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An underground research laboratory: new opportunities in the study of the stress-strain state and dynamics of rock mass destruction

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According to the existing international requirements, construction of an underground research laboratory that allows to obtain parameters of a host rock mass is a mandatory initial stage when siting a deep geological repository for high-level radioactive waste. 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 high-level radioactive waste repository. This structural and tectonic block is located in the field of action of time-varying and spatially varying tectonic stress fields as well as the heat field from high-level radioactive waste 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 Nizhnekansk massif for underground isolation of radioactive waste. Below we consider the influence of the seismotectonic environment, the geodynamic regime of the territory and anthropogenic factors on the possible destruction of the rock in a dynamic form at different hierarchical levels. *KEYWORDS:* stress-strain state; geodynamic observations; geodynamic zoning; GPS/GLONASS; underground research laboratory; high-level radioactive waste.

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Introduction

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 high-level radioactive waste (HLRW). 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) [*Martin and Chandler,* 1996; *Tsebakovskaya et al.,* 2015; *Kemppainen,* 2014]. In 2018, Russia will start the construction of a URL in the gneiss of the Nizhnekansk 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 Yeniseysk site for safe disposal of radioactive waste [*Anderson et al.,* 2011]. 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 HLRW 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 manmade facility (mine workings and heat-generating HLRW). Therefore, this paper considers the impact of tectonic stresses, rock pressure, and manmade factors on the possible manifestations of rock pressure in a dynamic form (earthquakes, microearthquakes, 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 HLRW. 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.

Method

The practice of developing bump-hazardous deposits shows that the rock mass hazard manifests itself by zones. This zonality is expressed in the fact that rock bumps occur not over the entire area of a mine field or a deposit (a group of deposits), but only in some parts of the same. Previously, this gave rise to the idea of early detecting hazardous areas of mine fields, i.e. geodynamic zoning [*Batugin and Petukhov,* 1990; [*Petukhov and Batugina,* 1999; *Batugin,* 2018; *Morozov and Tatarinov,* 1991]. As the stressed state of the rock mass is one of the main prerequisites for geodynamic hazards, the geodynamic zoning method is primarily focused on its evaluation. In the geodynamic zoning method, the stress state is associated with the interaction of the Earth' crust blocks at different hierarchical levels. Structurally, the geodynamic zoning method is the identification of active blocks and their boundaries (fractures) in the deposit area, the assessment of blocks (fractures) interaction, the assessment of the stressed state on the basis of the data obtained, and the elaboration of safety recommendations. In this paper, we present some results of the geodynamic state survey in the URL's area.

Result

The area of the URL construction belongs to the 8^{th} zone of seismic hazard waste [*Anderson et al.,* 2011] it is also known that even local, shallow earthquakes with $M \sim 4-5$ are able to create long enough fractures of up to 10 km. Weak earthquakes (when hypocenters are located in the immediate vicinity of an underground facility's boundaries) can initiate dynamic manifestations of rock pressure in the marginal zones of pit shafts and horizontal tunnels in the form of scaling, spalling, and rock bumps as such [*Batugin et al.,* 2016; *Lasocki.et al.,* 2017].

Without dwelling on the extensive experience of studying rock bumps in Russia and abroad when developing minerals resources [*Brzovic et al.,* 2017; *Kaiser et al.,* 2010; *Kotenko E.A.,* 1995; *Malovichko et al.,* 2012; *Melnikov,* 2010; *Melnikov et al.,* 2017, 2018; *Jianyong et al.,* 2016; *Petukhov,* 2004; *Petukhov and Linkov,* 1982; *Van Aswegen,* 2017; *Puchkov et al.,* 2015; *Rasskazov I.Yu. et al.,* 2012] we have to emphasize the following: rock bumps in the marginal part of a rock mass start from the depth of 200–300 meters from the earth's

Table 1. The Seismic Hazard Estimates

Cities	OSR-97-A $t = 500$	OSR-97-B $t = 1000$	OSR-97-C $t = 5000$	OSR-97-D $t = 10000$
Krasnoyarsk	6	6	8	8
URL areas	6	6	7	7

surface and manifest themselves not only during the production, but also during the development of mine workings; rock bumps occur in hard, brittle, elastic rocks; they arise directly due to the impact of rock pressure and tectonic stresses. They are the most probable where horizontal compressive stresses are $1.5 - 3$ times higher than those caused by lithostatic pressure; rock bumps occurred at deposit sites many years after the end of work.

Consider the influence of seismotectonic environment, geodynamic regime of the territory, and man-made factors on the possible destruction of the rock in the dynamic form at various hierarchical levels.

Seismotectonic Condition

The analysis of the geotectonic process in the region of the Nizhnekansk massif, including the seismic hazard assessment of the "Yeniseysk" site at the right bank of the Yenisey River (4.5 km) is given in [*Anderson et al.,* 2011; *Morozov et al.,* 2008b]. As a result of work carried out by Krasnoyarsk Scientific Research Institute of Geology and Mineral Resources, additional information is available on the seismic activity in the region of the L 580 lineament. In the related area, near the epicenter of the earthquake in 1938 (epicenter coordinates: 55.2° N, 94.6° E, magnitude: $M = 5.0$), a large paleoseismic dislocation, named Malinovskaya after the closest human settlement, was found. Its age is about 9 600 years. Based on the fracture edges dislocation, the intensity of the earth tremor in its epicenter was estimated at 9 points.

If we use the traditional formula to connect the tremor intensity I with magnitude M and the epicentral distance R of the earthquake [*Shebalin,* 1997]

$$I = 1.5M - 3.5 \lg R + 3.0$$

for magnitude $M = 7.0$ and at the distance from the epicenter of $R = 5$ km, we can obtain a very high value $I = 11$ points. If we use a realistic nonlinear "magnitude-distance-intensity" relation, in which we can see a "saturation" of the seismic effect near the epicenter, the effect would be somewhat lower, and with magnitude $M = 5.7$, the seismic effect would be $I = 9$. Thus, taking into account the "magnitude-distance-intensity" relation, as well as the age and place of this dislocation at the L 580 lineament, it is quite likely that the magnitude was $M = 5.7$.

When refining the model of potential earthquake source zones, based on OSR-97 (general seismic zoning), the following seismic hazard estimates were obtained (in points of the MSK-64 scale, for generalized soil conditions) (see Table 1) [*Anderson et al.,* 2011].

The development of the seismotectonic process in the region of the Nizhnekansk massif is associated with the prevailing compression stress at an angle of about 45° 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 rupture andmanifestations of seismic activity [*Morozov et al.,* 2008a]. 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 $M \geqslant 6$ in the continental regions [*Morozov and Manevich,* 2016, 2018]. It was demonstrated that tectonic earthquakes with $M \geqslant 6$ occur in areas of high stress intensity at a certain ratio between the main tectonic stresses in the local geodynamic zones [*Morozov and Tatarinov,* 2006].

Instrumental SSS studies in the mine workings of the Mining and Chemical Combine [*Morozov et al.,* 1999; *Tatarinov et al.,* 2015a] suggest that the magnitude of the principal stresses is $\sigma_{max} > 20-30$ MPa. By analogy with the area of the north-western Urals [*Zubkov,* 2012], σ_{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 [*Anderson et al.,* 2011; *Morozov et al.,* 2008a].

Building a large underground facility such as the DGR with dimensions of about 1.5×1.0 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 [*Morozov and Tatarinov,* 2006] provides an analysis of the mechanism of "draining" the accumulated deformation energy in the form of tectonic blocks destruction; the work [*Martin and Chandler,* 1996] analyzes the tectonic and physical conditions of rock bumps, and [*Tatarinov,* 1999] 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 [*Dobrovolsky,* 2009]. 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 principle of analogy, widely used in mining practice when designing the development of iron ore deposits in Gornaya Shoriya, the Severouralsk Bauxite Ore Field, and by "Appatit", JSC, may be useful to predict dynamic forms of the rock pressure manifestation in the area of the URL.

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 HLRW. 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 [*Tsebakovskaya et al.,* 2015; *Martin and Chandler,* 1996].

Assessment of Geodynamic Activity in the Region

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 [*Batugin and Petukhov,* 1990]. The Nizhnekansk 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, important is the task of studying the modern movements of the Earth's crust (MMEC) and predicting the maximum possible strain rates.

In terms of geodynamics, the location of the Yeniseysk site (Figure 1) is far from unambiguous for the purpose of safe accommodation of the DGR within its boundaries [*Anderson et al.,* 2011; *Morozov et al.,* 2008a]:

1. It is located at the margin of the Nizhnekansk 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 exo-

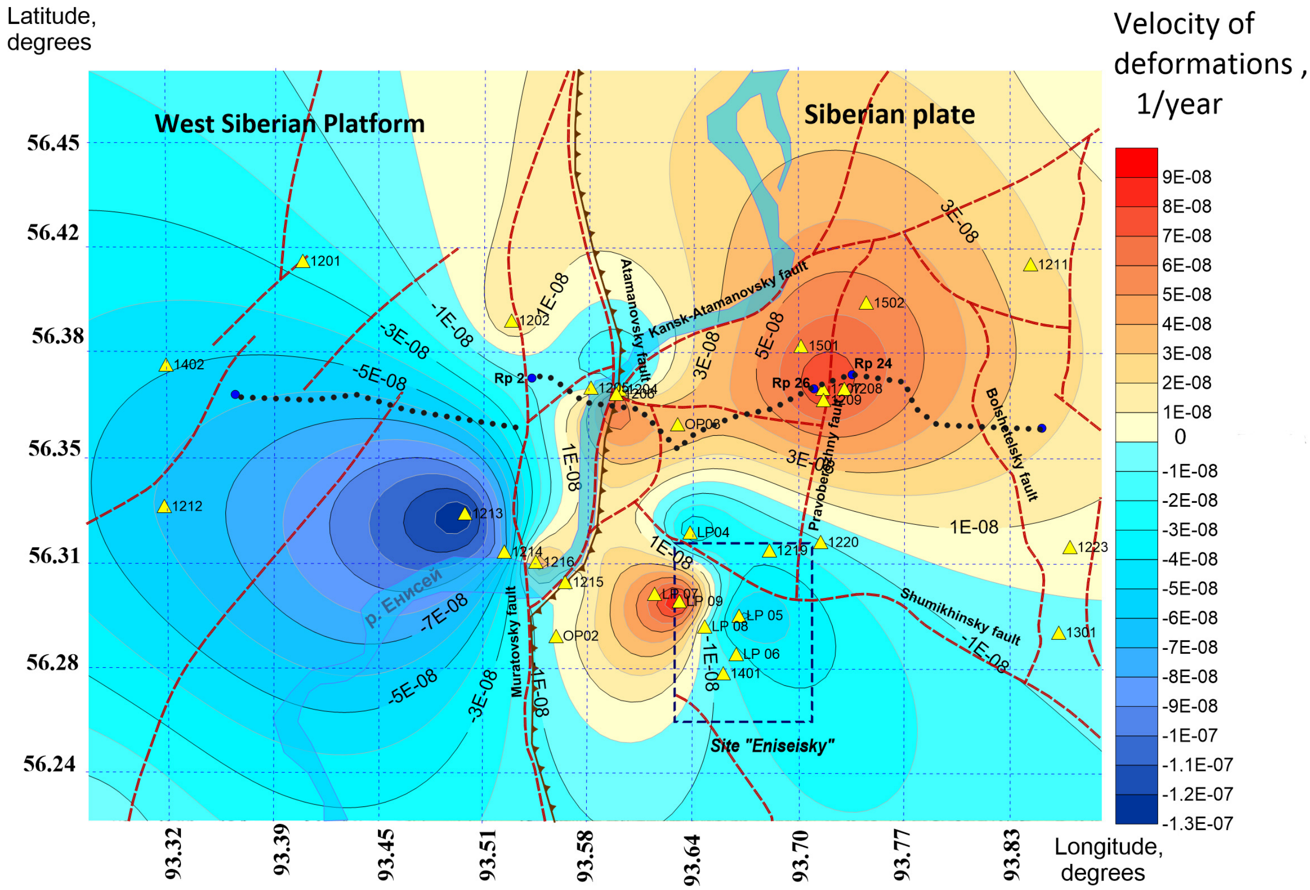

Figure 1. Dilatation map of the Earth's surface in the Nizhnekansk massif for the period from 2012 to 2016 according to GPS-observation data.

contact 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 of 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 neotectonic 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 [*Anderson et al.*, 2011], 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 Nizhnekansk massif, a geodynamic polygon was created for carrying out instrumental observations of the MMEC using the GPS/GLONASS [*Tatarinov et al.*, 2014;

Tatarinov et al., 2017; *Tatarinov et al.,* 2015b]. 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, Pravoberezny, and Bolshetelsky fractures. The calculation of dilatation Δ (the deformation rate) of the earth's surface for the period from 2012 to 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 Yeniseysk 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 [*Tatarinov et al*., 2014], we use the recorded deformation rates for calculation.

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

$$\Theta < \frac{C\varepsilon_n}{N},$$

where Θ is the average annual bending speed; ε_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 [*Kuzmin,* 2016]. 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 [*Methods,* 2010; *Morozov et al.,* 1990; *Tatarinov,* 2015a] describe a clear interdependence between the time of rock tectonic bumps and displacement of soil in underground workings or on the Earth's surface.

Man-Made Impact of the DGR

There are many man-made factors that can initiate rock destruction in a dynamic form. The main factors are: a) the geometrical shape and dimensions of the DGR underground part, determining the concentration of stress fields in the marginal zone; b) processes of displacement developing in the overlying formation; c) the thermal effects of containers with HLRW, especially, in the first decades of the DGR operation.

Compared with underground mining operations, the main difference of the DGR is that its openings will be used for storage of heat-generating HLRW. Therefore, when studying the program of the destruction of the DGR massif's marginal part, a detailed research is needed on HLRW with high heat output.

Figure 2a depicts the top view of the horizon with DGR openings, from which vertical shafts will be drilled for HLRW placement (horizon +5 m), and Figure 2b shows the sectional view of horizontal tunnels in two levels and a 75-meter vertical shaft for HLRW placement. The DGR's underground part is a system of openings located on two horizons measuring $1,500 \times 1,000 \times 80$ m.

Vitrified, highly active HLRW, enclosed in cases, will be placed in 75-meter deep vertical shafts, and conditioned HLRW with weak heat release in nonreturnable metal containers will be placed inside horizontal tunnels at two levels.

The maximum possible number of cases will be about 8,400 pcs. It should be noted that specific heat release from fresh vitrified HLRW is 2.7 kW cu^{-1} m^{-1} and decreases exponentially with time:

$$q = 2.7e^{-t/40},$$

where q is heat release, kW/cu.m, t is time, in years. The rate of decrease in the heat release power is about 2.5% per year.

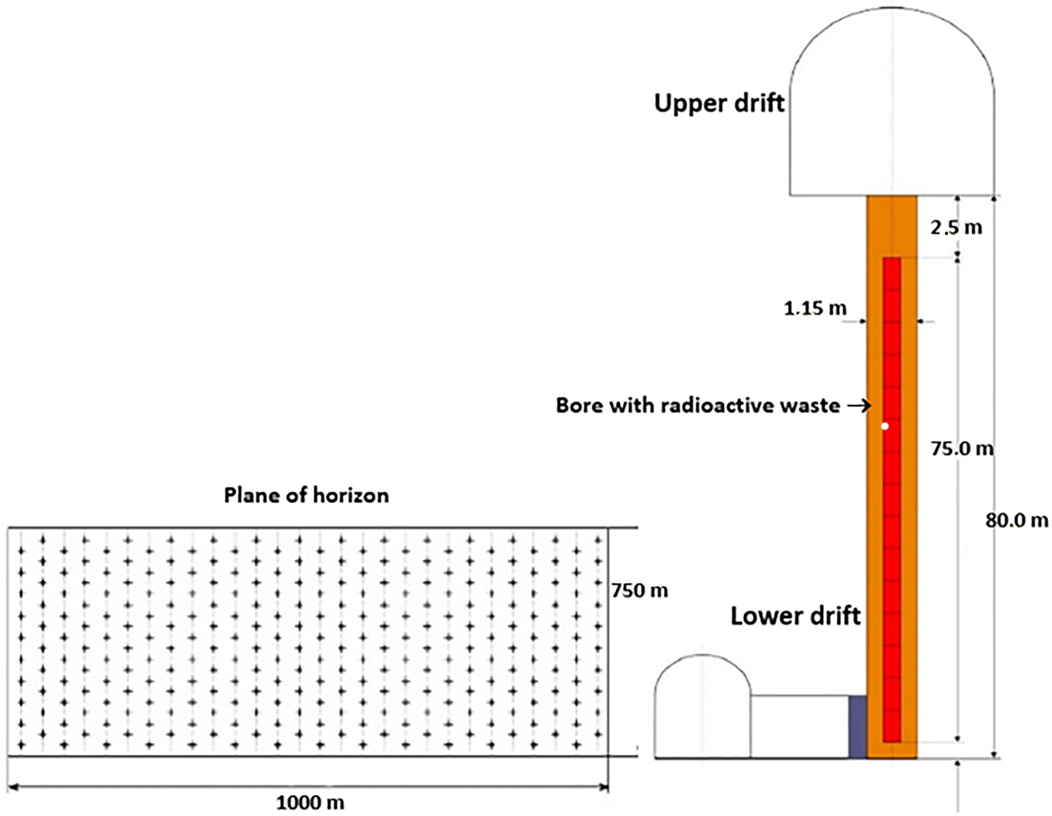

Figure 2. Layout of HLRW in the DGR. a – top view of the horizon +5 m, b – sectional view of horizontal tunnels in two levels and a vertical shaft for HLRW containers.

According to various estimates, containers with HLRW, at a temperature of about 120–200° C, release heat in the enclosing rock mass during 500–1000 years. Thus, in fact, in the DGR's working zone, there are three mutually influencing sources able to cause destruction of the geological environment. These are the lithostatic pressure reaching 15 MPa at a depth of 500 m, the tectonic stresses, which can exceed the lithostatic ones 2–3 times, and the thermal field from the HLRW impact.

In the three-dimensional model of the SSS in the DGR's underground part, the subject of the analysis is the intensity of stresses σ_i

$$\sigma_i = \Big(\sigma_x^2 + \sigma_y^2 + \sigma_z^2 - (\sigma_x \cdot \sigma_y + \sigma_y \cdot \sigma_z + \sigma_x \cdot \sigma_z) + 3\tau_{xy}^2 + 3\tau_{yz}^2 + 3\tau_{xz}^2\Big)^{\frac{1}{2}},$$

as well as shear stresses $\tau_x y$ as estimates of possible locations of stress discharge in a dynamic form.

Figure 3 and Figure 4 show geometric models for two possible types of the DGR arrangement and σ_i calculation results. Tectonic stresses were not taken into account in this calculation. Areas of high stress intensity arise in the marginal zone of the DGR and the enclosing rock mass.

They have significant differences: in Variant I, the discharge area covers the entire facility, whereas in Variant II, the discharge area is concentrated in the zone of the underworked rock mass. In this case, in the marginal zones, abnormal values of σ_i in the XZ plane at a distance of 5 m from the repository's boundaries enclose significantly different volumes. As the strain energy density is proportional to the squared σ_i, we can assume that rocks destruction in a dynamic form is the most probable in these zones. In the same zones, the maximum values $\tau_x y$ are recorded.

At the same time, the rock mass discharge above the underground facility promotes the displacement processes, and the elevated temperature stim-

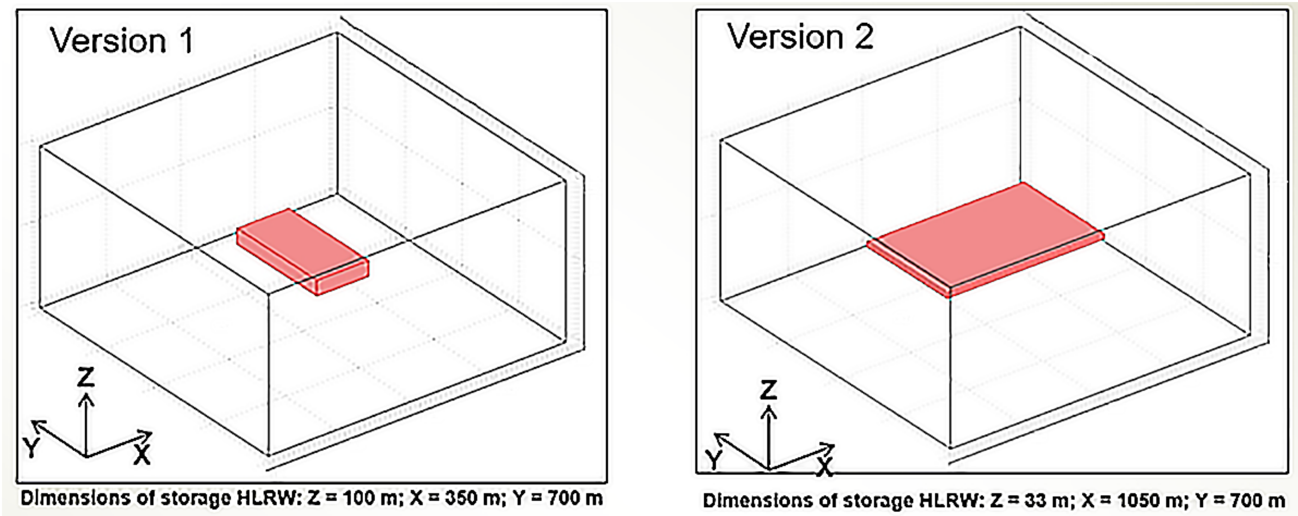

Figure 3. Geometric models of two types of the DGR's arrangement. I – the first variant, with two tunnel horizons and a system of vertical shafts ($L = 75$ m) with HLRW containers; II – the second variant with one horizon and 25 m shortened shafts with HLRW containers.

ulates this process. Experience in developing deposits using the underground method with backfilling of the excavated cavities suggests that the possible development of displacement processes facilitates the opening of cracks in the rock mass with the subsequent infiltration of groundwater to containers with HLRW. Anomalously high deformation energy density in the zone near the DGR can cause the destruction of rocks in a dynamic form. An example is the spatial localization of rock bumps at uranium deposits [*Morozov et al.,* 1990], at the Sheregeshevsk deposit [*Kopytov,* 2015], at the coal deposit [*Kolikov et al.,* 2018] etc.

According to available estimates, containers with heat-generating HLRW at a temperature of about 150–200°C release heat into the enclosing rock mass for over 1000 years. Therefore, designing the space-planning solution of the DGR's underground part inevitably raises the issue of optimal arrangement of tunnels and shafts for HLRW disposal. From an economic point of view, there is a desire to place them on a smaller area to reduce the DGR's dimensions. On the other hand, there is a need to increase the distance between them, to reduce the stress concentration zones overlapping. In this case, reducing the distance between the openings, surely, leads to an increase in stresses in the bearing blocks and on the boundaries, which increases the probability of dynamic rock destruction.

The placement of heat-generating containers and subsequent warming up of the rock mass in the zone near DGR helps to reduce the viscosity of inter-block boundaries in the rock massif even at low temperatures: 50–60°C. The basis for this statement are the results of instrumental observations of the large-section openings convergence at the Mining and Chemical Combine before and after placing heat-generating processes therein [*Morozov et al.,* 1999]. These observations showed a strong intensification of the chambers' wall convergence after warming up the rock mass to 60° C. Increase in the elasticity of inter-block contacts and the possible rotational effects of the inter-block interaction are the most probable namely in the marginal zones of the DGR where the stress intensity and temperature reach their maximum values.

In this connection, we calculated the SSS for shafts to store containers with heat-generating HLRW for various time periods. Simulation was carried out by the finite element method, using the FEMAP NX NASTRAN software; the model parameters and the finite conditions are described in [*Tatarinov et al.,* 2015a].

On the boundaries of the model, we defined the tectonic field of principal stresses. Inside the layer, there are stresses created by the thermal field of containers with HLRW. During the calculations, it was assumed that the axis of main tectonic tension

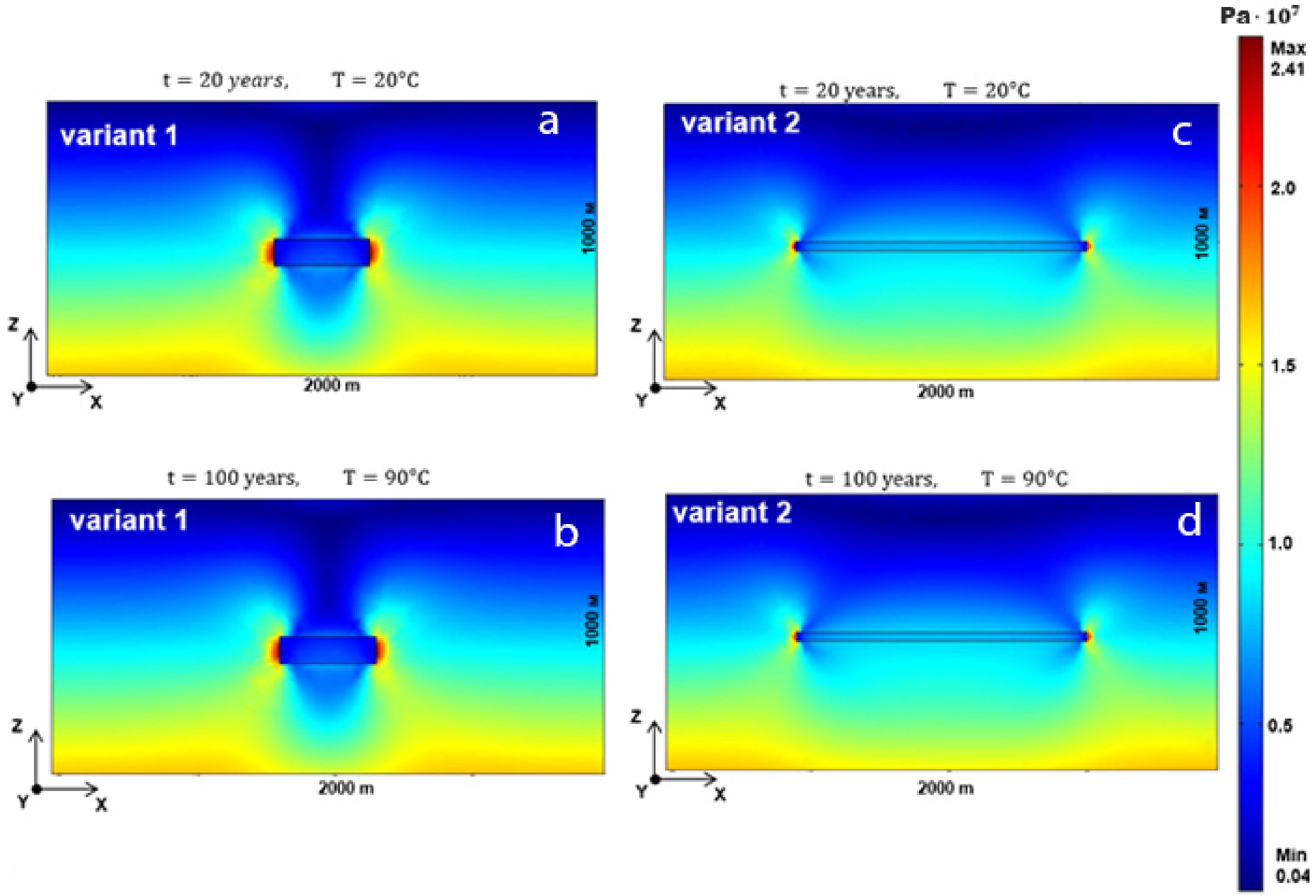

Figure 4. Stress intensity distribution σ_i excluding tectonic stresses: a – variant I, heat time = 20 years, $T_{\rm DGR}$ = 20° C ; b – variant I, heat time = 100 years, $T_{\rm DGR}$ = 90° C; c – variant II, heat time = 20 years, $T_{\rm DGR}$ = 20° C; d – variant II, heat time = 100 years, $T_{\rm DGR}$ = 90° C.

σ_{33} is directed along the OY-axis. Along the OX-axis, there is the lateral resistance stress of about $1/3\sigma_{33}$. Based on [*Anderson et al.,* 2011; *Morozov et al.,* 2011]. the main tectonic stresses were defined by the following values: σ_{yy} = 30 MPa, and σ_{xx} = 10 MPa. $T_M(x,y)$ is the rock mass temperature which depends on coordinates. The kinematic boundary conditions correspond to the conditions of fixing, when no movement in directions normal to the fringing contour is allowed.

Figure 5 shows the distribution of stress intensity in the shaft area 20, 100, and 400 years after placing containers with HLRW, respectively. We can see that, in this case, the stress concentration is higher than in Figure 6a (where thermal stresses were not taken into account). The σ_i distribution shape has also changed. Zones of the highest stress concentrations (~ 45 MPa) are still located along the X-axis on both sides of the well, but now they are wider (Figure 5b).

The total concentration of increased stress zones in the shaft area 20 years after the waste disposal (Figure 5b) is much larger than in the other two cases (Figure 5c, d).

Figure 6 shows the chart of the change in stress intensity at a point A on the OX-axis at a distance of 1.2 m from the center of the shaft with HLRW. As a criterion of destruction, we used the Bailey integral:

$$\int_0^{t_k} \left(\tau_0 exp \frac{U_0 - \gamma\sigma_i\left(t\right)}{RT\left(t\right)} \right)^{-1} dt = 1$$

where τ_0 is the period of thermal vibrations of atoms; U_0 is the destruction activation energy; σ_i is γ the structural coefficient; $\sigma_i\left(t\right)$ is the stress intensity; $T\left(t\right)$ is the temperature; R is the universal gas constant; t_k is the start time near-shaft area dispersion from the moment of the rock mass warming up.

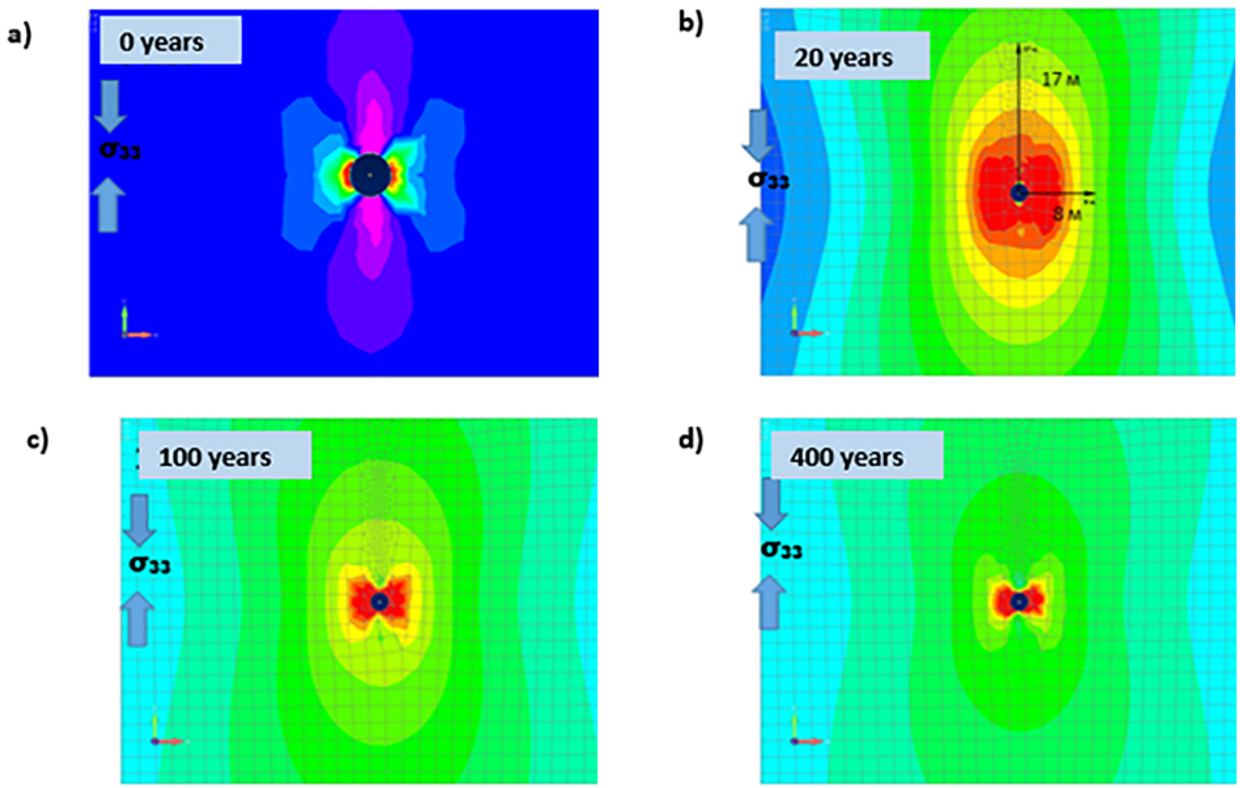

Figure 5. Stress intensity $\sigma_i\,(t)$ in the shaft area in MPa: a) excluding heat load; b) 20 years; c) 100 years; d) 400 years after placing HLRW.

Under these conditions, the time span of the near-shaft area dispersion is about 10 000 years. The dispersion area penetration into the rock mass is unavoidable; at the same time, this area does not exceed the initial shaft radius. The rock mass dispersion in the area near the shaft leads to a significant change in the physic-mechanical and thermal properties that are difficult to estimate in theoretical calculations, therefore, the model adjustment is required for field studies in the URL.

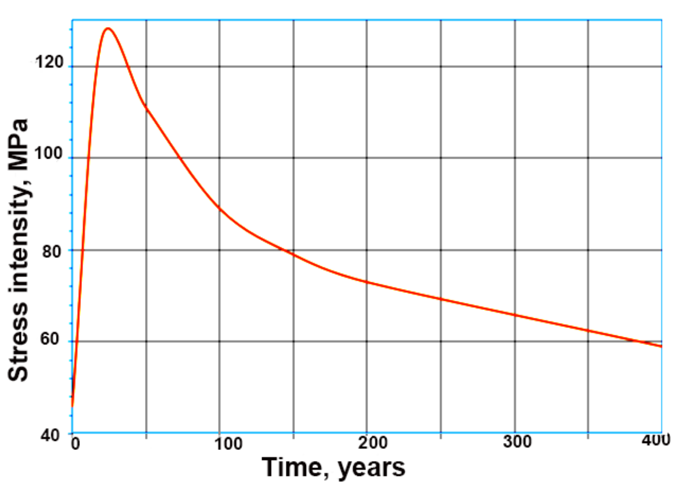

Figure 6. Changes in the stress intensity from the time recorded at the point A which is 1.2 m away from the center of the shaft with HLRW.

Figure 7 depicts the distribution of stress intensity in the area of a group including 4 shafts 20, 100, 400 years after the waste disposal, respectively. Most interesting is Figure 7b (20 years since HLRW disposal), as the σ_i values in the area between shafts are 50 MPa. This is significantly less than the compressive strength of undisturbed granites, but it can be dangerous in long term and lead to the destruction of the shaft.

Conclusions

During the UGRL construction and later, during the construction of the DGR, we must assess the hazard of rock bumps.

Therefore, any studies focused on the investigation of the SSS in rock mass in the near and far

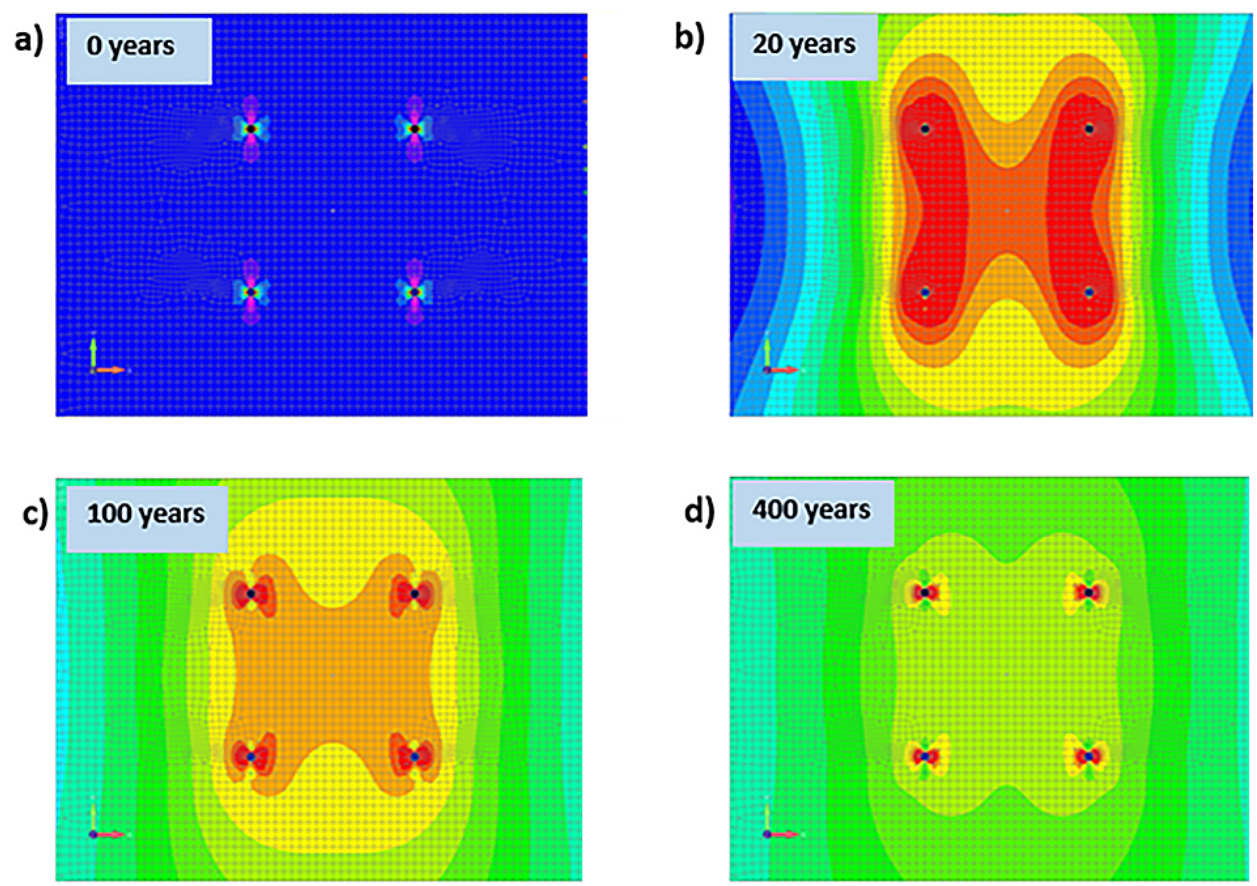

Figure 7. Stress intensity in the area of a group of shafts: a) excluding heat load; b) 20 years; c) 100 years; c) 400 years after placing HLRW.

area of a DGR require a comprehensive, hierarchically structured, and systemic instrumental observations, which shall include:

1. Geodynamic observations using the methods of space geodetics within a radius of 30 km from the DGR along the profiles crossing all nearby active fractures.
2. Seismological observations within a radius of 10 km, including a network of local seismic stations able of recording seismic events with an 4^{th} energy class.
3. Carrying out geodetic observations in the zones of suspected active fractures, including the method of high-precision leveling, combined with observations of horizontal deformations using the methods of space geodesy.
4. Estimation of the rock mass stressed state using instrumental methods and methods of tectonophysics.
5. Organization of geomechanical observations in underground openings of the URL.

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