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# Observations by Space Geodesy Methods on Objects of Using Atomic Energy

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**Abstract.** According to the existing international requirements, construction of an underground research laboratory (UGRL) that allows to obtain parameters of a host rock mass is a mandatory initial stage when siting a deep geological repository (DGR) for radioactive waste (RAW). The main idea of the basic international and Russian documents regulating the safety of handling high-level radioactive waste is that geological medium is *the main barrier* to the spread of radionuclides. The results of the world's leading research in this area are directly related to the development of methods, algorithms and software modules for predicting the stability of a structural tectonic block containing waste material of an underground HLWR repository and located in the field of action of time-varying and spatially varying tectonic stress fields as well as the heat field from HLRW containers. The results of modeling and implementation of the geodynamic monitoring system based on the use of GPS/GLONASS satellite systems will be used as the basis for the design development of «Rosatom» organizations for the construction of URL, which is created in accordance with IAEA requirements to justify the suitability of the Nizhnekansky massif for underground isolation of radioactive waste. Below we consider the influence of the geodynamic regime of the territory the possible destruction of the rock at different hierarchical levels.

## 1. Introduction

In the According to the existing international requirements, construction of an underground research laboratory (URL) that allows to obtain parameters of a host rock mass is a mandatory initial stage when siting a deep geological repository (DGR) for radioactive waste (RAW). To date, research activities in URLs have been carried out in 27 countries in various geological formations: in salts (Germany, the USA), granites (Sweden, Finland, Switzerland, Canada, Russia), clays (France, Switzerland, Belgium), and in tuffs (the USA). In 2018, Russia will start the construction of a URL in the gneiss of the Nizhnekanskiy massif as an initial stage of siting a DGR. The research activities in the URL, located at a depth of 500–600 m, are scheduled to be conducted until 2024; then, a final decision will be made on the suitability (or non-suitability) of this rock mass at the «Yeniseysky» site for safe disposal of radioactive waste [1]. Therefore, it is within this time span from 2018 to 2024 that it is planned to solve several fundamental interdisciplinary scientific and engineering problems, allowing predicting the safety of the geological environment for the whole period of RAW radiological hazard, which exceeds 10 thousand years.

A DGR shall be considered as a system that includes two interacting subsystems: a natural



environment (the geological environment) and a man-made facility (mine workings and heat-generating RAW). Therefore, this paper considers the impact of tectonic stresses, rock pressure, and man-made factors on the possible manifestations of rock pressure in a dynamic form (earthquakes, micro-earthquakes, rock bumps), that can lead to loss of insulation properties in the marginal part of the rock mass and to the destruction of engineering barriers and containers with RAW. The study of the design documents, which served as the basis for permit documents when obtaining a construction permit for the URL and the DGR, showed that this problem was hardly considered previously. At the same time, experience in developing deposits using the underground method shows that we should not exclude the probable destruction of the marginal part of the rock mass in the dynamic form both at the URL construction stage and during the subsequent operation of the DGR. For this reason, the problem definition regarding the Nizhnekansk massif and studying the way for its solving seem to be relevant and urgent.

## 2. Assessment of geodynamic activity in the region

The development of the seismotectonic process in the region of the Nizhnekansky massif is associated with the prevailing compression stress at an angle of about  $45^\circ$  to the meridian. It was previously shown that the presence of tectonic fractures in the upper part of the crystalline basement leads to the formation of high-gradient stress fields, which initiate the emergence of new tectonic fractures and manifestations of seismic activity [1]. The assessment of the SSS (stress-strain state) of block heterogeneous massifs, disturbed by a system of tectonic stresses, found confirmation in the SSS simulation in epicentral zones of crustal earthquakes with  $M \geq 6$  in the continental regions. It was demonstrated that tectonic earthquakes with  $M \geq 6$  occur in areas of high stress intensity at a certain ratio between the main tectonic stresses in the local geodynamic zones [2, 6].

Instrumental SSS studies in the mine workings of the Mining and Chemical Combine [3] suggest that the magnitude of the principal stresses is  $\sigma_{max} > 20\text{--}30$  MPa. By analogy with the area of the northwestern Urals,  $\sigma_{max}$  can reach significantly larger values: up to 40–50 MPa in zones of local stress concentration on closures, bends, and junctions of tectonic fractures. This also applies to the «Yeniseyky» site where, as is known, there are tectonic fractures [1].

Building a large underground facility such as the DGR with dimensions of about  $1.5 \times 1.0$  km at the depth of 500–600 m requires an analysis of possible catastrophic consequences, including from the dynamic manifestations of rock pressure. The work [4] provides an analysis of the mechanism of “draining” the accumulated deformation energy in the form of tectonic blocks destruction; the work analyzes the tectonic and physical conditions of rock bumps, and [1] consider the results of instrumental observations of the stress fields structure dynamics in the marginal part of the rock mass in relation to the problem of predicting dynamic phenomena. It is shown that the relative position of mine workings and tectonic fractures is the most important hazard factor of rock bumps. The seismic reactivation of even some small fracture, which is located in the immediate vicinity of the mine workings, can become a trigger for a large destruction, as is the case with trigger impact of mass explosions during field development. In this regard, we can assume the possible formation of a fracture crossing the DGR mining workings. The seismic effect of such a micro-earthquake with a hypocenter in the zone near the DGR, can lead to loss of insulation properties of not only engineering barriers, but also the isolation properties of the structural tectonic block as a whole. Therefore, the engineering assessment of the real hazard requires a detailed study of the failure tectonics, the external stress field, and monitoring of local micro-seismicity.

The structural-tectonic heterogeneity of the rock mass, including “metastable” areas, significantly complicates the ability to predict dynamic forms of rock pressure manifestation. Hence, monitoring of micro-seismicity over a wide frequency range in the area of the DGR is necessary at all stages of mining work, from drilling shafts to excavation of the URL underground openings and loading containers with RAW. This is confirmed by the experience of micro-seismicity survey and predicting, on the basis of the same, the places of future rock bumps, carried out by Canadian researchers in the AECL URL, as well as during the seismic monitoring when developing nickel deposits at great depths.

In the assessment of geodynamic environment and stress conditions in the areas of mining workings, the approach “from the general to the special” is widely applied [4]. The Nizhnekansky massif is located in a zone of active orogenesis, i.e. the process of its formation as a rock structure is not yet completed. It is located in the most complicated node of junction of three tectonic structures – the Siberian Platform, the West Siberian Plate, and the Altai-Sayan orogenic area. Its state of stress at the local level is determined by their strength interaction. Therefore, in addition to the problem under consideration, it is important to study the modern movements of the Earth’s crust (MMEC) and to predict the maximum possible strain rates.

In terms of geodynamics, the location of the «Yeniseysky» site (Figure 1) is far from unambiguous for the purpose of safe accommodation of the DGR within its boundaries [1]:

1. It is located at the margin of the Nizhnekansky massif and the enclosing Precambrian strata, the zones of exocontacts between magmatic bodies which, as a rule, feature an increased fracturing and structural heterogeneity. On the site, there are not only gneisses and granitoids, but also numerous bodies of irregular shape, as well as dikes of metamorphosed igneous rocks of basic composition. There is no analysis available of the influence of the exocontact zone on the massif’s filtration properties.

2. The eastern edge of the site is cut off by the ancient Pravoberezhny failure of outfall nature, activated at the present stage and forming the northeastern slope of the Atamanovsky ridge. According to N.V. Lukina, the maximum amplitude is 400–580 m with a length of 20 km. The fracture has been renovated at the newest stage: it was active in the Holocene and continues its displacement at present.

3. The records of repeated geodetic observations prove the existence modern movements along the fracture of up to 1–2 mm per year. The width of the dynamic impact zone of the Pravoberezhny fracture is 300 m to 3 km. Almost perpendicularly to it, there is the Shumikhinsky fault, separating the lowered neo-tectonic block from the central part. Thus, there are 2 deformations that divide the site into 3 different-height structural blocks.

4. At a distance of 2–3 km to the west of the site, there is the boundary of the Siberian Platform and the West Siberian Plate, which is clearly visible in the current terrain and, according to [1], belongs to the boundaries of large active blocks of the earth’s crust. Along the Muratovsky fracture, passing along this boundary, the West Siberian Plate is relatively lowered, whereas the Siberian Platform is elevated. The total amplitude of the vertical displacement along the fracture exceeds 3 mm per year, whereas the speed of the horizontal is 4–5 mm per year, according to GPS/GLONASS data.

In 2010, within the boundaries of the Nizhnekansky massif, a geodynamic polygon was created for carrying out instrumental observations of the MMEC using the GPS/GLONASS [2, 8]. The maximum speed of the MMEC was recorded along the line connecting the points that are located in the zone of the dynamic influence of the Muratovsky, Pravoberezhny, and Bolshetelsky fractures. The calculation of dilatation  $\Delta$  (the deformation rate) of the earth’s surface for the period 2012-2016 showed the presence of 4 abnormal areas (Figure 1):

- a) an area including the points 1204, 1205, 1206 ( $\Delta = 5 \cdot 10^{-7}$  per year), in the zone of the Atamanovsky fracture, which is a contact joint between the Siberian Platform and the West Siberian Plate;
- b) an areas on the left bank of the Yenisey River, point 1213 ( $\Delta = -1.3 \cdot 10^{-7}$  per year);
- c) compression and tension areas at the Yeniseysky site ( $\Delta = 8 \cdot 10^{-8}$ ,  $\Delta = -3 \cdot 10^{-8}$  per year);
- d) an area in the region of the Pravoberezhny fracture, points 1207-1209 ( $\Delta = -7 \cdot 10^{-8}$  per year).

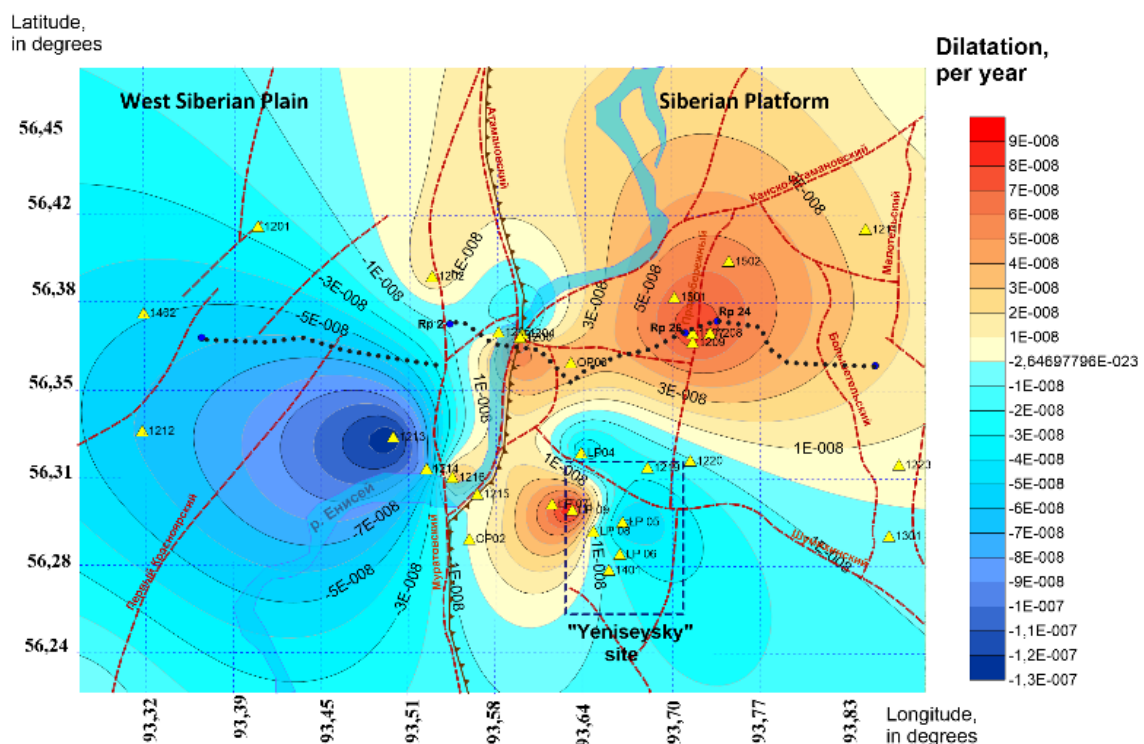
It is known that both creep and dynamic strains are dangerous for engineering structures. Given that instrumental observations carried out in this region using the methods of space geodetics, showed that the deformations are pulsating in nature [2], we use the recorded deformation rates for calculation.

The formula for calculating the threshold values of bending strains is as follows:

$$\Theta < \frac{C\varepsilon_n}{T}, \quad (1)$$

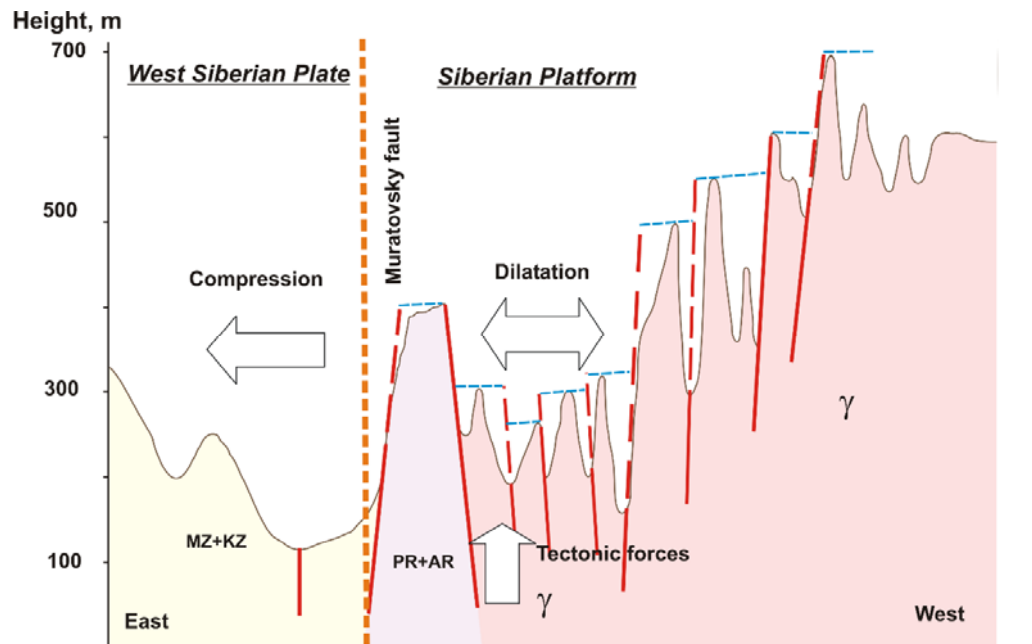
where  $\Theta$  is the average annual bending speed;  $\varepsilon_n$  is the threshold bending strain;  $T$  is the time;  $C$  is the empirical coefficient which, based on the results of numerous long repeated geodetic observations, varies in the range of 3–5. In such case, the maximum annual average rates of relative bending deformations shall not exceed  $5 \times 10^{-5} \div 10^{-4}$  per year. The above dependence determines the criterion for identifying dangerous fractures which can affect the safe operation of the DGR.

In addition to the accumulation of dangerous deformations as such, modern movements in the upper part of the Earth's crust lead to the formation of local zones of high stress concentrations, which can become rock destruction centers in a dynamic form. This relationship is established in the development of many bump-hazardous deposits. This, the works [1, 2] describe a clear interdependence between the time of rock tectonic bumps and displacement of soil in underground workings or on the Earth's surface.



**Figure 1.** Dilatation ( $\Delta$ ) map of the earth's surface in the Nizhnekansk massif for the period from 2012 to 2016 according to GPS-observation data

Figure 2 shows the region's longitudinal section from east to west as an alternative interpretation of the cyclical development of modern geodynamic processes in the area (the vertical scale is considerably stretched relative to the horizontal scale). Vertical tectonic strain at the Siberian Plate in the southern part of the Yenisei Ridge leads to the formation of the relative extension zones on the Earth's surface and at the same time to compression on the border of the West Siberian platform. After reaching a certain limit of compression, a relaxation of accumulated stress by right shift occurs along the Muratovsky and Atamanovsky faults. The rock massif returns to its former condition and after a while the geodynamic cycle repeats. These conclusions are confirmed by neotectonic diagram of the Baikal-Yenisei fault in [5, 8], which provides vertical velocities of the Pleistocene period. The scheme is very similar to the dilatation map shown in Figure 1. It can also be assumed that the modern geodynamic regime of the territory is close to the regime that existed, at least in the Pleistocene (from 2.5 mln. to 10 000 years ago).



**Figure 2.** Hypothesis of the geodynamic situation in the southern part of the Yenisei Ridge (the vertical scale is greatly increased relative to the horizontal). The red dotted line - the boundary of two tectonic areas: the West Siberian plate and the Siberian platform.

### 3. Conclusion

A geodynamic testing ground for observing modern crustal movements based on the use of global navigation satellite systems was established in the area of construction of an underground research laboratory for the study of ecological safety of disposal of high-level radioactive waste. For the first time we instrumentally determined the horizontal crustal movements rate for the area, located at the junction of two major tectonic structures - the Siberian Platform and West Siberian Plate, in order to assess the intensity and direction of tectonic processes at the present stage of development of the region and the values of the maximum strain rate.

In 2013-2014 an activation cycle was registered, which manifested itself in an increase in the absolute values of changes in baseline lengths and in the sign change (compression-tension) on the right and left bank of the Yenisei River. The annual rate of baselines' change during the activation period increased to 15 mm, with pre-existing baselines in the range from 0 to 10 mm in 2010-2013. The probable reason was the cyclical nature of space-time development of geodynamic movements.

As a result of equalization of observations data, we equalized baseline vectors' components and evaluated their accuracy. The mean square errors were in the intervals of 3-4 mm and 6-7 mm, respectively.

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