the same time, there are not any requirements for the physical nature of processes, i.e., the empirically identified processes of the structure formation are statical and universal in all the environments [8].

The establishment of statistical laws of separability has led to further development of the engineering probabilistic approach to the calculation of an expected seismic risk [14, 25, 26] and to the creation of the term "seismogeodynamics" [27, 28] for studying the shape of spatial-temporal and energy expressions of seismicity [29, 30], and for building the seismic zoning maps of Northern Eurasia in the concept of structural-dynamic and power unity of the geophysical environment [31–34]. Statistical (empirical) laws of seismicity are the foundation of various methods of the long-term and the medium-term earthquake prediction [31, 35–43].

It is believed that the identifying stage of a seismic cycle and of activation of a weak seismicity [24] by measuring the current crustal movement and by mapping the faults, allows us to establish (with some degree of probability) the location of several "candidates" for an expected strong earthquake, that is, of "potential sources" 44]. However, this approach brings about a low reliability of the contemporary long-term and the medium-term prediction ($65 \pm 10\,\%$ of predicted earthquakes in the regions with $70\,\%$ probability). The reliable prediction can be improved only when reducing the time range or the system size, and the growth of its structuring that reduces the event horizon to a level substantially below the Lyapunov factors of mixing the chaotic systems:

1. With respect to coordinates — using structural (linear, ring, radial) constructions;
2. With respect to time.

In this paper, we consider the first approach to the earthquake prediction, and the problem here is the absence of a formal definition of the structure character and of the allowable reduction without loss of information. The problem is intractable, because the modeling based on the ideas of self-similar hierarchical and rough discreteness of geo-environment shows that a probabilistic approach to the task of structuring environment is not applicable: "the number of blocks of a subordinate rank at any level is low, and averaging structural and dynamic characteristics in terms of the volume and time is inefficient" [45].

Therefore, we suggest that only involving physically comprehensible and justified practice of the standpoints of the processes in areas of earthquakes will "lift" a prediction of strong events out of hopeless pure statistics. The first priority is to clarify the identified earthquake-prone areas by the formalized methods associated with physical laws of fundamental deterministic actions. For example, the principles of the least action and of a minimum potential energy in a steady state requires the destruction of the environment integrity with forming flat or spherical surfaces of discontinuity under a flat or a point loading. When a two-dimensional loading the failure must form straight lines or circles, that is, all strong earthquakes should be located on the direct lines and circles connecting it (and inside the circles).

In the geographical information system EEDB [23, 24] there is implemented one of such formal methods [22] to build and to minimize a system of lineaments that includes a full set of the past earthquakes of selected

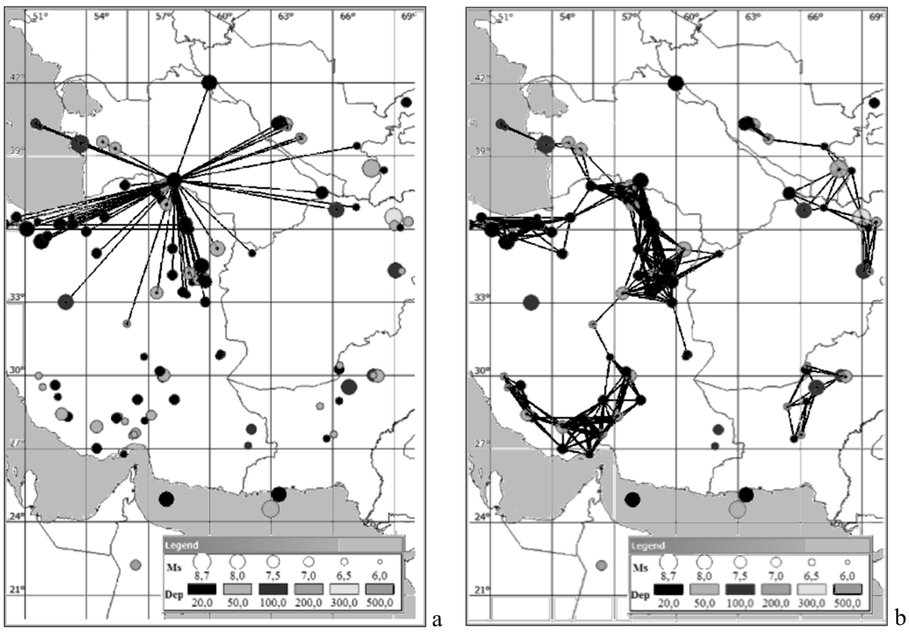

Figure 1. The earthquakes occurred in Iran, Afghanistan, and Kazakhstan, a total of 226 events (Significant Catalog; latitude— 20–45° N, longitude— 50–70° E, $H < 150$ km, $M_S \geq 6$, until January, 2005): a) the radial structures ($Az = 0.5°$, $L = 800$ km, $N_{\min} = 4$); b) the ring structures ($Az = 120°$, $L = 300$ km, $N_{\min} = 15$)

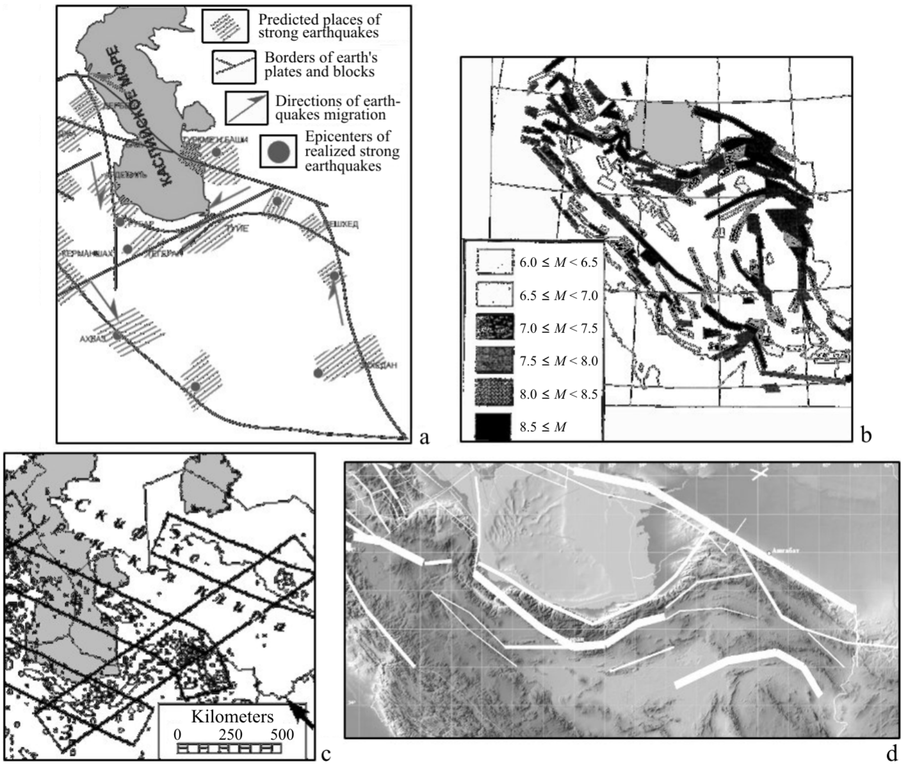

Figure 2. The maps of locations of expected earthquakes (seismic lineaments) obtained by other authors: a) in [46]; b) in [47]; c) the location of the profiles along which a spatial-temporal and seismic-energy evolution of geodynamic processes was investigated in [48]; and d) the system of lineaments built with the EEDB data [49]

ranks, with a view to identifying direct, circumferential and radial patterns of seismicity (Figure 1). The algorithm of structural image recognition using a set of points distributed in space is based on setting a maximum step L, the number of points in the chain $N_{\min}$ and a maximum deflection angle Az to find the next point (the epicenter of events).

Let us note that structural elements identified by this algorithm (see Figure 1), clarify the results previously obtained by other authors, which were based on a variety of materials and techniques (Figure 2).

2. The Afro-Baikal lineament

Let us consider an example of application of the algorithm proposed on a global scale. Despite a relative rarity of events and a low reliability of their characteristics, in the time interval of 2250 years, a transformal lineament was identified with the range of depths of events that permeates the entire crust and the upper mantle (Figure 3). Geometrically, it is imposed on

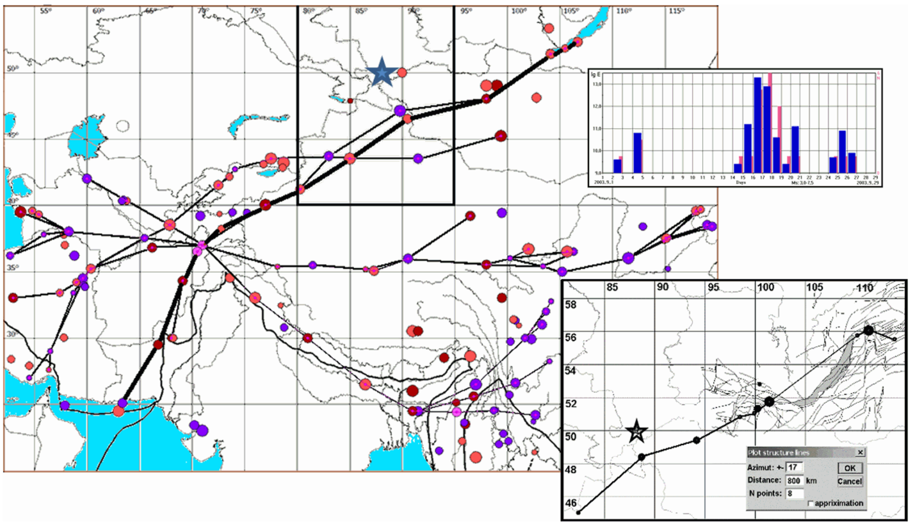

Figure 3. The system of lineaments African Horn — Baikal rift zone — Himalaya (Significant Catalog; $Az = 24°$; $L = 700$ km; $N_{\min} = 13$; $M_S \geq 6.5$; $H \leq 130$ km; -250–2008 year). A bright lineament is also identified by parameters for a lesser curvature: $Az = 18°$; $L = 600$ km; $N_{\min} = 16$; $M_S \geq 6.7$; $H \leq 130$ km; -250–2008 year. In the inserted pictures, the events cluster of September 14–20, 2003 with $M_S \geq 3$ in the last month (September) before the Chui earthquake ($M_S = 7.3$) are shown: at the top — on the timeline with a step of 1 day; at the bottom — on the map (the Chui event is marked with an asterisk)

the Afro-Indian cross-plate border by the southern end (over 1500 km), on the proposed edge of the China plate in its central part, and in the Baikal rift zone by the northern end, presumably repeating the contour of biaxial convergence of the European plate with Indo-Chinese agglomerate.

There are, of course, algorithmic difficulties of the correct construction of the lineaments. First, it is a necessity to increase the azimuth of the search when combining linear and radial structures into a single set, resulting in a loss of precision in the linear sections. The second difficulty is a statistical reliability of lineament constructions. However, the representation of the African-Baikal lineament is confirmed by numerous data (see Figure 3):

1. By exceptionally strong, rare events that make up the statistical reliability of a sample (nearly 50 of 130 events in the selected areas, including in-depth earthquakes, with 25 % of all the events occurred on the one direct line);

2. By the total confinement of all the events to a visually observed maximum gradient of the gravitational field [50] (the same confinement was noted, e.g., by [51]); and

3. By the Chui cluster (Altai region) of the same trend, but of a shorter-term (1 week) and of a weaker energy (found in the events with $M_S \geq 3$ [23]).

The latter argument indicates, in particular, to the algorithmic capabilities of the GIS EEDB system to identify short-term episode of a more global seismic process, which, moreover, became a prognostic feature for future major events (in this case, for the Chui earthquake of September 27, 2003, $M_S = 7.3$). A slight deviation in the geometry of the Chui cluster to the North of Baikal Lake from the direction of the super-lineament (anchored by the ends to the Earth's mantle) can be explained by the peripherality of the first and by the influence of the fluid introduces, affecting the peripheral movements transverse to the super-lineament (for example, according to [52, 53], a transform zone can dilate because of deep fluids). Such explanations require serious study, but it can be an important information to clarify contradictory concepts, such as those existing in the structure and dynamics of the crust evolution and ore formation.

The studies by means of the EEDB of the identified African-Baikal magistral lineament in the earthquake-prone zone (for example, the zones of the Chui occurred or possible Almaty expected), can give a bulk of relative looking information. For example, the research into the mechanisms of earthquakes belonging to a lineament zone, circumscribed by polygon (Figure 4), shows an abnormal increase in the relative number of events of the shift mechanism in the 12-year period before the Chui earthquake: 1991–2003

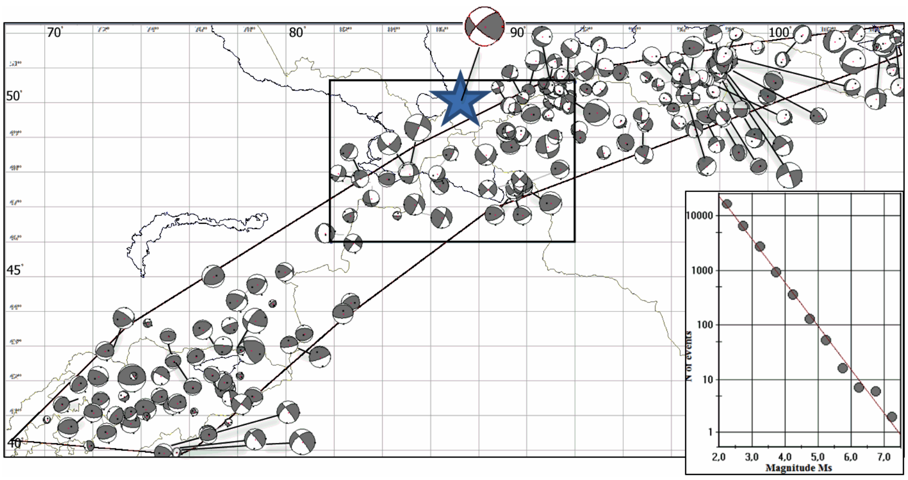

Figure 4. The mechanisms of seismicity around the Baikal-African super-lineament contoured by a polygon, and a magnitude-frequency graph for earthquakes of $M_S \geq 2$, COMPLEX catalog. The asterisk marks the location of 2003 Chui earthquake, having a reversed strike-shift mechanism

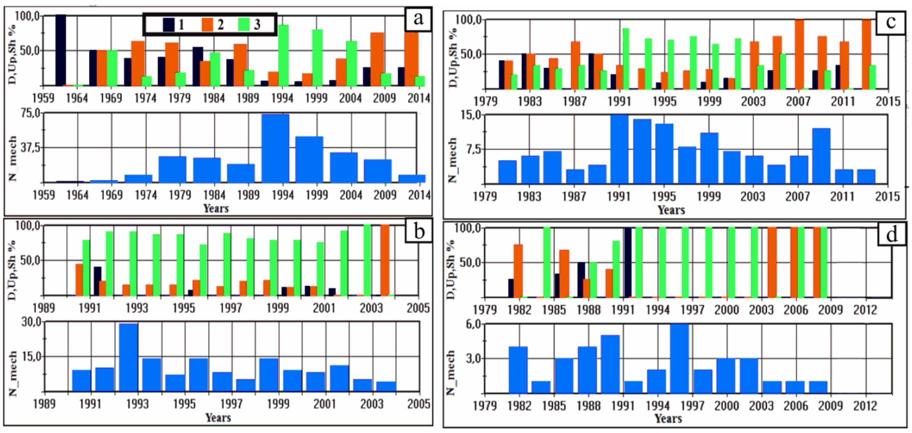

Figure 5. A temporal distribution of the relative number (in %) of different types of mechanisms (the upper graph) and of the total number of mechanism definitions (the lower graph) for the seismicity in the selected area (indicated by a polygon in Figure 4) of the Baikal-African super-lineament: a) COMPLEX catalog inside the whole polygon; b) COMPLEX catalog within the interval 1990–2003; c) NEIC catalog inside the whole polygon; d) NEIC catalog in the area marked with a frame in Figure 4. The legend explanation: 1 — downthrows, 2 — reverse faults, and 3 — shifts. The complex mechanisms are counted in both groups

(Figure 5), particularly, in the area adjacent to the preparation zone of this event (Figure 5d). This area is designated with the frame in Figure 4.

This regularity can be traced as according to a more detailed (by magnitudes) COMPLEX catalog (see Figure 5, a–b) of high representation in the polygon area ($M_R = 2$, which is supported by the linear magnitude-frequency relation in Figure 4) and, also, according to a lesser detailed but a longer-time NEIC catalog (see Figure 5, c–d).

Note that the presence of extensive subparallel right-shifted zones of NW-trending was really fixed near the Mongolian Altai ([54], their field of research is marked with a frame in Figure 3). The temporal distribution of mechanisms after the Chui earthquake shows that since 2003, the character of the geodynamic regime of the area again changes abruptly forwards increasing a reverse (upthrow) component (see Figure 5, a–d).

It can be concluded that for 12 years before the Chui event, in the fragment of the super-lineament under consideration (see Figure 4) the regime of occurring the shift zones associated with the regional compression (due to the convergence of the Tarim area and West Siberia [54]) or with the above-considered introduces of the materials, was activating thus preparing the Altai event of a rare strength and ending with this event. This means that the temporal cluster of smaller events ($M_S \geq 3$) along an extended Chui lineament, which is an episode of the regional super-lineament, was a short-term precursor of the Altai event.

Thus, the above has led to constructing very important geodynamic and geological findings. In particular, to clarify the boundaries of plates using deep earthquakes, to indicate the African-Baikal transform border created by converging plates, to assess its effect on the geodynamic regime of the surrounding areas, and, may be, to specify the width of the Transform Zone, defined by the northern and southern branches of the super-lineament. Given the poorly understood processes in the transformative areas, its ore genic importance and seismic danger, any information, including that provided by means of the GIS EEDB, is extremely important.

3. The technique of structural-predictive constructions

For structural-predictive constructions based on the described algorithm, we propose to conduct further minimizing a global system of the lineaments (a rank-by-rank decrease of the parameter L), during which the general field falls into geometrically related subsets, each one, we believe, taking a representative size of the crust area, experiencing from sides, bottom and top. We suggest that the analysis of the multilevel processes inside and outside the structure of each such subset could make us closer to a proven operational forecast.

An approximate value of the parameter L can be estimated from the size of the source (L_0), and from understanding the physics of the interaction transfer between the adjacent focal zones at a distance, much higher than L_0. According to the formula [55]:

$$\lg L_0 = (0.433 \pm 0.065) M_S - 1.468 \pm 0.510,$$

$$\text{in case } M_S = 6: \quad L_0 = 107 \text{ km} \quad \Rightarrow \quad L \cong 600\text{–}800 \text{ km};$$

$$\text{in case } M_S = 2.5: \quad L_0 = 2 \text{ km} \quad \Rightarrow \quad L \cong 10\text{–}15 \text{ km}.$$

These calculations take into account the physical idea that an earthquake is a switch (hub), whose stress decreases exponentially with distance and at a distance exceeding $2L_0$ from the source ellipsoid can be neglected. It should also be borne in mind that in seismically active areas, earthquakes occur more often and closer to each other, in less active ones — on the contrary. This makes necessary — when setting L — to increase or to decrease the multiplier of the parameter L_0 depending on the number of earthquakes per unit area.

Let us list some current physically understandable ideas about the geophysical environment during the preparation of an earthquake:

1. A lineament reflects the current stress state of the lithosphere, its fractal separability and interblock structural-coordinating relation [17].

2. The mutual coherence and synchronism of seismicity with faulting on the background of the netlike fractal structure of faults define the features of the fractal spatial-temporal dynamics of earthquakes and vice versa [56].
3. In some regions, for 1–9 months before strong earthquakes, there are formed chains of quakes caused by the increasing correlation of seismicity [57, 58], as well as multi-component effects of enhanced synchronization (the coherent behavior) of the statistical parameters of seismicity [59].
4. The epicenters of strong and strongest earthquakes tend to gravitate towards areas of intersection or the greatest convergence of "shallow" and "deep" rings of seismicity [60, 61].
5. Currently a most effective prognostic sign, as confirmed by the MEE algorithm, is the density of the seismogenic dislocations [44, 62, 63].
6. When developing the multiple cracks are pulled together to a plane of the preparing main rapture [64, 65]. An increase in the number of cracks when approaching the main magistral rapture is also known from the geological data.
7. The pulling together of cracks is accompanied by a gradual grows of breaks when approaching the moment of a strong earthquake [44, p. 145].

We propose to add this list with an assumption: increasing the rate of pulling together cracks in a particular area is a reliable sign of source transition to the irreversible gaining momentum phase (its time factor is discussed in another paper). The sign will be more reliable, when the enlargement of breaks accompanies it. Furthermore, based on the retrospective study, by means of the EEDB one can identify the characteristic features of small fracturing in the earthquake-prone zone, which is abnormal in the structure region. Therefore, we propose to build a prediction algorithm in the following sequence:

1. Mapping faults and identification of the ring and the radial seismic structures — minimizing the global system of structural elements, i.e., rank-to-rank (by M_S-ranges) decrease of the parameter L and/or $N_{\min}$;
2. The refinement of the phase of a seismic cycle by the degree of activating weak seismicity and by the velocity of pulling together cracks to concrete elements of fault structures;
3. Identifying active areas of the current movements as those accompanying the restructuration of the geophysical environment in selected areas.

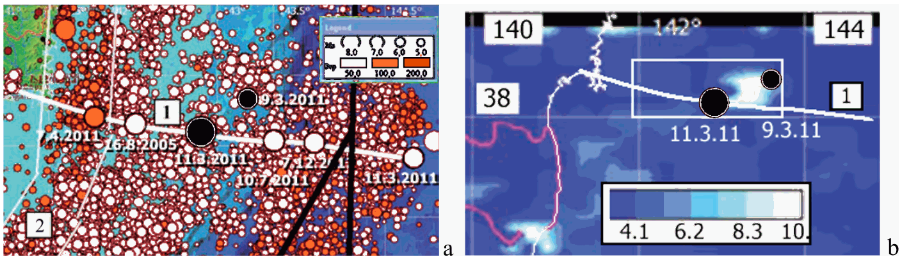

Figure 6. The identification by means of the EEDB: a) lineament structure (1); b) gradient of a relative seismic energy released by the earthquakes a year before the Tohoku event (according to [24]). The epicenters of the Tohoku event and its foreshock are marked. The frame marks the area under a detailed study, covering the area of a maximum gradient

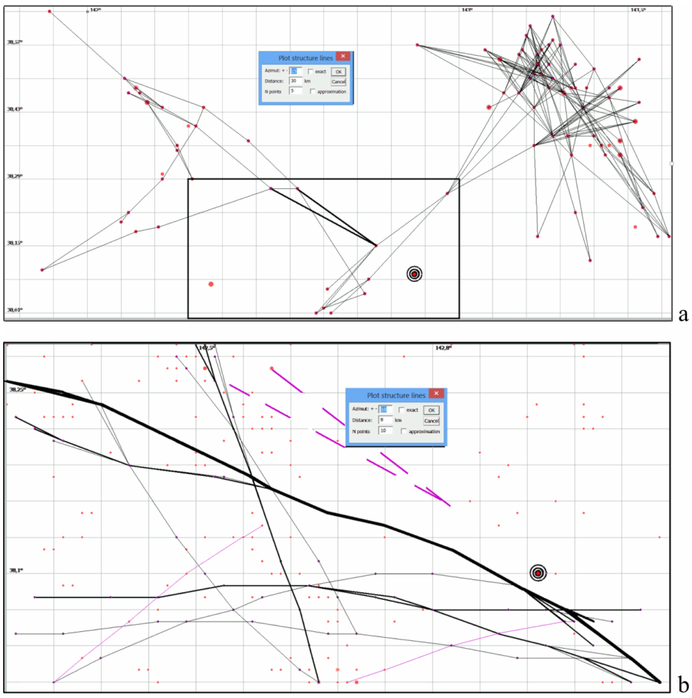

Figure 7. The most extensive lineaments around the source of an expected Tohoku earthquake (marked with a circle) using the JMA Seismic Catalog for 2003–2011, $H \leq 40$ km, and where $(Az, L, N_{\min})$ respectively are: a) $(15, 30, 5)$ $(M_S \geq 4)$, bold lines indicate to the ends of one of the "main" lineaments directed to the potential epicenter; b) $(10, 9, 11)$ $(M_S \geq 2.5)$, in the region indicated by a frame in Figure a, thin lines show less extensive lineaments $(10, 9, 10)$; a bold line denotes the "magistral" lineament $(10, 9, 13)$; the gray color does two lineaments extending transverse to the latter one and identified with parameters $(10, 7, 8)$. The dotted line shows a fragment of a lineament, highlighted in Figure a

Let us note that the first and second points of this sequence are complementary.

For example, when studying the preparation area of the Great Japan earthquake (Tohoku) by means of the EEDB [24], first of all, there was identified a major lineament of the strongest events ($M_S \geq 7$) of the last decade that was extending along the 38th parallel (Figure 6a). Then there was built a map of seismic quiescence and activation showing an abnormal gradient of the relative energy of weak seismicity in the area of this parallel between 141.8 and 143.6° E (Figure 6b).

In the area refined by this way, it is possible to proceed a detailed study of structural elements of a lower rank (for the range M_S = 4–6.9, and then M_S = 2.5–4.5) in order to locate the epicenter of an expected event (Figure 7).

Let us note that the catalog of the Japanese Meteorological Agency (JMA) is characterized by a sufficiently high representation ($M_R = 2.5$ for events with $H \leq 40$ km [24]), and, therefore, this is an example used here to demonstrate a detailed study of the major lineament.

Figure 7 shows that the epicenter of the expected event located in the region of intersection of the extended ("main") lineaments identified on the rank level M_S = 4–6.9, one of which being on a lower rank level: M_S = 2.5–4.5, finishes a branching area. The expected epicenter is located in close proximity to this area.

4. Conclusion

1. In spite of the successes of the current mathematics, the behavior of multidimensional nonlinear geophysical systems, generating natural disasters outside the Lyapunov event horizon, is in principle unpredictable.

2. A probabilistic prediction is based on the available geophysical information on the occurred and expected events, so it has gained in experience and is supported by the current expert information systems, in particular by the EEDB.

3. The problem of the earthquake prediction can really be solved only with an operational forecast, which, being deterministic, is difficult to implement since it requires a small event horizon (substantially, below the Lyapunov factors).

4. The methods of probabilistic long-term prediction implemented in the EEDB can identify the most dangerous earthquake-prone areas.

5. The formal lineament construction using the EEDB tools allows one to highlight super-lineaments and, at the same time, to more clearly outline local dangerous areas (previously, this was done with the assistance of expert, that is, inaccurate estimates).

6. A detailed study of the evolution dynamics of specific dangerous areas (sources) allows one to highlight the precursors of a low horizon of events that provide an operational forecast based on the detection of the place and the time of transition of the source to the irreversible gaining momentum phase with predictable results.

7. The approach proposed will require further development of the EEDB software and its translation into real time mode, which is an obligatory condition for the realizability of the real-time forecasting.

The examples discussed in this paper indicate that currently the GIS-EEDB system already allows us much from necessary for a reliable (rather than long-term) earthquake prediction: calculation, construction and visualization; localizing the most dangerous structures (areas); starting the refinement of the phase of a seismic cycle in localized structures.

The gravity data, mechanism catalogs and other components of complimentary information, constantly actualized in the EEDB, allow increasing the reliable level of allocating promising structures and reducing the ambiguity of the conclusions.

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