Development of complex model of evolution of structural-tectonic blocks of the Earth's crust for choosing storage sites of high level radioactive waste

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[1] The results of research aimed at predicting the evolution of structural-tectonic blocks of the Earth's crust for selecting Storage Sites of High Level Radioactive Waste (HLRW). The multifactorial structural-tectonic model of Nizhnekansky Granitoid Massif (NKM) was developed, as the most probable burial site of HLRW in Russia. The synthesis of methods of analysis of geological-geophysical data, paleotectonic reconstruction of stress and modeling of stress fields expand the area of predicting stability of geological environment thus providing the capability to make a more accurate assessment of its destruction during a long period of radiobiological danger of HLRW. As it was shown, blocks with high level of concentration of intensiveness of stress are potentially hazardous in relation to development of tectonic destruction. *INDEX TERMS:* 8004 Structural Geology: Dynamics and mechanics of faulting; 8011 Structural Geology: Kinematics of crustal and mantle deformation; 8038 Structural Geology: Regional crustal structure; 8110 Tectonophysics: Continental tectonics: general; 8120 Tectonophysics: Dynamics of lithosphere and mantle: general; 8199 Tectonophysics: General or miscellaneous; *KEYWORDS:* Nizhnekansky granitoid massif, structural-tectonic model, modeling of stress fields, radioactive waste.

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1. Introduction

[2] Development of nuclear energy in Russia is impossible without solving the problem of storing HLRW in deep geological formations. The method of selecting sites for dumping HLRW is based on a search of the less dislocated structural-tectonic blocks (STB) of maximal size [*Morozov and Tatarinov,* 1996, 2006] in relatively stable areas. However, the "suitable" conditions at the beginning of construction works don't guarantee insulating qualities of the rock during the whole period of radiobiological danger of HLRW, exceeding $10^4 - 10^5$ years. Geodynamic processes during this lengthy period can dramatically alter the hydrogeological regime of the area (the groundwater level, water-bearing pressure, net of fluidconductive channels etc.). Formation of the new or activizing of existing tectonic faults poses the greatest menace, as well as intrusion of superficial or subterranean waters to HLRW containers with subsequent emission of radionuclides. The applied expert methods of evaluating geological environment are important, but obviously insufficient for estimating the danger of such processes. It is necessary to predict the evolution of the isolated mode of the geological environment taking into account the loss of insulating qualities of the rock as the main barrier, preventing the spreading of radionuclides. To realize this in practice, we are working on developing a technology capable of evaluating stability of structural-tectonic blocks, including the range of consequent stages. Each of them represents a separate scientific and technological task (Figure 1). The given technology was tested at NKM, where a first burial site of HLRW in Russia was planned. At the first stage of works the construction of underground laboratory is suggested.

[3] The algorithm of predicting the tectonic evolution of STB is based on the following objectives [*Morozov and Tatarinov,* 2006].

[4] 1. Analysis of construction, search of active structural heterogeneities and geomorphological indicators of tectonic activity of the region and development on its basis of a multifactorial structural-tectonic model.

[5] 2. Reconstruction of the tectonic history of the region, representation of the dynamics of alterations taking into account the fragmentary heterogeneous distribution of stress-strain properties.

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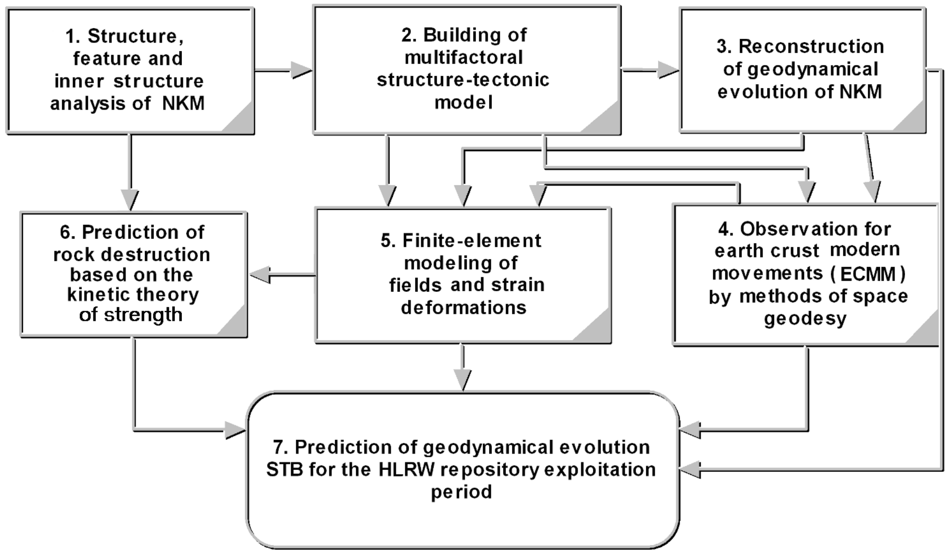

Figure 1. The basic stages of technology.

[6] 3. Modeling of distribution of strain fields at the present stage and possible trajectories of formation of new tectonic destructions. Zoning of the area according to the degree of its geodynamic stability, prediction of the possible order of destruction of existing STBs.

[7] 4. Carrying out observations of the modern movements of Earth's crust using the methods of space geodesy and high accuracy relevelling methods over 5–6 years, revealing the most active sectors, correction of stress-strain state models and models of destruction of the geological environment.

[8] 5. Selection of the most stable STB, the stable state of which is guaranteed over $10^4 - 10^5$ years, for the construction of an underground research laboratory.

[9] The basic models: 1) multifactorial structural-tectonic model; 2) model of geotectonic evolution; 3) model of stress-strain state; 4) model of predicting of stability of STB.

2. Results of Research

2.1. Multifactorial Structural-Tectonic Model of NKM

[10] The Nizhnekansky Granitoid Massif is located in Siberia a few dozens of kilometers to the east of Krasnoyarsk. It protrudes from the north-west to south-east at approximately 60 km, at an average width of about 30 km (Figure 2). According to the data of geological-geophysical and structural-geomorphological research, carried out in the western part of the massif and partly in the enclosing rocks, 3 sites were selected for storing HLRW: "Kamenniy", "Itatskiy" and "Yeniseiskiy" [*Anderson et al.,* 2001].

[11] The NKM is an integrate autonomously formed syn-orogenic batholit. The morphology of its upper and lower edge, vertical magnitude, location of its stem root, interactions of phases, character of contacts, linearity, and the most important – the inner structure of the massif, is a result of self-development (of cooling down and crystallization of the magma and formation of endokynetic contraction cracks), and on the other part – a consequence of superposition of the later tectonic process. The morphology of top edge of HKM is rather complicated and heterogenous. It appears to be a "mirror" of its geodynamic activity. The massif occupies the area of about 2000 km^2, 60 km long and 23–35 km wide. The structure of the massif's crystal edge is rather complicated and heterogenous. It is intensively divided by modern erosion processes. The spread of absolute elevations is around 250 m reaching 500 m at the maximal elevation mark. For revealing the general pattern of its structure the relief smoothing operation was applied, accomplished by subtracting from elevation marks the average magnitude of porous deposits, comprising about 50 m. As a result the scheme of NKM top edge morphology was developed, shown in Figure 3 [*Belov et al.,* 2007].

[12] The analysis of this scheme has shown that the top edge consists of approximately equal parts, the eastern half (section 2) is more elevated and has a rather simple flat undulated topography, reflected by the placid disposition of isolines and a small part of sections with sharp gradients of the massif's top contour. The western part (section 1), in comparison to the eastern, is 200–250 m lower and very irregular. Its indention is subordinate to sub-meridional direction, according to which the considerable part of large tectonic faults of the area is developing. These peculiarities of the relief's indention provide the opportunity of indirect estimating of the trends of modern tectonic stress in the area.

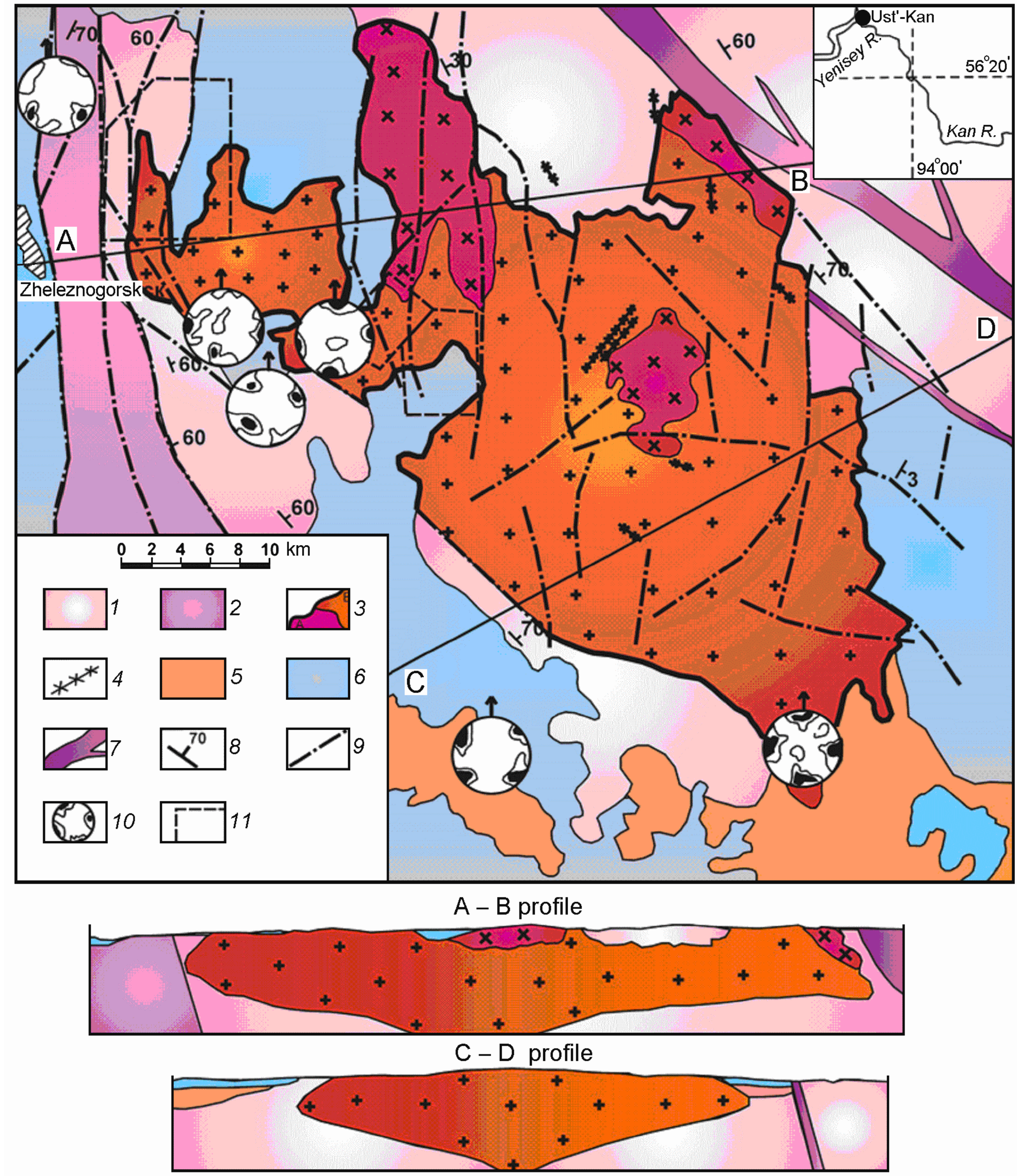

Figure 2. NKM area geological structure scheme. 1 – gneiss (AR); 2 – amphibolite, quartzite and marble (AR-PR); 3 – contour of NKM granitoids: a – diorite of 1st stage; b – granite of 2nd stage; 4 – dikes; 5 – terrigenous-volcanic deposits (PZ_2); 6 – terrigenous deposits (J); 7 – mylonite zones; 8 – main faults; 9 – diagrams of jointing orientation; 10 – bedding of rocks; 11 – areas of detailed research (from south-east to north-west: “Kamenniy”, “Itatskiy”, “Eniseiskiy”).

2.2. Tectonic Features of Relief

[13] The second element of the structural-tectonic model of NKM, reflecting its modern tectonic activity, is the contemporary relief, revealing fairly well the recent movements of the crust and its modern tectonic activity. For its analysis the coefficient of relief dissection intensity (K_{id}) was used, calculated by sliding window of a uniform grid 4×4 km as the ratio of maximal and minimal elevation marks to a unit area. The higher is the velocity of elevation of the area, the higher is K_{id}. Figure 4 shows the scheme of relief fracturing, shown in isolines of coefficient K_{id}.

[14] Analysis of the scheme proves that, according to the

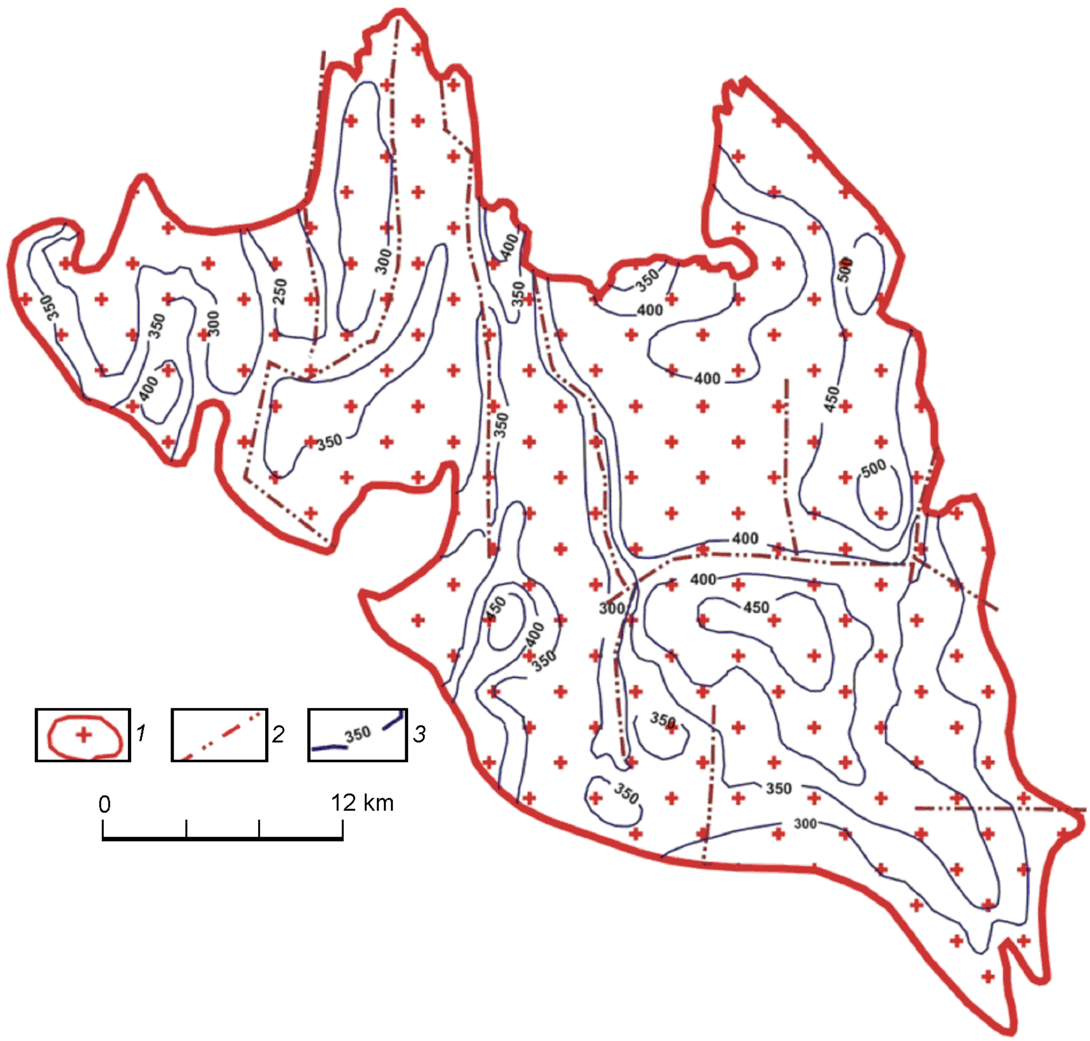

Figure 3. Scheme of NKM top edge morphology. 1 – NKM contour; 2 – main faults; 3 – isolines of NKM top edge.

character of isolines K_{id}, nonconforming to contact, the elevation of NKM is related not merely to the "floating" granites, but to the more general tendency of vertical uplift, characteristic to the southern part of the Yeniseiskiy Ridge. At that the territory of NKM according to the intensity of its elevation is divided into two parts by the sub-meridional Maliy Itatsky fault. The right part of the massif, located to the east of the Maly Itat river, is characterized by the most intensive elevation ($K_{\mathrm{id}} = 200$–400).

2.3. Analysis of Block Morphological Structures

[15] Selection of tectonic faults by various authors is mainly based on the study of satellite images, geomorphological analysis of the relief and riverbeds. The works by S. V. Belov, V. M. Datsenko, R. M. Lobaskaya, D. V. Lopatin, N. V. Lukina, V. L. Milovidova provide an ambiguous interpretation of the geometry and characterize the modern activity of tectonic faults.

[16] The faults and over-faults appear in the form of terraces of the modern relief up to 100–150 m high. In the zones of faults the geniculate displacements of the river drainage system are marked with the amplitude of horizontal displacement up to 100–450 m, from 3–5 to 15–20 km long and 100–300 m wide. Within the Nizhnekansky massif the system of fractures of north-western orientation is the most striking (with azimuth 325–345°). The second by intensity of its manifestation is the system of fractures with strike azimuth 10–35°. The third one is the system – with azimuth 295–315°. The research carried out by the geologists of the "NPO V. Khlopin Radium Institute" [*Anderson et al.,* 2001] has revealed the zones of dynamic influence of active faults in the northern part of NKM. There in the contact zone the processes of strain, residual ruptures and plastic alterations are revealed. HLRW burial is possible only outside these zones. Their width is directly proportional to a length of

active faults. Within the area a ratio of width to length of the fault zones is close to 0.05 in separate cases reaching 0.08–0.1. At the uplifted fault walls the zones of dynamic influence are wider, at down-thrown (passive) – narrower.

[17] To reveal the regional block structure a morphological structural analysis (scale 1:200,000) (method of A. Orlova) was carried out, providing the capability to select relief-generating faults and multiple-elevation structural blocks (Figure 5).

[18] It is significant that the morphological-structural analysis has recorded practically all considerably large faults, selected by N. V. Lukina and R. M. Lobatskaya by deciphering aero- and satellite images. Altogether 10 levels of multi-elevation blocks were detected with the difference of hypsometric levels equal to 50 m. Within NKM there are 7 levels in the interval of heights from 580 m to 230 m. They are of a predominantly isometrical form from 2 km to 8 km in transverse. The eastern sector of NKM has the higher hypsometric level, the elevation marks of structural blocks vary from 530 m to 380 m, in the western section they are more subsided, up to 430–280 m.

[19] The comparison of positions of sections in the general block morphological structure of the region shows that the most favorable position belongs to area "Kamenniy". About 70% of its area lies within the contours of one STB with low hypsometric level of 330–280 m. The position of area "Itatskiy" is less favorable, because it is located within the limits of two adjoining multiple-elevation blocks. The position of "Yeniseiskiy" area is even less favorable, it is traversed by the Provoberezhny fault and by a series of adjoining inter-block distortions.

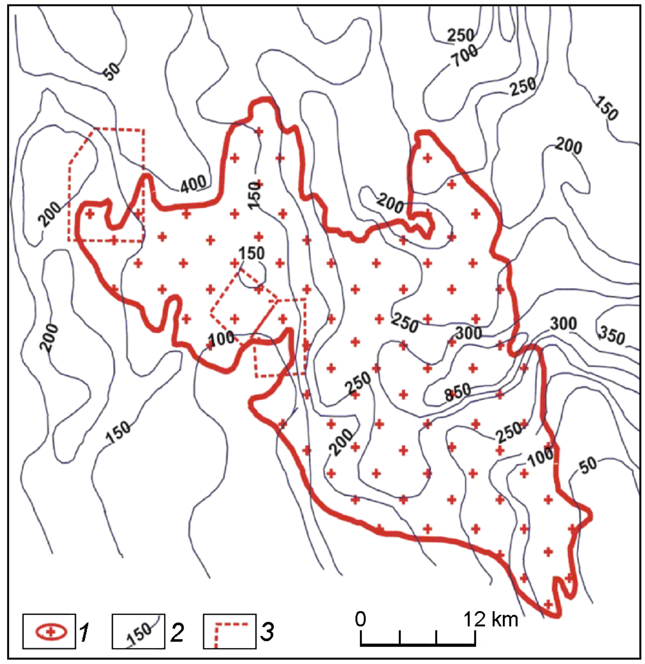

Figure 4. Relief dissection intensity map of NKM region. 1 – granites, 2 – isolines of C_{IR}; 3 – contours of "Kamenniy", "Itatskiy", "Eniseiskiy" areas from south-east to north-west.

2.4. Finding Structural Non-Uniformities and Sign of Tectonic Activity

[20] The above-mentioned model of NKM was amplified and corrected on the basis of analysis of geophysical fields. For this purpose the data of aero-magnetic survey (scale 1:200,000) were used. For obtaining data on the massif's structure on the anomaly component of the magnetic field new algorithms of cluster analysis were applied, based on the analysis of location of specific points of the anomalous field, marking a roof and center of anomaly-generating objects. Besides the location of specific points, marking the roof, in many cases location of specific points, related to centers of magnetic masses of selected objects, can be established. Such points mark objects that can be physically identified with porphyritic veins or highly magnetic gneiss as a part of the crystalline base. For determining the position of specific points the methods were used, based on the cluster analysis of equivalent sources, obtained from a local linear pseudo-inversion (the method of Euler deconvolution-MED). For the further analysis the algorithms of cluster analysis RODIN and KRISTALL were used, applying the fuzzy logic principles, elaborated by the scientists of the Institute of Physics of the Earth's department of mathematical geophysics and geoinformatics, headed by A. D. Gvishiani. The work provides its detailed description [*Mikhailov et al.,* 2003].

[21] For determining the depths of upper edges of anomalies structural index value $n = 0.5$ was used. Applying the linear pseudo-inversion method 25371 marks of specific points were obtained. After the cluster analysis 16183 points were detected, forming dense clusters. The depths of these points were interpolated by a Kreiging method on a iniform grid with 1 km interval. The obtained points distribution is shown in Figure 6.

[22] It has to be mentioned that about 30% of obtained linear zones aren't related to the available geological data of tectonic deformations. It could be: a) zones of strongly magnetized rocks, emerging at the formation of NKM; b) healed zones of jointing, faults and contacts with intrusive bodies; c) tectonic deformations, not detected earlier. Thus, if a decision about selecting an area is taken, anomalies have to be checked by detailed geologic-geophysical exploration works. The cluster analysis also allowed to establish that isometrical STBs of 6–8 km in size prevail in the NKM structure.

2.5. Modeling of Stress-Deformed State

[23] The above-mentioned structural-tectonic model lies in the foundation of modeling of the strain-stress state of NKM based on the method of finite elements. For this purpose we used a deflection model of the generalized plane stress state. A layer was selected in the three-dimensional rock massif, whose width is small in comparison to the massif's length. The kinematic boundary data correlate with the grip conditions, not allowing displacements towards the directions, corresponding to the surrounding contour. Selection of the

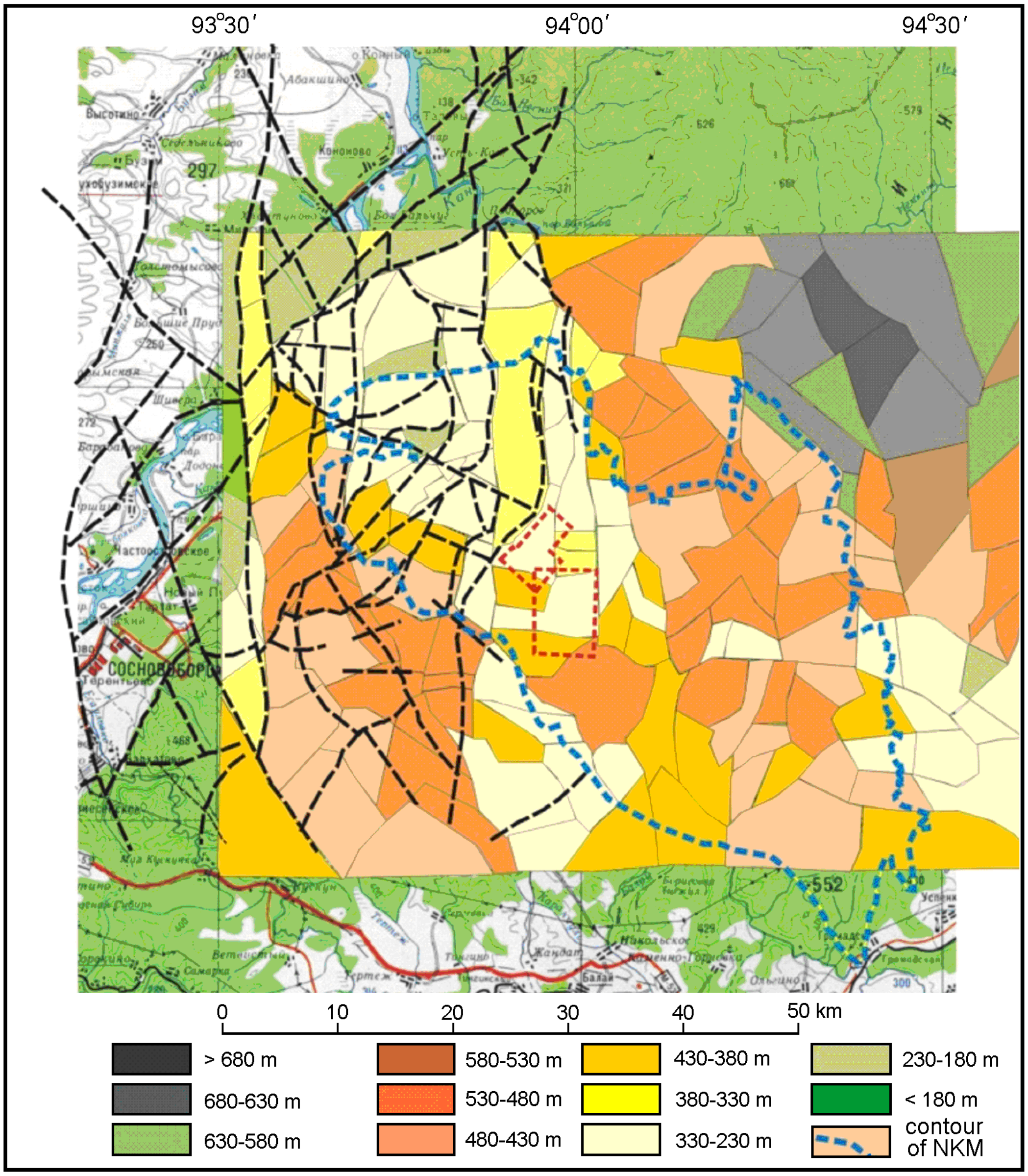

Figure 5. Structural-tectonic blocks (STB) of NKM.

boundary data provides the capability to reveal the clusters of stress intensity related to structural heterogeneities, typical for a geological environment.

[24] The stress intensity value is calculated by formula:

$$\sigma_i = \sqrt{\sigma_x^2 + \sigma_y^2 - \sigma_x^2\sigma_y^2 + 3\sigma_{xy}^2}\ .$$

[25] The presented expression of stress intensity serves as a measure of the energy, accumulated in the rock by deformations of specific potential energy of stress. As a unified criteria of the stress-strain level of local parts of the Nizhnekansky Granitoid Massif stress intensity σ_i, and distribution of the shear stress component τ_{xy} were used (Figure 7a).

2.6. Monitoring Modern Earth Crust Movements by GPS and GLONASS

[26] It is obvious that verification and correction of the results of stress-strain state modeling of NKM and its parts can be completed by field observations in holes or underground working. The more rapid method demands using the Earth crust movements data based on the methods of space geodesy. In 2005 within the borders of NKM a geodynamic testing region was established. Figure 7b shows the map of the polygon's main objects. The project envisaged carrying out observations of the five geomorphological sections, different by relief parameters, related to the modern tectonic activity of the region: 1. The Yenisei river valley, 2. Scarp

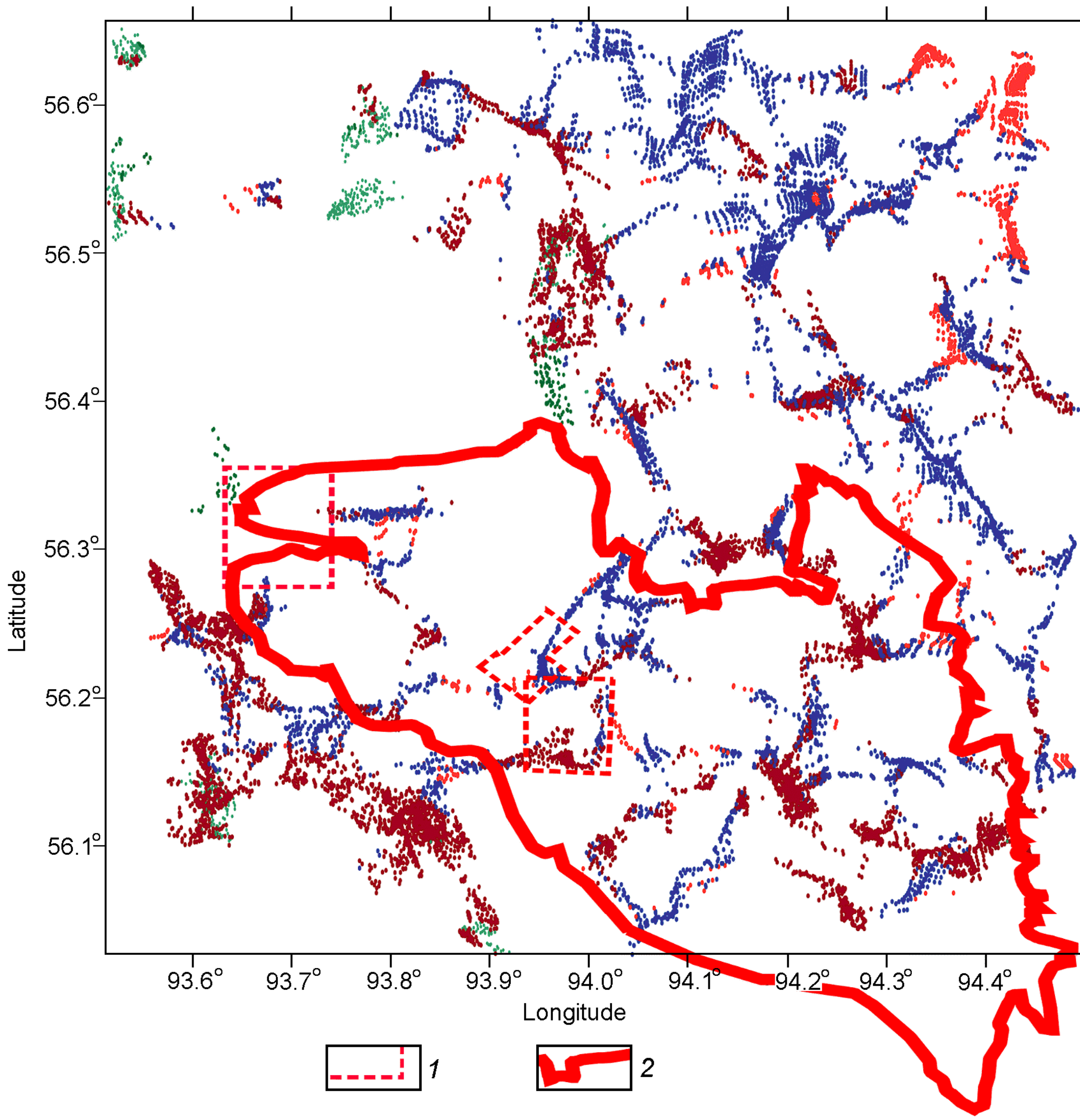

Figure 6. Interpretation of anomaly magnetic field. 1 – linear zones of different nature, 2 – contour of NKM.

of the Yeniseiskiy range, 3. Saddle between the Yeniseiskiy range scarp and river Kan valley, 4. Valley of the river Kan, 5. South-eastern edge of NKM.

[27] On optimizing the location of points of geodynamic network a number of alternative requirements to their location sites was taken into account: absence of forestry, availability of roads, bedrocks, optimal size of basic lines between observation points. However due to the absence of roads in the north-western part of the region the geodynamic network was asymmetrically shifted to the west. In 2006 the processing of first 6 bases was accomplished. The arrows in Figure 7b show the first directions of displacement of separate points.

[28] In 2008–2009 the network extension is planned in “Yeniseiskiy” area, where it would be possible to set up the main points of observations of the basement rock of the most representative structural blocks. In order to exclude the influence of freezing at the control points, exploring shafts or wells up to 5 m deep would be essential.

[29] Thus, as a result of the research the technology of predicting stability of geological strata at selecting the HLRW burial sites was developed, tested in the Nizhnekansky Granitoid Massif. For the development of a multifactorial structural-tectonic model and predicting stability of structural-tectonic blocks of the Earth’s crust new algorithms of cluster analysis for searching the indicators of modern tectonic activity and structural heterogeneities and finite-element models of stress-strain state of heterogenous block media were suggested. In order to correct the boundary data of stress of models of STB deformations the results of GPS-observations on the Earth crust movements will be used in the future.

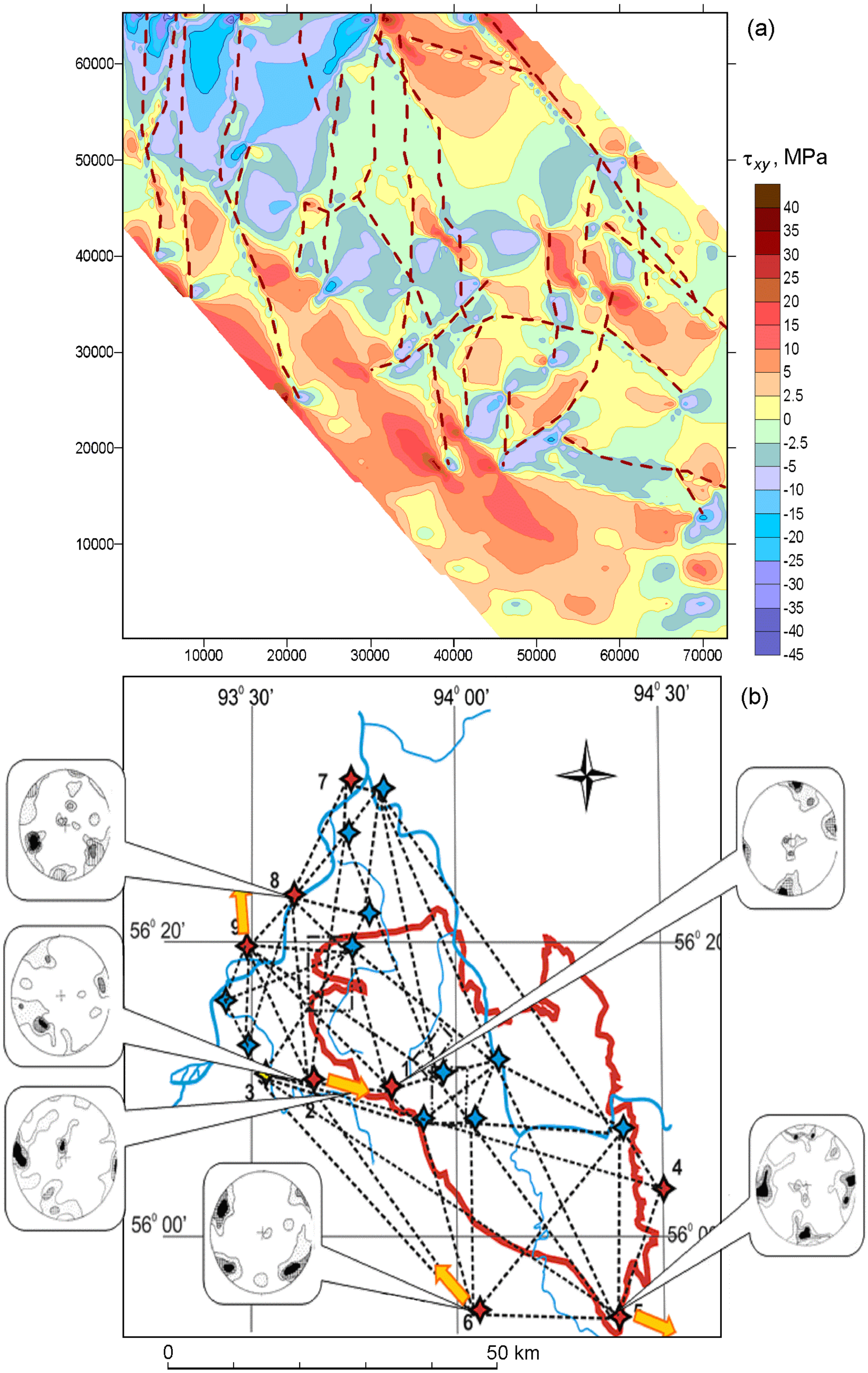

Figure 7. SDS simulation, τ_{xy} component (a) dotted lines are faults; and GPS point location (b). Directions of displacement are indicated by arrows. Fracturing diagrams are shown on the local insets.

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