Research Square

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Seismic Domain Identification Algorithm using Fuzzy Logic Methods with Combined Geological and Geomorphological Data for the Case of Sakhalin Island

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Research Article

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Abstract

An algorithm for identifying seismic generation zones or “seismic domains” using fuzzy logic has been developed and tested on the island of Sakhalin. Initial data were obtained from diagrams of the distribution of "weak" zones, relief height distribution skewness, and magnitude of recent area deformation for one year. These data were processed using a γ-operator in fuzzy logic with γ=0.9, which allowed us to identify areas with high seismic activity. The areas where these active areas intersect with zones with increased compressive stress values, as determined by computer modeling, were considered to be seismic zones. It was shown that, if there are not enough source materials available, it is possible to exclude information about the recent deformation field from consideration and use an assumed grid of active faults for computer modeling. This approach may be useful when analyzing areas that have not been studied well.

Introduction

Currently, research is underway to formalize the methodology for identifying earthquake foci in different regions and to clarify lineament-domain focal models. This could be achieved by complex geological and geophysical data processing with a fuzzy logic algorithm[1, 2]. Due to the fact that a significant portion of the Russian Federation's territory has not been sufficiently studied in terms of seismology, we have developed an algorithm for identifying areas that encompass homogeneous geological features and dissipated seismicity, which we call seismic generation zones here or “seismodomains”, “seismic domains” in Russian [3]. This is achieved by processing geological and geomorphological data using the fuzzy logic γ-operator. The effectiveness of this approach is justified by comparison with data on the modern seismic activity of Sakhalin Island, where during the instrumental observation period, more than 300 earthquakes have occurred with a depth up to 45 kilometers, including 13 that were sufficiently strong with magnitudes of $M \geq 5.5$.

Materials and methods of research

The initial data consisted of an ASTER digital elevation model (DEM) with a resolution of 1 arc second (~ 30 m)[5], river hydrography [6] and a database of active faults [7]. The DEM and hydrography were used to calculate morphometric relief parameters, which are related to the nature of neotectonic movements. These parameters include: 1) density of "weak" zones, identified by the method [11]. 2) elevation distribution skewness. 3) steepness of slopes. 4) absolute curvature of the relief. 5) The difference between the basic surfaces of the 2nd and 3rd orders. 6) average elevation. 7) difference between the base surfaces of the 1st and 2nd orders. 8) difference in the of the relief elevation and the base surface of the 3rd order. 9) depth of vertical dissection. Seismically active zones have been identified according to their positive anomalies, where the corresponding values exceed the median or third quartile. In these zones, more than half of earthquake epicenters (for the median) or more than a quarter of earthquake epicenters (for the third quartile) are located (see Table 1). Calculations of skewness, average height, and depth of vertical dissections were performed using a 15x15 km grid.

Due to the fact that the current stress-strain state determines the nature of seismicity, the values of the areal deformation (ϵ_S) of the covering elements were calculated. These covering elements are Delaunay triangles [12], the vertices of which correspond to the GNSS points. Data on the location, velocity and direction of displacement of the latter are given in [13]. The values of ϵ_S are determined by the formula $\epsilon_s = \frac{S_2 - S_1}{S_1}$, where S_1 is the area of the triangle, S_2 is the area of the triangle but with annual displacement of its vertices accounted.

Table 1
The relationship of positive anomalies of morphometric parameters of the relief of the Sakhalin Island with modern seismicity.

Morphometric parameters of the relief	**The proportion of earthquake epicenters located in the areas where the values of the morphometric parameter ≥ Q2**	**The proportion of earthquake epicenters, where the values of the morphometric parameter ≥ Q3**
1	0.62	0.35
2	0.57	0.31
3	0.51	0.29
4	0.51	0.28
5	0.54	0.27
6	0.55	0.22
7	0.56	0.28
8	0.54	0.25
9	0.58	0.23

Note: Q_2 - the median, Q_3 - the 3rd quartile. The numbers indicate: 1) density of "weak" zones, identified by the method [11]. 2) elevation distribution skewness. 3) steepness of slopes. 4) absolute curvature of the relief. 5) The difference between the basic surfaces of the 2nd and 3rd orders. 6) average elevation. 7) difference between the base surfaces of the 1st and 2nd orders. 8) difference of the relief elevation and the base surface of the 3rd order. 9) depth of vertical dissection

The analysis of morphometric parameters of the relief and the modern deformation pattern by fuzzy logic was performed using the γ-operator [4] in the ArcGIS environment. The corresponding bitmaps were transformed by a linear algorithm and stacked-up into fuzzy sets. Then, we use the fuzzy gamma function: $\mu(x) = (\mu_{Sum})^{\gamma} \times (\mu_{Product})^{(1-\gamma)}$, where γ are set in the range from 0 to 1, μ_{Sum} – fuzzy set sum, and $\mu_{Product}$ – fuzzy set product. If the value of γ is close to 1, then the result is close to the fuzzy sum, and vice versa: if γ is close to 0, then the result is close to the fuzzy product. Assuming that this gamma function is parametrized with relief morphometrics and modern horizontal displacement indicators we apply this function to each cell to acquire the neotectonics activity index *I*. The values of γ equal to 0.25, 0.50, 0.75 and 0.90 were tested. When applied to each bitmap cell

Confidence analysis was permed with ROC binary classification method parametrized with integral parameter *I* and earthquake epicenter map. Each dataset was gridded with cell size of 15km×15km and adjusted. Thus, each cell was assigned with two values: maximum integral parameter *I* and 1-or-0 value of earthquake epicenter(s) presence, zero being not.

In addition, the proposed algorithm for isolating seismic generation zones involves the use of the results of computer geodynamic modeling, which allows us to identify areas with increased relative compressive stress values. The methodology of the algorithm and the results obtained for Sakhalin Island are described in [14]. It should be noted that the scheme of active faults, as given in [7], was used as initial data. Due to the fact that the active faults in a number of regions in Russia have not been studied sufficiently, we use the example of Sakhalin to assess the effectiveness of their identification by DRM according to the method of YV Nechaev [15]. This method involves determining the degree of tectonic fragmentation by the specific length of the "weak" zones within a cell with side *a* for a depth of h = *a*/2 The specific length of these "weak" areas is calculated as the ratio of the total length of these areas to the area of the cell (a^2). By varying the values of *a*, the degree of fragmentation was estimated in the depth range of 2.5–20 km and the vertical profiles were compared for this parameter with data on active faults.

Results and discussion

As the most informative parameters, 2 morphometric parameters were selected – the density of "weak" zones and the skewness of relief elevation distribution. These parameters are based on the number of earthquake epicenters falling into areas where the values of these parameters exceed the median (Q2) or the 3rd quartile (Q3). The proportion of earthquake epicenters located within areas contoured by values ≥ Q3 is 0.35 for density of "weak" zones and 0.31 for elevation distribution skewness, respectively. This exceeds similar values for other morphometric characteristics that were considered. Additionally, during the transition from Q2 to Q3, the proportion of epicenters decreases by less than a factor of 2 (see Table 1). In general, areas with positive values of elevation distribution skewness have a high potential energy in the relief, while areas with increased density of weak zones correspond to regions where brittle deformations occur (Fig. 1).

At the first stage, three parameters were processed by the γ-operator – the density of "weak" zones, the elevation distribution skewness, and the magnitude of modern dilation at γ = 0.9 (Fig. 2B). The choice of this gamma value is due to the fact that it provides the largest range of values for estimating the degree of belonging of parameter I to set mu. Seismically active regions are characterized by elevation values of I from 0.6 to 0.9, occupying 47% of the studied area. This is 19% less than the entire island, due to the lack of data on the values for its northern and southern extremities. 44% of epicenters fall within these limits, including 70% with M_w ≥ 5.5, while 78% of events and 92% of high-magnetic events fall within the uncertainty zone, which varies from 0.4 to 0.6 at this stage. At the second stage, a simplified methodology for allocating seismically active areas was tested. In this case, with γ = 0.9, only two parameters were processed: the density of "weak" zones and asymmetry of relief heights. It was

discovered that 47% of epicenters, including 30% of earthquakes with Mw ≥ 5, occur in areas with elevated values of I (between 0.6 and 0.9) that occupy 66% of the area of the island. (Fig. 2C) The reliability of these models was confirmed through ROC analysis. The first model's prognostic accuracy was analyzed for both all earthquakes (Fig. 3I) as well as events with M ≥ 5.5 (Fig. 3II) For the first case, AUC value is 0.60 and for the latter it is 0.70 For the second, the corresponding values are 0.66 and 0.86 (Figs. 3III and 3IV).

Compressive stresses predominate on Sakhalin Island, as evidenced by the nature of the field of modern area deformation. This is confirmed by the reconstruction of the main normal stress axes by YL Rebetsky method of cataclastic analysis of discontinuous displacements for focal mechanisms of earthquake foci (17) (Fig. 1C, inset). Overall, the configuration of seismically active areas identified by increased I values is consistent with the contours of areas of compressive stress localization previously established by computer geodynamic modeling (14). The zones with increased relative compressive stress values, where the calculated I ranges from 0.6 to 0.9 for 3 parameters, are considered here as seismic generation zones. This approach validates the allocation of all previously identified seismic generation zones (Fig. 2D, Nos. I-VI in Table 2), as described in [14] and also allows for the identification of 5 new seismic generation zones (Fig. 2D Nos. VII-XI in Table 2). Estimates of the maximum magnitude of the expected earthquake for each domain were made according to 18 by adding 0.5 magnitude units to the magnitude of the strongest known earthquake. The exception is seismic generation zone XI, where no seismic events were recorded during the entire observation period. However, based on the results we obtained, it is considered an area where earthquakes with M ≥ 5.5 are possible. It should be noted that the proposed seismic domain model is consistent with the Lineament Domain Model IMGiG-97 19, complementing and clarifying it.

Table 2
Estimation of the maximum expected magnitude (Mmax) within the limits of the Sakhalin Island seismic generation zones

Seismic Generation Zone Number	Mmax
I	8
II	6.1
III	6.8
IV	7.6
V	5.5
VI	6.7
VII	6.1
VIII	6.1
IX	6.1
X	6
XI	5.5

The construction of vertical sections of the tectonic fragmentation field (Fig. 2A, 4) showed that most of the active faults considered in [7] are manifested in them. The 5 profile lines in Fig. 2A show between 60 and 80% active faults with an average of 74%. This result shows that with an insufficient level of insight to use data on suspected active faults identification using method as in [12] one can use the YV Nechaev method [15] with DEM data.

Conclusion

We have proposed an algorithm for identifying seismic generation zones. It involves analyzing 3 parameters: the density of "weak" zones; height asymmetry; and values of modern areal deformation. We use the γ-operator from fuzzy logic to analyze these parameters and compare them with the configuration of areas with increased relative values of compressive stress, which were identified by computer modeling. It is shown that, without initial data, an analysis of only 2 parameters can be acceptable (without considering modern areal deformations). It is also possible to carry out modeling using information on potential active faults identified using the YV Nechaev method (1967) with DEM [2010] data. The testing of this algorithm using the example of Sakhalin Island has shown its effectiveness and allowed us to expand our knowledge of the configuration of seismic zones or, in Russian, "seismodomains".

Declarations

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Figures

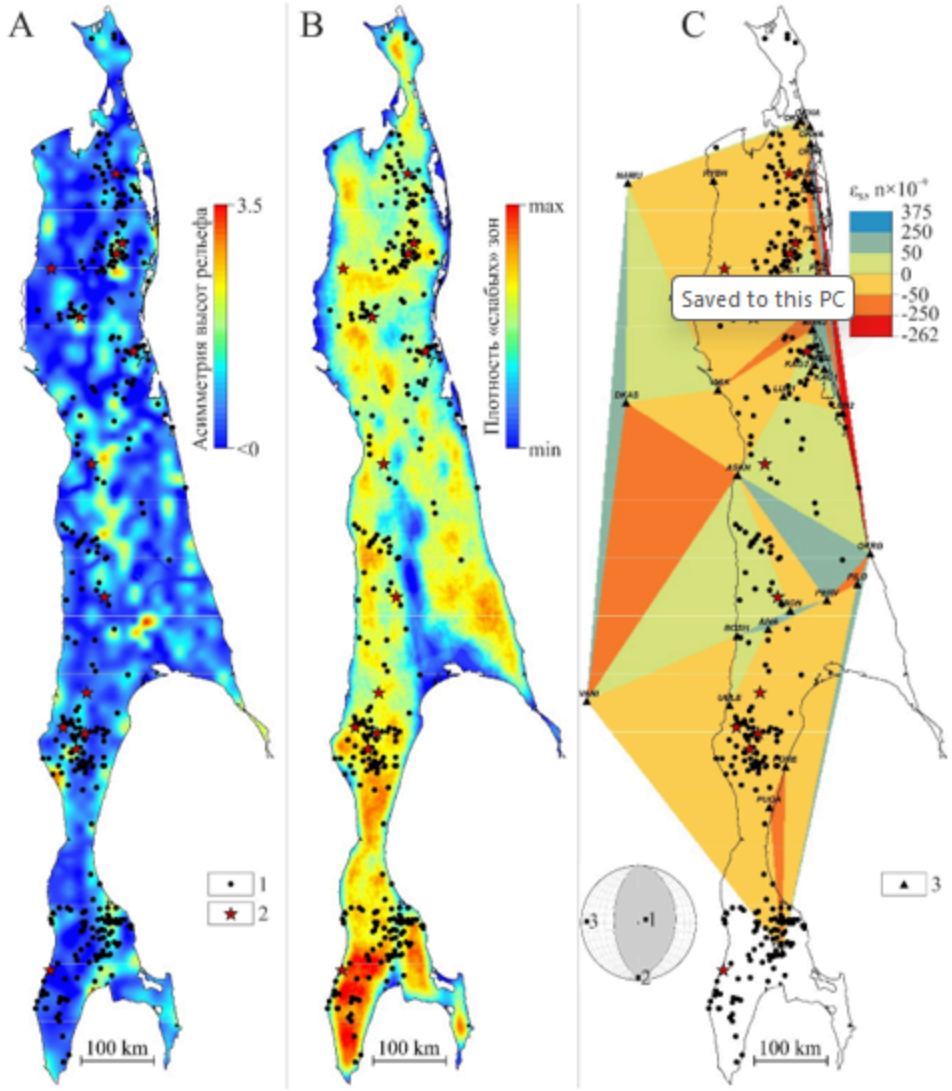


Figure 1

Mapped parameters derived of initial data for the analysis with the γ-operator: relief elevation distribution (A), density of "weak" zones (B) and modern areal deformation (εs) of the island of Sakhalin(C). 1-2 – epicenters of earthquakes with magnitude: 1 – M<5.5; 2 – M≥5.5; 3 – GNSS points. In the round inset on Fig. 1C we show the reconstruction of the main normal stress axes by YL Rebetsky method of cataclastic analysis of discontinuous displacements for focal mechanisms of earthquake foci[17] (lower hemisphere): 1-3 are the main normal stress axes: 1 – stretching, 2 – intermediate, 3 – compression.

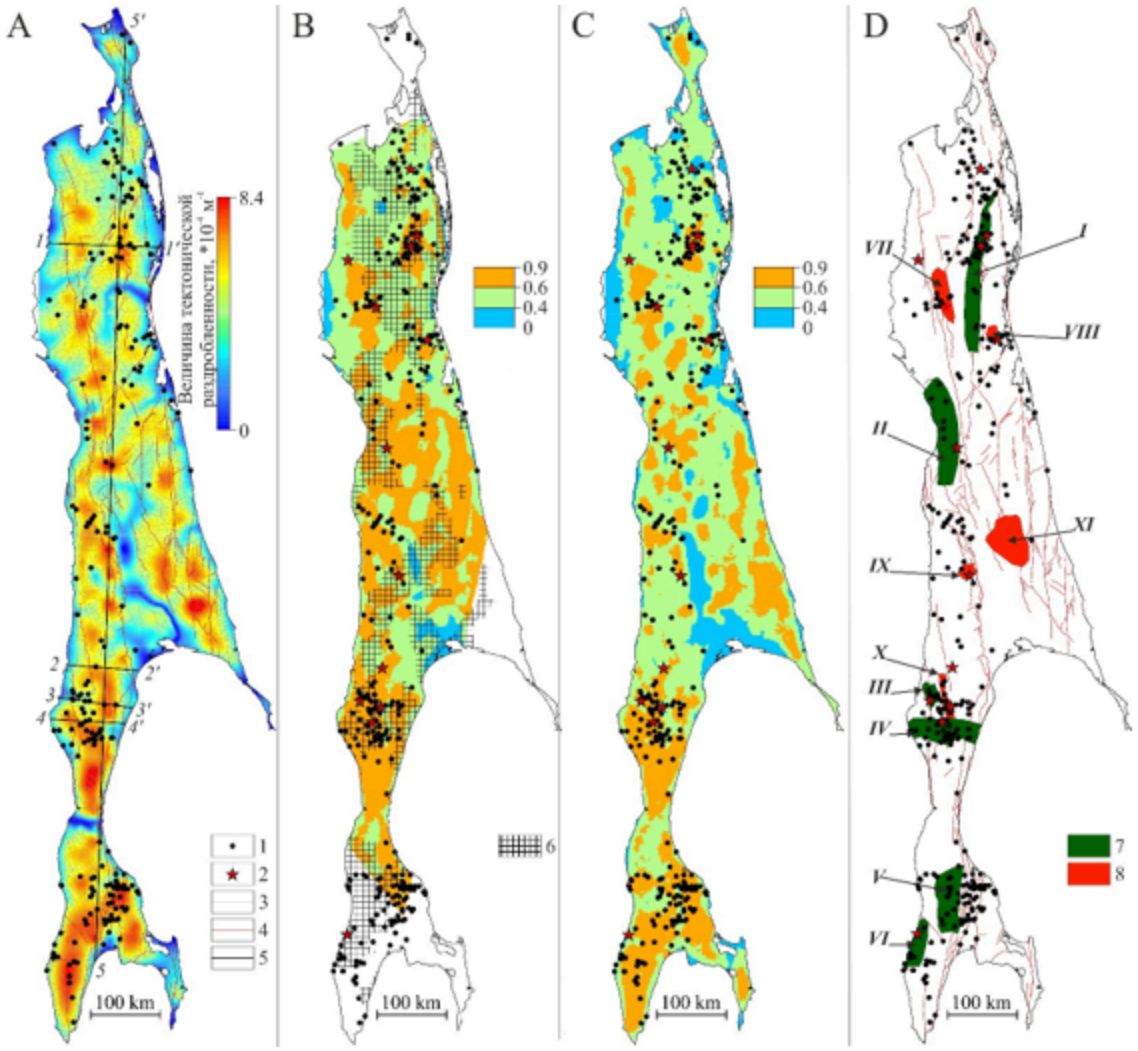


Figure 2

Map of tectonic fragmentation of Sakhalin (A), the results of processing by the γ-operator with GNSS (B) and without GNSS data (C), seismic generation zones (D).1-2 –epicenters of earthquakes with magnitude: 1 – 5.5<M; 2 – M≥5.5; 3 – "weak" zones; 4 – active discontinuous disturbances, according to [7]; 5 – the position of tectonic fragmentation profiles; 6 – areas of localization of maximum compressive stresses, according to [14];7 – seismic generation zones, according to [14]; 8 – seismic generation zones highlighted by the algorithm considered in the text.

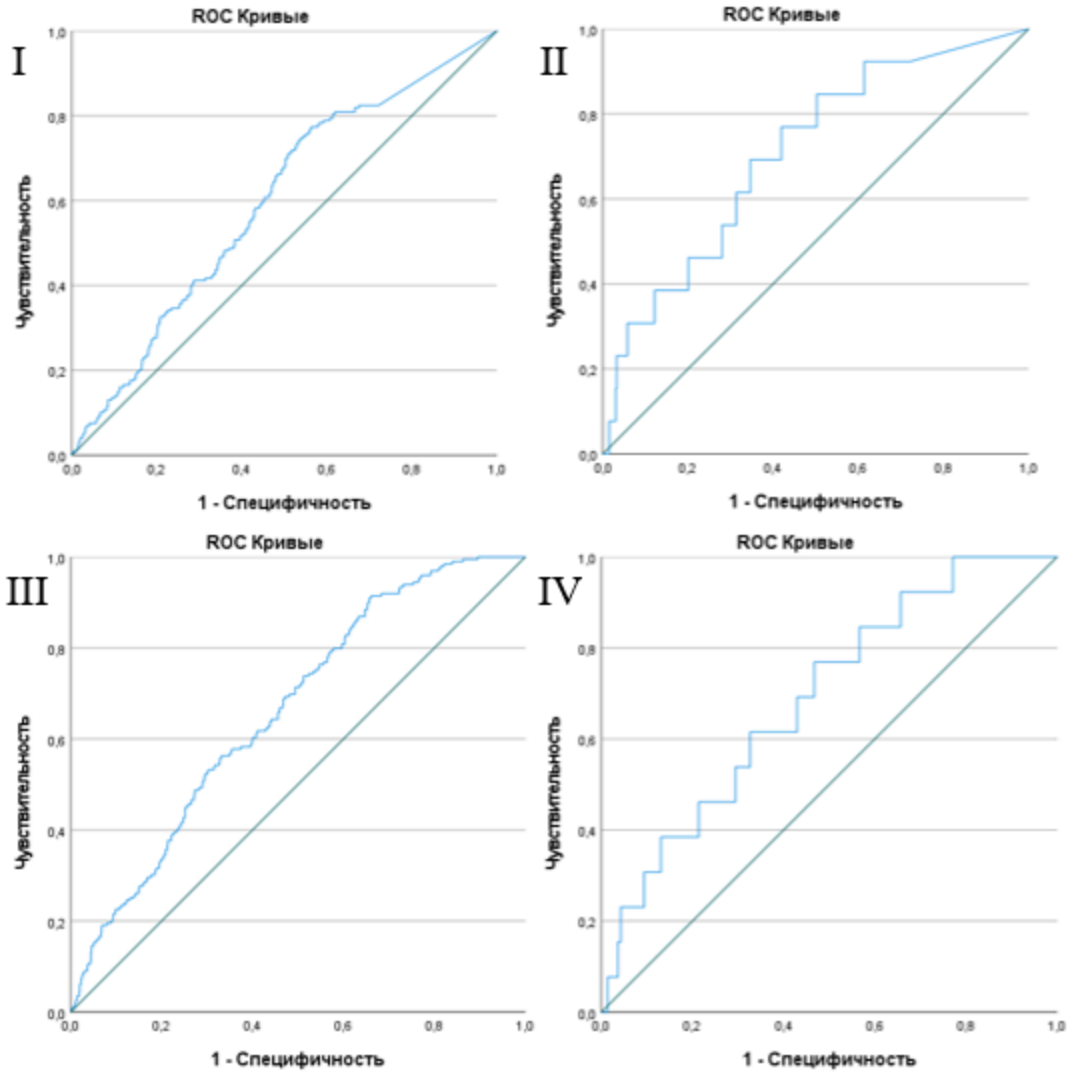


Figure 3

ROC curves (blue lines) constructed for the neotectonic activity index (I) and earthquake epicenters of Sakhalin Island: I–II for the first model (explanations in the text): — I taking into account the entire magnitude range under consideration, II — only for earthquakes with M≥5.5; III–IV — for the second model: III — taking into account the entire considered range of magnitudes, IV — only for earthquakes with M≥5.5. Diagonal lines are the boundaries of a random distribution. Specificity and sensitivity are two important characteristics of an algorithm. Specificity refers to the ability of the algorithm to accurately identify objects in a sample that have a specific feature, while sensitivity refers to its ability to differentiate between objects that have and do not have the same feature. [20].

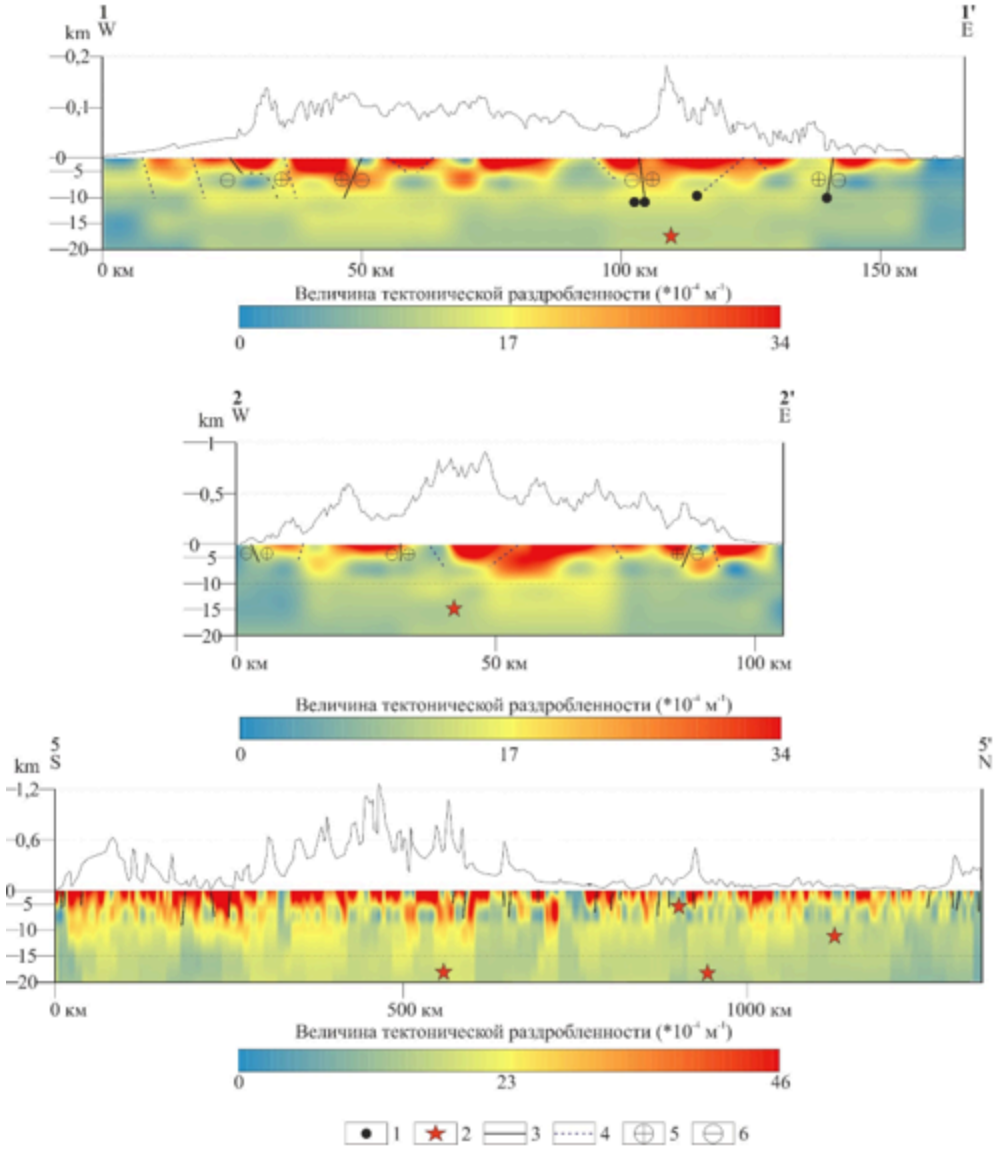


Figure 4

Profiles of tectonic fragmentation (Fig. 2A) through the foci of the Neftegorsky (1-1’) and Uglegorsky (2-2’) earthquakes, and through the entire Sakhalin Island (5-5’). 1-2 – hypocenters of earthquakes with magnitude: 1 –M <5.5, 2 –M ≥5.5; 3 – faults [7] as seen from tectonic fragmentation perspective; 4 – "weak" zones as seen from tectonic fragmentation perspective; 5 – upthrown block of the fault; 6 – downthrown block.