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INVESTIGATING THE GEOLOGICAL ENVIRONMENT AT THE YENISEISKY SITE: TASKS FOR THE CURRENT STAGE OF THE DISPOSAL PROJECT

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The article evaluates currently available knowledge on hazardous geological features, events and processes at the Yeniseiskiy site and in the surrounding area. This territory in the Krasnoyarsk Krai was selected to host the first Russian repository for HLW, including those containing long-lived radionuclides. Analysis of the work performed has shown that the level of geological exploration in this area seems to be insufficient for unambiguous interpretation of data on the geological, structural, hydrogeological and other conditions at the future facility's site. To clarify them, it is necessary to conduct additional research, mainly in the underground research laboratory, as well as on the surface.

Key words: *radioactive waste, geological repository, safety assessment.*

Introduction

Exploration of geological environment under the projects associated with RW disposal is viewed as an important activity: the geological environment is considered as an integral part of the multi-barrier system ensuring the safety of deep radioactive waste disposal facilities (DRWDF). The overriding role of the geological environment in ensuring the long-term safety of DRWDF designed for the disposal of RW classes 1 and 2 is stated in relevant Russian regulations [1]. Such exploration of the geological environment is challenged by the presence of substances being in various phases (solid, liquid and gaseous), high inhomogeneity of their properties and complex structure due to the presence of linear and block structures varying in their sizes by many orders of magnitude (hierarchical). Processes occurring in this medium are measured by their duration — from seconds (earthquakes) to many millions of years (tectogenesis and metamorphism).

DRWDF at the Yeniseiskiy site is considered as a unique and first of its kind facility being developed in Russia. Underground Research Laboratory (URL) is being constructed at the site of the future DRWDF to perform relevant R&Ds aimed at demonstrating the safety of the underground RW isolation concept and testing the proposed design solutions [2]. In fact, URL is a scientific mega-installation with relevant R&Ds lasting for a decade and a half (2025—2030). URL development is seen as a global trend evolved under the projects on the disposal of highly active and long-lived radioactive waste. There are no other ways allowing to address some important issues under relevant safety assessments. URLs are either constructed in already existing mines or built specifically both to study certain types of geological medium and the environment being directly available at the site of the future repository [3]. It is important to emphasize that URLs and DRWDF are not identical to ordinary mines that are built for mining purposes. Construction of these structures and activities performed therein are regulated by provisions of Federal laws and regulations issued by different authorities, namely, those containing provisions on radioactive waste management, use of subsoil resources and construction of mine structures. Moreover, not all of the activities involved are being regulated. Hence, some contradictory interpretations of the activities' contents are possible if the hierarchy of the existing documents and goals stated under the URL construction are ignored. Goals and objectives for the URL and DRWDF construction are set based on provision of the Federal Law 190-FZ "On Radioactive Waste Management" [4] and some technical regulations, including "Disposal of Radioactive Waste. Principles, Criteria and Basic Safety Requirements" [1] and "Requirements on the Structure and Content of Safety Analysis Report" [5] of Rostekhnadzor. Geological exploration is considered as the method providing practical implementation of the goals associated with the demonstration of geological disposal safety. Relevant sequencing and contents of these activities are regulated based on the regulations issued by the Ministry of Natural Resources and Ecology of the Russian Federation (Russian Ministry of Natural Resources). These regulations, first and foremost, involve the following: Guidelines on Providing the Rationale Behind the Selection of Subsoil Sites for the Purposes Not Being Associated with Mining [6] and Rules for the Development of Design Documentation [7].

This article provides general overview of hazardous geological processes, phenomena and factors associated with the Yeniseiskiy site and its region with relevant areas requiring some further study being identified based on the requirements of regulatory documents and the primacy of DRWDF safety, as well as the immediate tasks of geological exploration.

Background of geological explorations covering the southern part of the Yeniseiskiy range

Implementation of RW disposal projects involves several stages: siting, construction, operation and closure of disposal facilities [1, 4]. IAEA recommendations state that the siting stage should be divided into stages involving, among other things, establishment of the disposal concept and site assessment, consisting of the following stages: site selection, site verification and validation of its suitability [8]. Site selection stage involves a survey exploration of a vast territory with subsequent reduction of the area space involving more detailed investigation of alternative sites allowing to single out only candidate for an in-depth study [9]. These stages to some extent correspond to relevant stages of geological exploration activities: prospecting, appraisal and exploration [6].

Studies aiming to find a suitable site for repository construction in the Krasnoyarsk Territory have been conducted there since 1992 [10, 11, 12, 13, 2].

Initial (survey) stage implemented in 1992—2001 involved some regional studies in the southern part of the Yenisei Ridge. Prior to the adoption of Rostekhnadzor's criteria allowing to evaluate the geological environment for repository siting purposes in Russia in 2004 [14], site suitability could be evaluated in accordance with recommendations of competent international organizations (for example, IAEA) [15, 16, 17 and others]. The factors being evaluated for these purposes involved the suitability of potential host rocks, hydrogeological conditions, tectonic stability and availability of fault tectonic deformations in particular, prospects for the discovery of valuable minerals, as well as the administrative position, features of the social structure, etc. Based on this set of criteria, two most promising sites were selected first out of 20 and then out of 8 sites considered: Verkhneitatskiy and Yenisei Verkhneitatskiy. The latter one appeared to be divided by a regional fault into separate blocks: Itatskiy and Kamenniy [13]. The Verkhneitatskiy site was initially regarded as a priority one with the Yeniseiskiy site considered as an alternative one. Later, the Yeniseiskiy site appeared to be the only candidate considered for DRWDF siting. Both sites were complying with the existing geological criteria. However, the socio-economic criteria played a decisive role in the selection of the Yeniseiskiy site: its proximity to the infrastructure facilities of the Mining-Chemical Combine (4 km versus 24 km for Itatskiy and Kamenniy sites) and its location within the restricted administrative and territorial entity Zheleznogorsk [11].

Carried out since 2002, the exploration work within the Yeniseiskiy site started with a comprehensive geophysical study of the territory. This work was carried out in stages with consequent reduction in the space area covered and more and more detailed research involved. At the first stage of drilling activities (until 2005), three core drill wells were constructed (E-1, E-2, E-3) reaching a depth of 100 meters with one exploratory well (1-E) going to a depth of 600 m enabling full core sampling. Interval filtration tests (IFT) and a complex of geophysical research activities was performed [18].

Due to the lack of relevant regulations issued by the Ministry of Natural Resources of Russia that were approved only in 2007 [6], it was only in 2009 that the study of subsoil at the site started to be carried out in keeping with modern regulations as a prospecting stage for geological exploration. In 2010, three 700-m deep wells were drilled by JSC Krasnoyarskgeologiya (P-1, P-2, P-3) which was done in parallel with comprehensive geological, hydrogeological and engineering-geological studies. In 2010, relevant findings were for the first time evaluated by the Federal Agency for Subsoil Use of the Russian Federation (Rosnedra). The Yeniseiskiy site, according to its geological, hydrogeological, tectonic and seismic features, was considered as a promising one with further studies to be performed to assess its suitability for the construction of a disposal facility for radioactive waste [13].

In 2011—2012, JSC Krasnoyarskgeologiya completed the next assessment stage of geological exploration on the site. Seven exploratory and four hydrogeological wells were drilled with a full range of geophysical logging and filtering experiments performed which was considered as the key method of the assessment. From the surface, the site was studied by areal geophysical method. Geological patterns of primary deposits for the surface and target-interval level were developed. Rosnedra's findings (2012) confirmed the suitability of the Yeniseiskiy site for deep disposal of radioactive waste based on revealed geological, hydrogeological, tectonic and seismic setting [2]. At the same time, Rosnedra gave relevant recommendations concerning some issues that had not been resolved at the assessment stage and were to be addressed at the subsequent (exploratory) stage. Some of these recommendations were already implemented during engineering and geological surveys under the design activities on the development of the mine facility considered as a continuation of the assessment stage (2013—2015). Additional exploration activities performed at the site were aimed at increasing the capacity of the underground RW storage facility by expanding the emplacement interval from 25 to 75 m. At this stage of the study, wells were drilled (2013) at the place of future URL mine shafts (wells P-11, P-12 and P-13 with a depth of 508—539 m). To perform pilot and filtration studies in the area of P-11 well, two cluster wells P-11-1 and K-1 reaching the depth of 509 and 50.1 m were drilled. A complex of geophysical surveys and filtration tests was also performed in these wells. In 2014, the ПР-1 well was drilled to a depth of 520 m to carry out specific activities on refining the hydrogeological model of the site. In the same year, additional engineering and geological surveys were performed covering the sites of ground structures and roads. 47 exploratory wells were drilled to a depth of 45.0 m. Drilling of these wells for mapping purposes did not affect the level of detail associated with the geological map of the site, compiled mainly based on relevant geophysical data.

A total of 14 deep (up to 700 m deep) wells was drilled (Figure 1) during the exploration, engineering and geological studies. Their drilling involved a full core sampling. In some wells, rare samples of oriented core were taken enabling to determine the occurrence of rocks associated with the host metamorphic stratum. The geophysical activities performed at this stage included magnetic surveying and geophysical well surveys. In 2016, the GKZ Rosnedra received a positive expert opinion on the suitability of the site for the construction of RW disposal facility given a 75 m distance between the horizons [2].

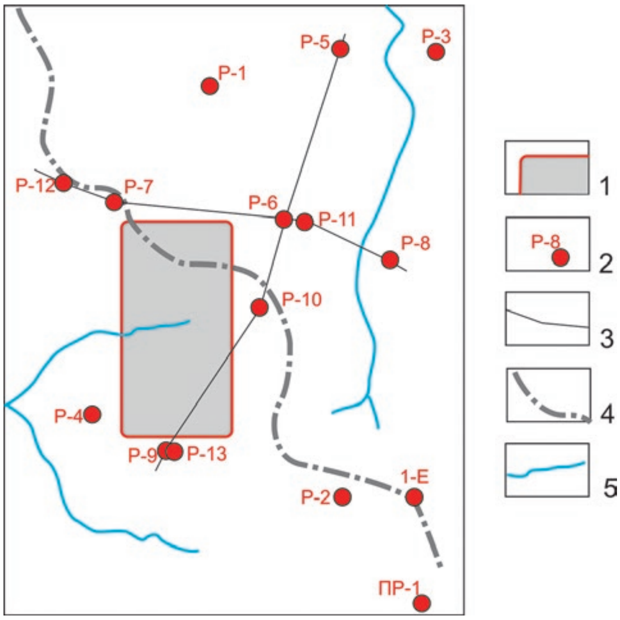

Figure 1. Deep wells drilled at the Yeniseiskiy site (compiled based on materials provided by JSC Krasnoyarskgeologiya): 1 — boundaries of RW disposal zone within the repository; 2 — wells; 3 — schematic sections (Figure 2 and 3); 4 — main watershed; 5 — streams

Exploration findings served a basis for the development of the "Safety Analysis Report as Part of the Underground Research Laboratory" (SAR). It presented the results of modeling activities performed to illustrate the long-term release of contaminated groundwater from the facility via the geological environment. Dose loads for the population were evaluated, which confirmed the assumption on future facility's compliance with relevant provisions of Russian regulations and international recommendations [13].

After the completion of assessment, engineering-geological activities in 2015, no other geological exploration efforts at the Yeniseiskiy site were undertaken up till early 2019, which, on the one hand, apparently suspended the progress on the Yeniseiskiy disposal project, and, on the other hand, gave an opportunity to comprehend the ways in which it should be further developed. In this period, design documentation was examined and various permits were issued by Rostekhnadzor (2016), Rosnedra (2016), FAA Glavgosexpertiza (2016) [2]. Strategic Master Plan for Research Demonstrating the Safety of the Facility Construction [1] was developed with the Strategy for the Development of a Deep Radioactive Waste Disposal Facility approved [20]. Approval of URL construction and relevant R&Ds to be conducted in the URL seen as an independent stage during the implementation of the entire project on DRWDF establishment should be considered as an important point stated in the Strategy [2, 21].

In keeping with relevant regulations of the RF Ministry of Natural Resources, URL construction and R&Ds performed therein can be considered as the next (exploratory) stage of exploration activities. The wordings presented in these regulations [22 (p. 4.1.3), 6 (p. 4.4)] provide wide opportunities for achieving safety demonstration goals for the RW disposal facility proposed to be built at the Yeniseiskiy site (scheduled for 2029—2030). These are considered as optimal ones given the complex geological setting and a variety of exploration method, including mining. Currently DRWDF designs are being upgraded according to URL stage of the project with relevant tasks being set for those being responsible for geological exploration performed on the surface and during the excavation of underground workings and R&D program for the URL being developed. All these activities are being implemented under methodological guidance of Nuclear Safety Institute of RAS. URL will provide the necessary setting enabling the required research "...to gain deeper knowledge on the characteristics of the rock mass and groundwater in the RW disposal area considered essential in terms of assessing the long-term safety of DRWDF under in-situ (field) and laboratory conditions ... "as stated in relevant Rostechnadzor regulations [5 (section 4 4, paragraph 190)].

Main features, events and processes associated with the geological environment at the Yeniseiskiy site

In keeping with Rostekhnadzor requirements [5 (p. 3.1.1)] on DRWDF siting, it is necessary to obtain information on hazardous processes, phenomena and factors of natural and technogenic origin for the Yeniseiskiy region and the Yeniseiskiy site.

According to globally accepted terminology, "hazardous processes, phenomena and factors" are referred to as "features, events and processes" (FEPs) [23]. FEPs are considered dangerous as they may trigger negative changes in the DRWDF and undermine its safety. In this regard, recommendations of Russian and international organizations on SAR development or its foreign counterpart — the Safety Dossier (Safety Case) provide for the mandatory procedure enabling to identify FEPs being considered relevant for the disposal region (site) [5, 24].

Extensive geological information on the FEPs relevant for the Yeniseiskiy region and the site was obtained during survey, prospecting and evaluation efforts conducted as part of the siting process. [25] provides a summary of geological FEPs relevant for the site. Unfortunately, the main part of geological information obtained at exploration and assessment stages, still accounts for the "gray zone" of restricted access reports. For this reason, present article provides only limited actual data needed to evaluate geological FEPs.

Thus, as early as at the regional survey stage, it became clear that no particularly strong earthquake can occur in the region (estimated seismic activity accounted for 7 points on the MSK-64 scale). The same is true for volcanism (absent), erosion of overlying rock (the rate of vertical elevation of the earth's surface over the past 5 million years does not exceed one meter over 10 thousand years) with no abundant groundwater inflows expected in the region (the host rocks are practically considered as water-resistant, and their water saturation is low) and no unintentional human intrusion (no mineral resources) Thus, the vast majority of theoretically possible evolutionary paths that could lead to scenarios assumed as catastrophic or highly detrimental in terms of relevant consequences [26] was excluded from consideration. Subsequent stages of geological exploration mainly involved the evaluation of those FEPs being considered crucial in terms of flow driven migration of radionuclides through the geosphere. It is the water migration of radionuclides that was recognized as the main mechanism accounting for the transfer of radionuclides from the underground structures to the biosphere. It is this mechanism that serves the basis for the development of a mathematical model describing the geosphere transport under predictive calculations of doses and risks for the population.

Location of the Yeniseiskiy site within the regional geological structure. The site is located at the junction of three large geological structures — the Siberian platform in the east, the West Siberian plate in the west and the epiplatform Altai-Sayan orogenic zone in the south. The site is located in the southwestern (Angara-Kanskiy) part of the Yeniseiskiy Ridge being considered as a ledge on the surface of a very ancient foundation associated with the

Siberian platform. Within the modern conception, the Angara-Kansk part of the Yeniseiskiy Ridge is a microcontinent, which joined the Siberian Craton 650—550 mln years ago i. e. during the Baikal era [27]. The ridge and the plate are connected via a system of sub-meridional reversed faults and northwestern strike-slip faults associated with them. The amplitude of surface displacements of the Precambrian basement relevant to the Muratovskiy reversed fault being considered as the nearest one to the site is estimated as being equal to 720 m [28].

The foundation of the region accounts for a crystalline mass with rocks of various compositions. If the Verkhneitatskiy site is composed of granitoids associated with the Nizhnekanskiy massif, the Yeniseiskiy site is composed of gneisses. Gneisses of the southern part of the Yeniseiskyi Ridge belong to the Early Archean granulite complex, framing the Nizhnekanskiy granitoid massif. The data on the structure of the latter and the gneisses enclosing it [10] indicate that all together they form a typical granite-gneiss dome [26]. Such geological structures have been formed during a long time in the areas where thick sedimentary-volcanogenic strata are being developed under the influence of deep fluids. Metamorphic rocks prevail in the peripheral parts of the granite-gneiss massif, while granitized and magma rocks are mainly associated with the central parts of granite-gneiss domes. The structure of the Nizhnekanskiy crystalline rock mass involves magmatic bodies of granitoids, migmatites, granite gneisses varying in their granitization degree, gneisses of predominantly granitoid composition, metabasites, amphibolites and diabases. The oldest Lower Archean rocks of the Angara-Kanskiy microcontinent were metamorphosed under granulite facies impact 1.8—1.9 billion years ago with the original sedimentary rocks supposedly being even more ancient — 2.5—2.7 billion years [27]. The complex multi-billion-year history of the dome's formation is considered practically useless as a source of information in terms of demonstrating the repository's safety. Of interest are the FEPs dating back to the last millions of years. It is during this time span associated with geological history that certain events and processes have occurred that may recur during the time period while the disposed radioactive waste is considered potentially hazardous.

On the regional scale, the Yeniseiskiy site is located in the central part of a relatively geologically homogeneous unit (Baikal-Shumikhinsk area). This unit is bounded by large faults, but no faults are available within the unit itself [18]. Weak tectonic activity, moderate seismicity and low vertical velocity of earth surface corresponds to the basic suitability criteria specified in relevant regulations [1]. This, however, is not enough to provide a reliable forecast on the long-term safety of the repository. Available data [29, 30, 31, 32, etc.] allow to classify the regional faults as active considering the latest tectonic stage (started about 26 million years ago). Currently, there is no definite information on the distribution of active faults in the Yeniskeiskiy area. Itatskiy right shift considered as a largest one in the region (identified from the analysis of the topographic base), stretching north-west from Bolshoy Itat River to Shumikha River and along it is situated only 1 km north of the intended site. Amplitudes of horizontal displacements identified based on waterflow displacements along the faults of this system during the Pleistocene (the last 2.5 million years) amount to 800—900 m or 0.4—0.5 mm per year [30].

It is especially important that the activation extent and intensity for specific faults located within the area of potential spread of radioactive contamination, their permeability and their role in shaping the structure of groundwater flow remains unclear. According to mathematical modeling, this area extends from the repository site towards the Yenisei River. Simulation of contaminant spread with groundwater flow showed that presence of a hypothetical sub-latitudinal (i. e., extending along the filtration streamline) highly permeable fault will not result in a significant decrease in the reliability of the geological environment and repository safety only if the distance between the fault and the repository amounts to kilometers [26]. Within the site area, not only vertical, but also modern horizontal movements of earth crust's upper part were revealed [33]. All these movements determine the stress-strain state of the rock mass, as well as a risk implying the deformation of underground excavations and rock unit movements along the fracture systems.

Rocks at the Yeniseiskiy site. Site foundation is mainly composed of strong gneisses, which in terms of their physical and mechanical properties are able to ensure the technical safety of the underground structure, as well as RW disposal safety in the long-term perspective [18]. Two terranes can be distinguished within the structure of the site's gneiss stratum, the boundary between which is conditionally drawn by the petering out of hypersthene and the occurrence of cordierite present in rock-forming amount [26]. Gneiss occurrence mode is sub-horizontal. Prevailing incidence angles for gneiss-shaped stripes account for some 5—30° amounting to 40—60° in local tectonic dislocation points, for example, in locations where these are contacting dolerite dikes [18].

At the Yeniseiskiy site, the gneiss stratum is invaded by dyke complexes of at least two generations. The first includes the dolerite dike complex being from 1 to 40 meters thick. Later gabbro-diabase, trachidolerite and lamprophyre dikes are secant with respect to the dyke complex associated with the first-generation stage. Their thickness varies from tens centimeters to several meters. Formation of the dike complexes at the site dates back to the turn of the late Archean — Early Proterozoic time, which corresponds to the completion of progressive regional metamorphism. In addition to dikes, crystalline rocks are penetrated by veinlets of quartz, carbonate-quartz, carbonate and, less often, by veinlets of other composition. In some locations, iron disulfides impregnations are observed presented by pyrite and chalcopyrite [18].

All ancient rocks underwent surface weathering many times. The time of the last weathering era and the age of the corresponding base-level peneplain was identified as the Danish-Paleocene-Eocene one, i. e. 15—20 mln years ago [34, 35]. Potentially, it characterizes the main watershed peneplain hosting the repository site. Its subsea depth ranges from +370 to +430 meters. The elevation of the Yenisei River accounts for +120.6 m [18]. The preserved part of the weathering crust's eluvium has a thickness of 5—25 m. In addition, ancient rocks are covered with quaternary rocks, mainly deluvial ones being of up to 30 m thick [18]. Presence of loose eluvial-deluvial cover is considered as a significant obstacle in terms of compiling a detailed map of the site's bedrock.

Long-term exposure to surface factors resulted in the formation of a near-surface zone within the ancient rocks involving exogenous disintegration and fracturing. In some areas, it reaches 80 m. According to geophysical data, the bottom of the decompression zone lies at depths of 20—50 m, rarely up to 100 m from the day surface [18]. To a depth of 80—120 m, and in some cases much deeper, pseudomorphic iron hydroxides are found in the core. They anchor the near-surface oxidation zone — a product formed by the penetration to the depth of surface waters containing oxygen and oxidizing iron disulfides [36].

Geological and structural setting. Available data on the core and general geological considerations suggest that dolerite dikes fall steeply towards the east at a sub-meridional strike, while later ones occupy a secant position in relation to the former ones (Figure 2). Under this interpretation, dolerite dikes divide the area into a series of plates varying in their thickness and elongating in the sub-meridional direction. Figure 2 also shows the projection of the RW disposal area within such a plate. Figure 1 shows that according to the designs, the disposal area is located southern to the section shown in Figure 2.

Available knowledge suggests that the information obtained during the registration of the core samples taken from the wells and dealing with the elements of rock occurrence, dikes, deformation zones and other discontinuities under the repository conditions allows for some alternative options describing the relationship between various structures within the volume of the studied rock unit. Figure 3 illustrates this uncertainty. Experts from JSC Krasnoyarskgeologiya combined the largest dolerite dykes into a synclinal structure, whereas IGEM RAS specialists showed that they can be combined into an anticlinal structure [37]. Uncertainties with linking small dikes and discontinuous faults are even more significant. Obviously, actual location of dikes and other structures at the waste emplacement level will have a significant impact on the final siting decision within the RW disposal project with relevant tectonic disturbances playing some special role in this.

Discontinuous tectonic disturbances available at the site are considered as most important factors affecting the safety of RW geological disposal facility. These FEPs will affect the emplacement options for RW packages within the rock mass, i.e., the final layout of engineered barriers. According to the existing designs, the packages are to be placed in a strict geometric order with maximum use of the underground space. In reality, part of this space will be occupied by tectonically disturbed rocks. In these areas, waste emplacement is ruled out for two possible reasons: (1) tectonic movements along cracks can deform the packages and (2) tectonically weakened zones can serve as good groundwater flow paths contributing to the degradation of the engineered barriers.

To date, it has been established that tectonic disturbances of only high orders are available inside the potential waste emplacement unit, being relatively small. They vary in their nature, mineral composition and permeability. As for the currently available knowledge on the tectonic disturbances of the Yeniseiskiy site rocks, we can state the following: ancient tectonic deformations, often accompanied by dike intrusions, were sealed under the processes associated with ultra-metamorphism and granitization. The inheriting later faults present in the form of brecciation, crushing and fracturing zones are often sealed by regressive metamorphism (diaphoresis) processes. The mineral composition accounting for this stage is quite diverse: veinlets of carbonate, quartz, chlorite, epidote, chlorite with calcite and breccia cement. At

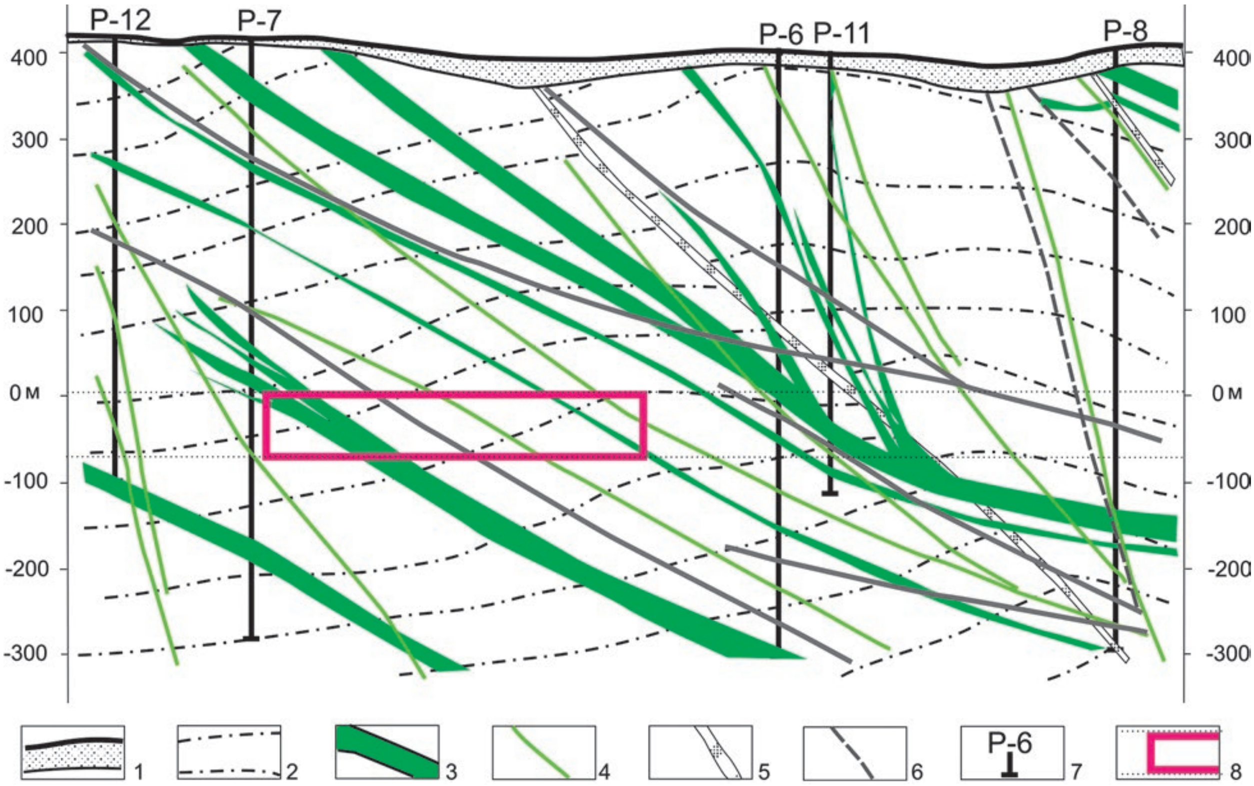

Figure 2. Schematic sub-latitudinal section through wells P-12, P-7, P-6, P-11 and P-8 (according to JSC Krasnoyarskgeologiya with simplifications and additions applied):
1 — cover of loose deposits; 2 — gneisses; 3 — early dikes (dolerites); 4 — late dykes (diabases);
5 — zones of ancient cemented breccias; 6 — zones of open fracturing; 7 — wells and their ID numbers;
8 — waste emplacement horizon and projection of the radioactive waste disposal zone onto the section plane (red outline)

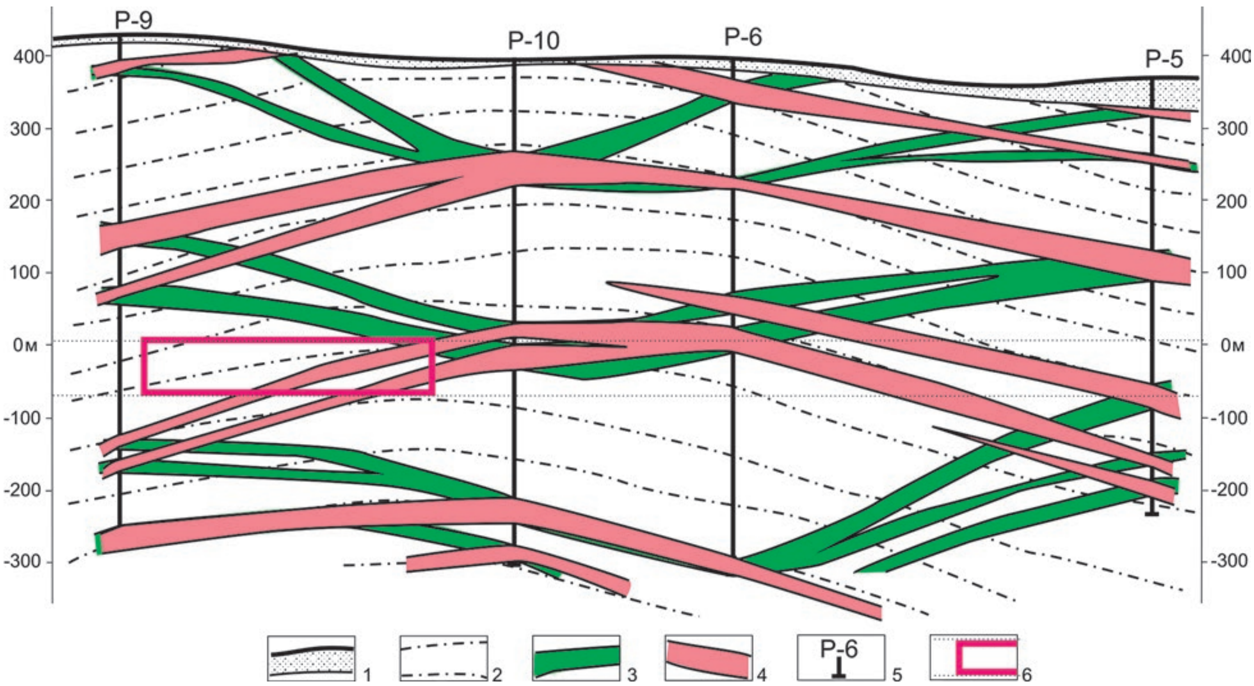

Figure 3. Schematic section through wells P-9, P-10, P-6 and P-5 with alternative linking of dolerite dikes in the sub-meridional direction (based on the materials provided by JSC Krasnoyarskgeologiya with simplifications and additions applied):
1 — cover composed of loose deposits; 2 — gneisses; 3 — dolerite dikes according to JSC Krasnoyarskgeologiya;
4 — dolerite dikes according to IGEM RAS; 5 — wells and their ID numbers;
6 — waste emplacement horizon and position of the radioactive waste disposal area (red outline)

the same time, open cracks are present in the rocks. These are associated with the latest tectonic movements and, for this reason, were not sealed by newly formed minerals [26]. Due to the presence of different-scale fractures within the waste emplacement unit, a problem arises at the target level — to identify the intervals of undisturbed (slightly disturbed, monolithic) rocks. A statistical study of fractures varying in their size by several orders of magnitude showed that, against the background of regular primary fractures (5th order), longer fracture zones (4th order) and the largest — crushing zones (3rd order) are characterized by an uneven distribution. Larger faults (2nd and 1st order) do not impinge upon the potential waste emplacement unit. Tectonic faults of the 3rd order (crushing zones) form the unit structure of the rock massif, faults of the 4th order (zones of local fracturing) represent intra-unit fracturing. Single cracks correspond to fifth-order fracturing. The length of the crushing zones and fracture zones accounts for 10—100 m and 1—10 m, respectively. The thickness of the crushing zones amounts to more than 2 m and the vertical frequency in the lower parts of the studied section is about 50—100 m. The thickness of the fracture zones commonly amounts to some 10—15 cm, less often exceeding these values. The vertical interval between them appears to be unstable. The maximum frequency falls on the interval of 1—2 m, minimum — up to 18 m with local maxima of 5—6, 7—8, and 12—13 m. In general, the authors of the cited report believe that the fracture and crushing zones present in the rock massif are extremely uneven [38].

The structure of the filtration flow in crystalline rocks is mainly characterized by the presence of discontinuous disturbances. These, in their turn, are known to be distinguished by their thickness, crushing intensity, presence of mineral filling and aperture depending on their position within the stress field. This makes it extremely difficult to study the structure of the filtration medium. In addition, the solution of the problem is associated with the uncertainties in the interpretation of filtration test results. General ideas about the flow structure obtained by hydrogeological methods should be clarified under specific experiments to be conducted directly in the URL.

Differentiation of the filtration flow between the upper strongly fractured part of the section being up to 150 m thick and the underlying slightly fractured part of the section is viewed as a specific feature of *regional* hydrodynamics within the hydrogeological mass of fracture and crack-vein waters. In the upper part, the flow mainly depends on the topographic features of the area. Whereas in the lower part other factors may become significant, primarily — regional hydrodynamics. As for the repository region, availability of separated filtration groundwater flows in the rock mass excludes short migration paths for radionuclides enabling them to reach the surface from the waste emplacement horizon, as well as their transfer to the surface hydrographic network in the vicinity of the repository. To clarify regional hydrodynamics, required are some additional studies on the distribution of pressure in deep wells located beyond the repository site on the way to the discharge area with the Yenisei River being considered as such [38, 39].

Methods applied to study the local hydrodynamics of the Yeniseiskiy subsoil area included hydrogeological studies and aquifer testing in exploratory wells reaching the maximum depth of 700 m, geophysical logging, rock permeability studies conducted under laboratory conditions and involving core samples taken from rock monoliths and etc. Interval aquifer testing was carried with an approximate interval of 50 m. A total of 129 experiments was performed, resulting in 125 filtration coefficients recognized as reliable ones following relevant analysis of the results obtained [40, 41, 42].

Below the exogenous disintegration zone, gneisses and dikes (excluding tectonic cracks) are considered as practically water-impermeable. They are able to pass water through themselves only under the influence of sufficiently large pressure gradients. At the same time, a small amount of gravitational water capable of filtration was found both in permeable and practically impermeable parts of the rock mass located below the aeration zone.

Data characterizing the filtration properties of monolithic non-fractured rocks were obtained during laboratory tests of core samples. They were found to be characterized by filtration coefficients amounting to $n{\cdot}10^{-5}$—$n{\cdot}10^{-6}$ m/day. Availability of weathering cracks, contacts of dolerites and gneisses or rare tectonic discontinuities can result in filtration coefficients within the rock mass amounting to $n{\cdot}10^{-3}$ m/day and higher [41]. The fissured-vein type of aquifers has an extremely limited distribution, but its presence in the tested interval can increase the conductivity to over 0.3 m^2/day. Aquifer testing has shown that although water-impermeable rocks with an average filtration coefficient of some 0.0007 m/day, average water conductivity of 0.002 m^2/day and water loss ranging from 0.02% to 0.4% prevail in the interval starting from site surface and reaching a depth of 700 m, the studied subsoil section cannot be considered as a classical hydrogeological massif with a hydraulically unified system of fractures. This is evidenced by multidirectional changes in levels reaching some tens of meters [40, 42]. Different orientation of the vertical pressure gradients for adjacent intervals shows that no single direction for groundwater flow really exists. Presence of intervals with lower level marks compared to the overlying intervals, clearly indicates the predominance of horizontal movement over the vertical one. There are no obvious regularities between the water level and rock permeability in the tested intervals. This indicates the complex, multifactorial nature of groundwater flows, which cannot be described by a single formal model involving a standard set of filtration and migration parameters [41].

Combination of geological and hydrogeological data shows that apparently there is no single continuous groundwater flow in the heart of the rock mass. By comparing the position of discontinuous disturbances varying in their order and aquifer testing (AT) data, it was confirmed that there is no direct correlation between the presence of discontinuous disturbances and filtration parameters [36]. The low sensitivity of AT to fracture zones is explained by weak hydraulic continuity of these zones [38]. Infiltration water entering a deep interval through a relatively open fracture system is redistributed into neighboring fracture systems via monolithic rocks. Experts involved in the studies of the Yeniseiskiy site's hydrogeological setting argue that the methods applied did not make it possible to identify the actual directions of groundwater flows given the three-dimensional space of the rock mass [40]. In terms of relevant safety assessment, the significance of this uncertainty should be determined before the start of URL construction, as after the shaft sinking starts, going in parallel with the drainage of the adjacent rocks, the hydrogeological setting of the rock mass will change irreversibly. On the whole, the general survey indicates the absence of hydraulic connection between the assumed depth of RW emplacement and the day surface. However, such connection may manifest itself in any particular system of cracks during the operation of the underground structure. Therefore, during construction and experiments in the URL each significant crack system should be identified and studied to check if such connection is available. Iron hydroxides found in some cracks at great depths, are exactly those substances indicating such potential connection.

Data discussion

Analysis of available materials on the geological exploration of the rock massif indicated the presence of significant information gaps regarding relevant FEPs, important in terms of demonstrating the safety of future RW repository. For some FEPs, the information is simply not available, for example, on microflora and colloids in the underground hydrosphere.

Uncertainties in the interpretation of geological information are introduced due to a rare network of deep wells. All deep wells were drilled beyond the boundaries of the RW emplacement unit (see Figure 1) which can be directly explained by the fact that one shall not technically interrupt the existing minimum hydraulic connection between the RW emplacement horizon and the surface [1]. Detailed data on the internal structure of the RW emplacement unit may be obtained following the study of vertical and horizontal URL excavations, as well as by drilling research wells inside of URL. Absence of oriented core in existing wells is seen as another reason for structural uncertainties. For this reason, various interpretations of the disposal zone's internal structure are possible. Purpose oriented efforts to be conducted in the URL will enable to minimize these uncertainties.

Lack of a reliable geological map representing the surface at a scale of 1:2000 makes it difficult to construct a three-dimensional geological and structural model of the site. Given the considerable thickness of loose deposits, it seems reliable to establish the position of dikes and discontinuous disturbances on the surface by drilling shallow mapping wells.

Uncertainties in the interpretation of hydrogeological information are associated with uneven and generally low water saturation of the rocks, complex structure of the filtration medium consisting of pores and cracks varying in their size with methodological shortage of the performed hydrogeological studies.

Exploration stage is basically aimed at the elimination of the above discussed uncertainties.

The objectives of the exploration stage are directly specified based on the requirement of NP-100-17 [5 (Section 4.4, Section 190)] to clarify the characteristics of FEPs associated with the rock mass and groundwater within the RW disposal zone. Permanent digital volumetric model showing the distribution of rocks, the frame of the fracture network and its saturation is viewed as a working tool allowing to address this issue.

It's argued that the following key tasks can be addressed by the development of a high-quality geological and hydrogeological framework:

- to demonstrate the feasibility of constructing purpose designed excavations and wells for in-situ experiments already at the first stages of mining operations;
- to bind excavation and well designs suggested for RW package emplacement in the repository to

areas located outside and being considered hazardous in terms of relevant structural, hydrogeological and engineering-geological setting;
- to obtain evidence needed to address the issues associated with modeling the transfer of radionuclides from the underground structures of the facility to the far field and biosphere.

Starting from URL construction stage, it is considered totally unacceptable to lose any kind of information necessary for reliable justification of the future repository safety [5]. Successful achievement of geological research goals requires the establishment of certain organizational and technical setting and, consequently, additional financial expenses compared with the construction of a conventional mine for ore mining.

- A team of qualified specialists fitted with modern equipment should be put together at the construction site;
- Observations should start simultaneously with the start of excavation activities with no significant interruptions in the observations;
- All the excavations should be subject to certification and testing in a continuous manner;
- During their certification, the surface excavations should not contain any type of support;
- During the excavation, sufficient technological breaks should be provided so that the researchers could access the hole bottom.

Conclusions

1. At the stage of R&Ds conducted in the URL, geological FEPs dating back to the last millions of years in the region's geological history seem to be of particular concern. It was during this period that occurred the processes and events that could potentially reveal themselves during the time period associated with the potential hazard presented by the radioactive waste subject to disposal. The most important of them relate to the formation of active fracture structures and permeable fracture systems in the host rock mass.

2. At present, there is no definite information on the distribution of active faults and their permeability in the area of the Yeniseiskiy site. It is especially important that the activation scale and intensity associated with specific faults within the area of potential radioactive contamination spread, their permeability and role in shaping the structure of the regional groundwater flow still remains unknown. The reliability of currently available data on active faults mainly obtained by applying geomorphological methods requires further verification via geodetic observations. For this, purpose developed studies are required to identify and determine the position of seismogenic and aseismic active faults in the vicinity of the Yeniseiskiy site. To clarify the regional hydrodynamics, additional studies enabling to identify the pressure distribution in deep wells outside the repository site are required, namely, in those located along the line leading to the potential discharge area.

3. Obviously, actual location of geological structures at the repository level is deemed to have a significant impact on the final alignment (layout) of RW disposal excavations. In this respect, of an overriding concern will be active or/and permeable tectonic disturbances. Their identification is viewed as an important task in the process of URL construction and relevant experiments to be conducted.

4. On the whole, hydrogeological studies indicate the absence of a direct hydraulic connection between the assumed level of RW disposal and the day surface. However, such a connection may manifest itself in any separate system of cracks, therefore, during URL construction and relevant experiments conducted therein, each significant fracture system should be studied to identify if such connection is available.

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