Influence of tectonic perturbations on the migration of long-lived radionuclides from an underground repository of radioactive waste

Victor Malkovsky[1] · Axel Liebscher[2] · Thomas Nagel[3] · Fabien Magri[4,5]

Abstract

We studied the influence of tectonic perturbations on the transport of potentially mobilized radionuclides in groundwater from a deep-mined repository of solid high-level radioactive waste. The study was carried out by the method of mathematical modeling. Key parameters of the model correspond to the site of a potential federal repository in Russia. The groundwater flow domain is delimited on one side by a water divide (i.e., boundary of the catchment basin) and on the other side by the river bank. 2D simulations of groundwater flow and radionuclide migration are carried out along a vertical cross-section normal to the water divide. The groundwater flows through the rock massif, which encloses the repository, and discharges into the adjacent river. It is supposed that tectonic activity may form a fault which is parallel to the river bank. We analyzed how repository safety depends on the time of the fault emergence and on the distance between the repository and the fault. The results of our simulations suggest that: (1) emergence of a fault due to tectonic perturbations is not inevitably associated with a substantial growth of radionuclides released from the repository to the environment; (2) influence of the fault on the repository safety depends on the distance between the fault and the repository as well as on the time interval between the repository development and the fault emergence; (3) the influence of the fault on the repository safety can depend substantially on local elevations of the relief at the repository site.

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Introduction

The estimated annual world production of spent nuclear fuel (SNF) by atomic power plants is 11,500 t, 5000 t of which are then subjected to reprocessing at radiochemical enterprises (Lovasic 2008). Reprocessing of SNF leads to the production of radioactive waste (RAW) in the form of highly mineralized aqueous solutions with a substantial content of different radionuclides (RN) including long-lived actinides with a half-life of hundreds and thousands of years. Since these radionuclides pose a serious ecological threat, RAW has to be isolated from the biosphere for at least several thousand years depending on the RN inventory. From the viewpoint of technical feasibility and ecological safety, the most effective method for the isolation of RAW for such long periods is the disposal of solidified RAW in underground repositories at a depth of several hundreds of meters (Krauskopf 1988; Ewing et al. 2016).

National programs of RAW management are based on projects of so-called mined repositories where canisters with solidified HLW are disposed in short boreholes drilled in foot and side walls of long horizontal underground galleries.

Reliability of such isolation of RAW from the biosphere is provided for by engineered and natural barriers of the repository (National Research Council, 2003). The engineered barriers include waste forms, steel canisters for the solidified RAW, and backfill for holes in rocks where the canisters are disposed. Half-life of many hazardous radionuclides in RAW is long. The engineered barriers can fully degrade during the time period which is comparable to the half-life of these radionuclides. As a result, the role of the natural barrier in the isolation of these RAW from the biosphere becomes of key importance. The main mechanism of radioactive pollution propagation through the rocks is the transport of RN by groundwater. Protection properties of the natural barrier are sufficient if concentration of RN in the groundwater decreases up to an ecologically safe level due to radioactive decay during migration from the repository to the biosphere. The migration time of the radionuclides depends on groundwater flow velocity which, in turn, is controlled by hydraulic gradients and permeability of the enclosing rocks. For this reason, it is of paramount importance for the safety of RAW disposal to select a site where the bulk permeability of the rock massif is low. Since any discontinuities (e.g., geological, structural) tend to increase the permeability of rocks significantly, one of the main requirements for the repository site is the absence of large-scale faults and zones of fracturing in the selected massif. However, since the host rocks have to ensure the isolation of RAW for a very long period, the probability of tectonic activity development during such time is not negligibly small, even in tectonically stable regions. Therefore, it is important to analyze how the location of future tectonic perturbations and the time interval between RAW disposal and the development of tectonic activity affect groundwater flow, radionuclide migration and the safety of the repository.

We carry out this analysis for rock massifs similar to the Yeniseiskiy Site (YS, Fig. 1) which is selected for the development of a federal deep-mined repository of solid high-level waste in Russia (Laverov et al. 2016).

Hydrogeological setting and mathematical model

In general, the groundwater flow within a rock massif in absence of buoyancy forces is topography-driven, i.e., groundwater flow patterns extend from the elevated part of the basin towards the discharge areas (Tòth 1963). From a hydrogeological point of view, a rock massif for a repository of HLW can be considered as a drainage basin where the groundwater flow is topography-driven from the elevated part of the basin to the discharge zone, e.g., to an open reservoir (Fig. 2). In this case, the basin is confined from its elevated side by a regional water divide and by a bank of the reservoir from the opposite side. The lower boundary of the basin is low permeable tight crystalline bedrock. Position of the lower boundary is defined from the data of geophysical survey and analysis of core samples obtained at the drilling of exploratory boreholes. The repository is planned to be constructed at a depth of 500–700 m below surface.

The YS is a characteristic example of a such drainage basin. Its eastern boundary is the regional water divide; the western boundary is the river Yenisei (Fig. 1). The boundaries are near parallel to each other at the site selected for the repository development. As it follows from data of geophysical survey, the basin is confined from the bottom by low permeable rocks approximately at a depth of 1500–2000 m. The YS is situated in the northern part of the Archean granite-gneiss Nizhnekansky massif in the Krasnoyarsk region (Siberia, Russia) in metamorphic rocks of the Atamanovskaya group (Laverov et al. 2016). It belongs to a zone of Neogene–Quaternary post-platform tectonic activity. Compared to other repository sites in crystalline rocks that are considered tectonically stable, e.g., in Scandinavia (Pastina et al. 2006; Boedvarsson et al. 2006) and in China (Wang et al. 2014), seismic perturbations are potentially relevant in YS. To investigate the influence of potential faults created during the repository operation time, some assumptions regarding their orientation, occurrence and properties need to be made based on the currently known site characteristics. For example, old rivers are often adapted to ancient regional tectonic perturbations, and tectonically stable regions are characterized by quasi-steady-state regional stress conditions. Therefore, one can expect that the orientations of ancient and new tectonic perturbation zones will be similar. Hence, it is likely that a new tectonic
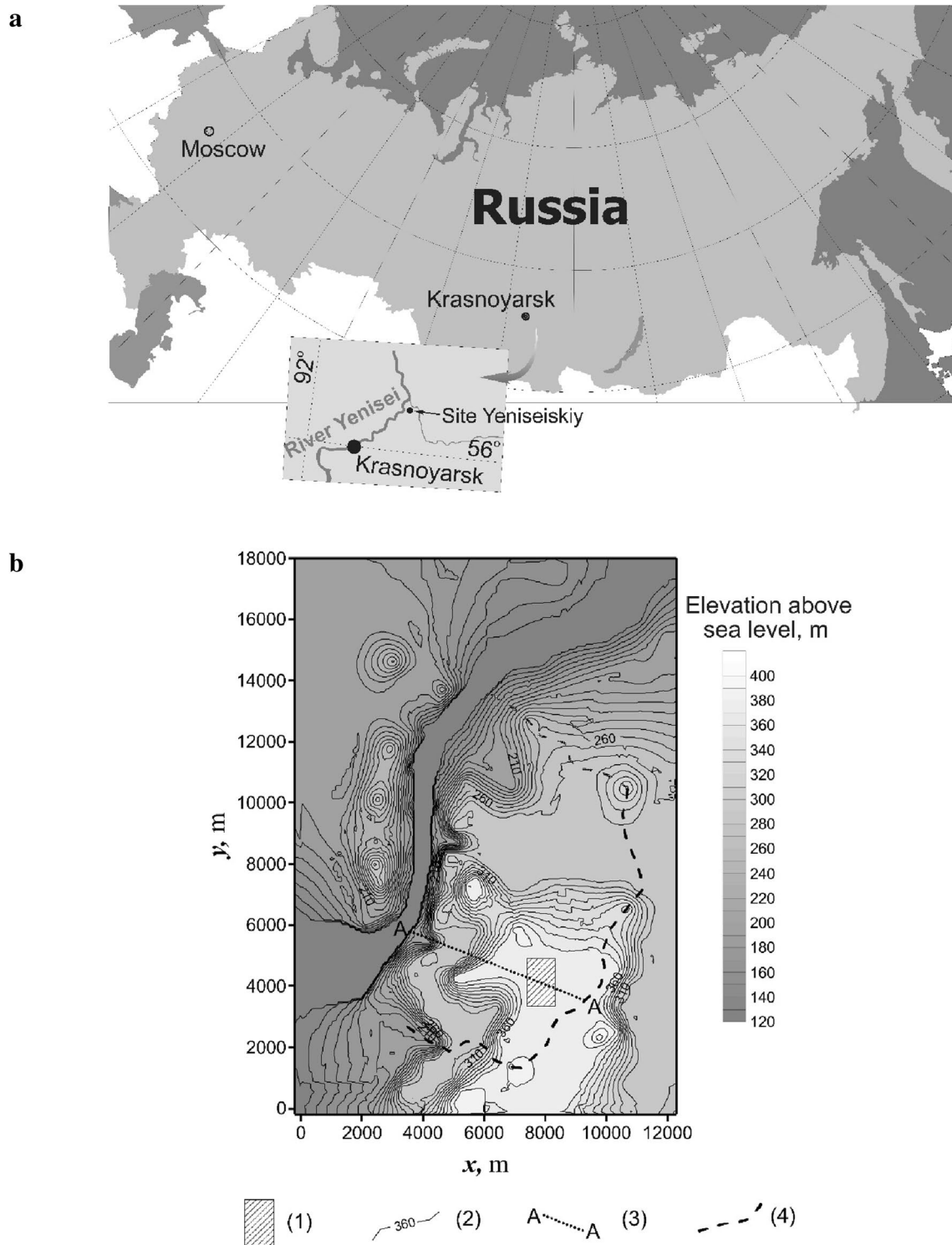
Fig. 1 Water table at the Yeniseiskiy site (YS). Legend: **a** Location of YS; **b** position of the watertable at YS (1) repository site; (2) isohypses of the watertable; (3) position of cross-section for 2D modeling; (4) regional water divide

perturbation (fault or large-scale fracture system) at the YS will be approximately parallel to the river bank.

The regional water divide can be parallel to the river at the repository site, e.g., at YS (Fig. 1b). The regional flow of

the groundwater, in this case, is normal to the side boundaries of the drainage basin.

Placement of underground galleries of the mined repository parallel to the river bank is the most reasonable,

a

b
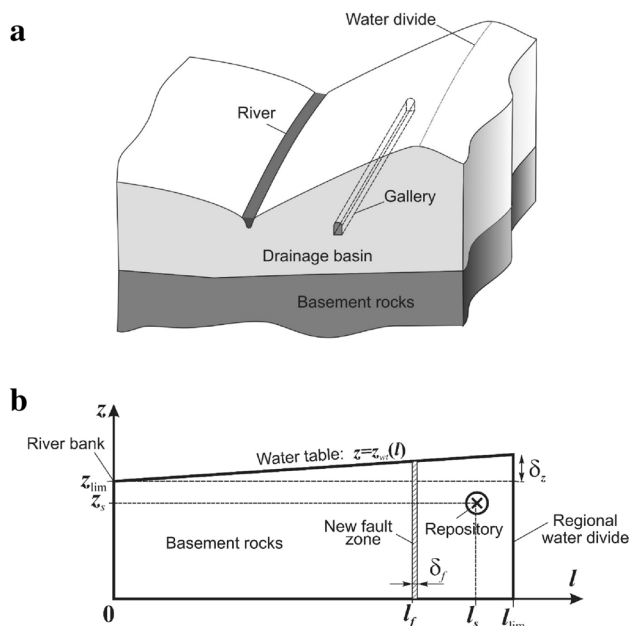
Fig. 2 Diagram of the drainage basin at the site of underground repository of RAW. Legend: **a** Diagram of the drainage basin; **b** 2D modeling domain l: distance from the river bank; z:elevation above the bottom boundary; l_{lim}: location of the regional water divide, z_{lim}: depth of the bottom boundary; l_s, z_s repository co-ordinates. $l_f < l < l_f + \delta_f$ is the fault zone parallel to the regional water divide. In the YS, $l_{lim} = 6000$ m, $z_{lim} = 2000$ m, $\delta_z = 250$ m, $z_s = 1500$ m. It is assumed that $\delta_f \approx 100$ m

otherwise the shortest path from the repository to the river bank will decrease (Fig. 2a).

As a first approximation, groundwater flow and radionuclides migration in such case can be described by a 2-D model in a vertical cross-section which is normal to the side boundaries of the drainage basin (Fig. 2). Since the objective of this numerical example is the simulation of radionuclide migration, the 2-D profile is located such that it cross-cuts the repository perpendicularly to the river bank.

We estimate the influence of fault emergence on radionuclides migration with the use of such model at parameters corresponding to the YS case.

Let us introduce the Cartesian coordinates l, z in the cross-section, as it is shown in Fig. 2b: l is the distance from the river bank along the cross-section, z is the elevation above the lower boundary of the basin; l_{lim} is the distance between the river bank and the regional water divide, z_{lim} is the depth of the bottom boundary; l_s, z_s are the coordinates of the repository in the cross-section.

Although fluid flow in crystalline rocks is typically fracture controlled with very low permeability of the rock matrix itself, we assume that groundwater flow in our model can be described by Darcy's law:

$$v_l = -\frac{k}{\mu}\frac{\partial p}{\partial l}, \; v_2 = -\frac{k}{\mu}\left(\frac{\partial p}{\partial z} + \rho g\right) \tag{1}$$

where v_l, v_z are the components of Darcy velocity, p is the pressure of water, ρ and μ are the density and the dynamic viscosity of the fluid, k is the local permeability of the rocks ($k = k_f$ within the fault and $k = k_r$ in non-perturbed rocks of the basin; k_f and k_r are constant), g is the acceleration due to gravity. The timing of faulting is designated t_f and therefore if $t < t_f$, the fault is absent, and the permeability is equal to k_r in the whole modeling domain. At $t \geq t_f$ the permeability in the fault zone ($l_f < l < l_f + \delta_f$) is equal to k_f.

We assume in the first approximation that the heat generation by RAW is weak, and ρ and μ are approximately constant.

By virtue of the continuity equation, pressure satisfies the equation (de Marsily 1986)

$$\frac{\partial}{\partial l}\left(k\frac{\partial p}{\partial l}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial p}{\partial z}\right) = 0 \tag{2}$$

Boundary conditions for Eq. (2) take the form

$$
\begin{aligned}
l = 0, \quad & \partial p/\partial l = 0; \quad l = l_{lim}, \quad \partial p/\partial l = 0; \\
& z = z_{wt}(l), \quad p = p_{atm}; \\
& z = 0, \quad \partial p/\partial z + \rho g = 0
\end{aligned} \tag{3}
$$

where p_{atm} is the atmospheric pressure, z_{wt} is the local elevation of the water table above the lower boundary in the considered cross-section.

In the YS (Fig. 1b), $l_{lim} \cong 6.1$ km, $l_s \cong 4.7$ km. According to geophysical survey findings, $z_{lim} = 1.5$–2 km. Since it is planned to dispose RAW at a depth of 500–700 m, it follows that $z_s \cong 1.5$ km.

The migration of radionuclides in the rocks of the drainage basin is governed by the equation (de Marsily 1986):

$$
\begin{aligned}
&\frac{\partial C}{\partial t} + \frac{1}{\varphi + \rho_r K_d(1-\varphi)}\left(v_l\frac{\partial C}{\partial l} + v_z\frac{\partial C}{\partial z}\right) = \\
&\frac{1}{\varphi + \rho_r K_d(1-\varphi)}\left[\frac{\partial}{\partial l}\left(D_l\frac{\partial C}{\partial l}\right) + \frac{\partial}{\partial z}\left(D_z\frac{\partial C}{\partial z}\right)\right] - \chi C
\end{aligned} \tag{4}
$$

where t is the time, C is the weight fraction of the considered radionuclide in the groundwater, K_d is the coefficient of the equilibrium distribution of the radionuclide between the rocks and the groundwater, ϕ and ρ_r are the porosity and the rock density, D_l, D_z, are the components of the hydraulic dispersion, χ is the radioactive decay constant ($\chi = \ln 2/t_{hl}$ where t_{hl} is the half-life period of the radionuclide).

It follows from Eq. (4), that the mobility of the radionuclides in the groundwater-rock system depends substantially on the value of the distribution coefficient K_d which characterizes bulk sorption properties and therefore retardation potential of the rock with regard to the specific radionuclides.

The larger K_d, the smaller is the ratio of radionuclide migration velocity to the groundwater flow velocity. However, radiation monitoring at sites of severe radioactive pollution showed that the velocity of radionuclides migration was much higher than it was predicted from known values of K_d (Kersting et al. 1999). The reason was that radionuclides can be carried by the groundwater not only as a dissolved component (in ionic form) but also attached to colloidal particles (radiocolloid). Values of K_d are typically measured for radionuclides in dissolved, ionic form and do not account for their transport in colloidal form. Because the sorption of radiocolloids on rocks can be much weaker (which would correspond to much smaller effective values of K_d), the migration velocity of radionuclides in colloidal form can be much higher than in ionic form and may even reach a velocity of the groundwater flow (Honeyman 1999; Malkovsky 2011). Leaching of vitrified RAW with non-radioactive simulators of radionuclides showed that the most part of non-radioactive analogues of actinides are contained in the leaching solution in a colloidal form (Malkovsky et al. 2018a). Experimental study of filtration of the leaching solution through a crushed rock sample from the YS from a depth of $\cong 500$ m demonstrated that the velocity of actinide analogues was almost equal to the velocity of solution flow (Malkovsky et al. 2018b). This implies that K_d for actinides in colloidal form from leaching products was practically equal to zero. Since this form of actinide analogues in the leaching solution prevails, we assume that $K_d = 0$ for actinides from RAW in our modeling. Assuming $K_d = 0$ simplifies Eq. (4) to:

$$\frac{\partial C}{\partial t} + \frac{1}{\varphi}\left(v_l \frac{\partial C}{\partial l} + v_z \frac{\partial C}{\partial z}\right) = \frac{1}{\varphi}\left[\frac{\partial}{\partial l}\left(D_l \frac{\partial C}{\partial l}\right) + \frac{\partial}{\partial z}\left(D_z \frac{\partial C}{\partial z}\right)\right] - \chi C \tag{4a}$$

The initial condition for Eq. (2) is uniform:

$$t = 0, \quad C = 0 \tag{5}$$

It is expected that the repository will be filled with groundwater in the post-closure phase. Radionuclides enter groundwater due to the leaching of RAW. Let C_s be the equilibrium weight fraction of leaching products in the groundwater in the repository. Then the weight fraction of the radionuclide in the groundwater within the repository is $C_s \gamma \exp(-\chi t)$ where γ is the weight fraction of the radionuclide in RAW at the time of emplacement into the repository. Then, boundary conditions for Eq. (4a) can be written as

$$z = 0, \quad \partial C/\partial z = 0; \qquad z = z_{wt}(l), \quad \partial C/\partial n = 0;$$
$$l = 0, \quad \partial C/\partial l = 0; \qquad l = l_{\lim}, \quad \partial C/\partial l = 0; \tag{6}$$
$$l = l_s, z = z_s, \quad C = C_0 \exp(-\chi t)$$

where $C_0 = C_s \gamma$.

Since $\delta_f/l_{\lim} << 1$, the application of successive over-relaxation methods or similar techniques for the solution of Eq. (2) leads to time-consuming calculations. That is why the boundary-value problem (2)–(3) was solved by the finite elements method (Zienkiewicz, Morgan 1983). The components of the Darcy velocity were calculated from the obtained solution by Eq. (1) for substitution into Eq. (4a) which was integrated with respect to time by means of the method of alternating directions (Roache 1976) taking into account the initial condition (5) and boundary conditions (6).

Parameters

Based on the dimensions of the rock massif at the YS (Fig. 1), the following basic parameters of the modeling domain are specified: $l_{\lim} = 6000$ m, $z_{\lim} = 2000$ m, $\delta_z = 250$ m. The location of the repository is $l_s = 4700$–5700 m, $z_s = 1500$ m. One of the most hazardous long-lived actinides in RAW, which are produced at application of PUREX technology for reprocessing of SNF, is ^{241}Am (Choppin et al. 2013). That is why we will consider migration of ^{241}Am with a half-life period of $\cong 433$ years ($\chi \cong 0.0016$ 1/year). It is supposed that interaction between the groundwater and RAW is established immediately after waste emplacement. According to Bredehoeft and Norton (1990), the typical permeability of low-fractured igneous rocks varies within the range of 10^{-17}–10^{-15} m^2. Since the basin is comprised of low-fractured crystalline rocks, we set $k_r = 10^{-16}$ m^2. A comprehensive review of permeability and architecture of fault zones is presented in Scibek (2020). Permeability of fault rocks can reach values of 10^{-14} m^2 (Wibberley, Shimamoto 2003). According to Achtziger-Zupan et al. (2016) and Vidal and Genter (2018), the thickness of the fault core usually does not exceed 100 m. The contrast between k_r and k_f can be even more significant. As it is indicated by Rempe et al. (2018), the ratio k_f/k_r can exceed four decimal orders. However, as it follows from previous estimations, if k_f satisfies the inequality $k_f \delta_f/(k_r L) > 10$ (where L is the vertical length of the fault in our case), a further increase of k_f exerts no substantial influence on the structure and characteristics of fluid flow in the rock massif which contains the fault (Malkovsky and Pek, 2014). Accordingly, the width of the fault zone in our calculations is set to 100 m and its permeability to 10^{-14} m^2. According to (de Marsily 1986), components of the dispersion tensor can be written as

$$D_l = (\alpha_L - \alpha_T)\frac{v_l^2}{v} + \alpha_T v, \quad D_z = (\alpha_L - \alpha_T)\frac{v_z^2}{v} + \alpha_T v$$

where α_L, α_T are longitudinal and transverse coefficients of dispersion.

It is recommended to specify for sedimentary rocks $\alpha_T/\alpha_L = 0.1$–0.3 (Freeze, Cherry 1979). However, it is indicated in (deMarsily 1986) that α_T and α_L can be close to each other and α_T/α_L can even exceed 1 insight fractured rocks. Hence we can suppose in the considered case that $\alpha_L = \alpha_T = \alpha$.

As it is indicated in (deMarsily 1986) dispesion coefficients in fractured rocks are of the order of 10^2 m. That is why the dispersion coefficient of low-fractured crystalline rocks of 50 m was selected.

Results and discussions

Linear water table

We first consider an ideal case where the surface of the water table is near-linear and $z_{wt}(l) = z_{\lim} + l\delta_z/l_{\lim}$. Stream lines of the groundwater in absence of tectonic

perturbations (i.e., homogeneous permeability of the rock mass) are shown in Fig. 3. The closer the repository is to the regional water divide (right side boundary of the domain), the longer is the streamline which passes through the repository. The extent of the contaminant plume 5000 years after repository loading and closure is shown in Fig. 4. One can see that descending flow carries the plume downward and westward. The influence of hydraulic dispersion leads to a diffusion of the plume as it is carried by the groundwater flow. Containment properties of rock massif and reliability of RAW isolation in the repository area can be characterized by the maximum concentration of the considered radionuclide at $z = z_{\lim}$: $C_{\max}(t) = \max_{0 \le l \le l_{\lim}} C(t, l, z_{\lim})$. At the beginning of the process $C_{\max} = 0$. Groundwater carries radionuclides from the pollution source to the surface which induces an increase of $C_{\max}$. As a result, $C_{\max}$ becomes noticeable after approximately 200 yrs, increases up to 1500–2000 years and then decreases asymptotically to zero because of radioactive decay (Fig. 5, curve 1).

It follows from an analysis of the streamlines in Fig. 3 that it is reasonable to develop the repository as close as possible

Fig. 3 Groundwater streamlines in the cross-section of the homogeneous drainage basin
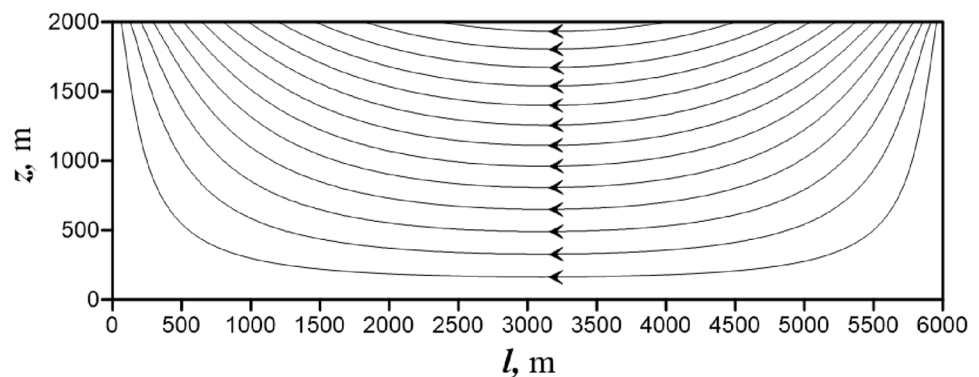
Fig. 4 Position of the radioactive plume 5000 years after repository loading ($l_s = 5700$ m, $z_s = 1500$ m) in the homogeneous drainage basin

C/C_0

0,00036
0,00032
0,00028
0,00024
0,0002
0,00016
0,00012
8E-005
4E-005
0
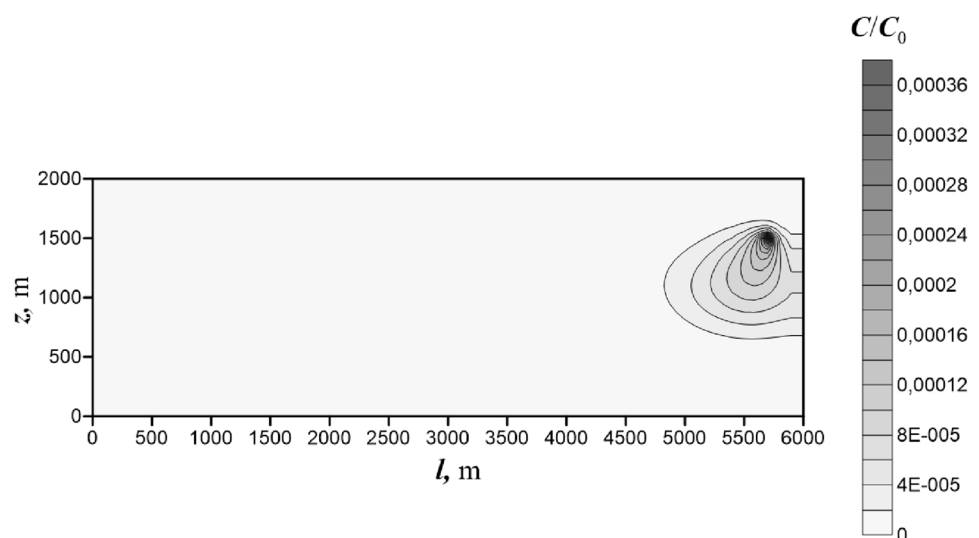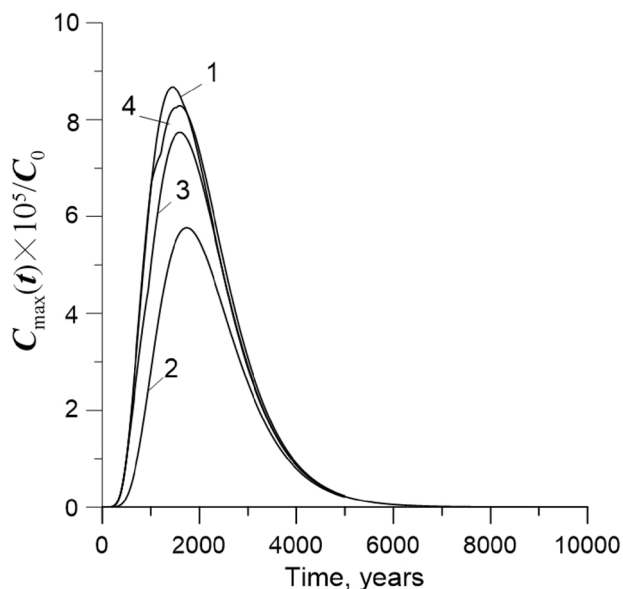
Fig. 5 Temporal dependence of the maximum concentration of the radionuclide at the surface in homogeneous rocks and in presence of the fault. (1) homogeneous rocks; (2) the fault emerges immediately after repository loading; (3) time between repository loading and fault emergence is 500 years; (4) 1000 years

to the water divide. Hence it is likely in this case that the fault emerges between the river bank and the repository. Calculated $C_{\max}(t)$ in the case of emergence of the tectonic fault at $l_f = 5200$ m and at different fault appearance t_f are also presented in Fig. 5 (Curves 2, 3, 4). One can see that the formation of the fault leads to a decrease of $C_{\max}(t)$ under the considered conditions. The most noticeable decrease takes place at the emergence of the fault immediately after loading of the repository ($t_f = 0$, Curve 2). If $t_f \neq 0$, $C_{\max}(t)$ remains the same as in absence of the fault up to $t = t_f$ and deviates only at $t > t_f$. The smaller t_f is (i.e., the sooner the fault appears), the smaller $C_{\max}(t)$. The reason becomes clear by observing the simulated groundwater streamlines in presence of the fault (Fig. 6). One can see that the fault focuses the descending flow and draws the contaminant plume downward (Fig. 7).

Multiple simulations show that the influence of the fault on $C_{\max}(t)$ depends not only on the time of tectonic perturbation, but also on the positions of the fault and the repository, i.e., on l_f and l_s. However, the function $C_{\max}(t)$ characterizes the safety of RAW disposal only at certain time t. Safety for the entire time can be characterized by maximum of $C_{\max}(t)$. We designate $\max_t C_{\max}(t)$ as $C_{\sup}$. Value of $C_{\sup}$ in absence

Fig. 6 Groundwater streamlines in presence of the fault at $l_f = 5200$ m
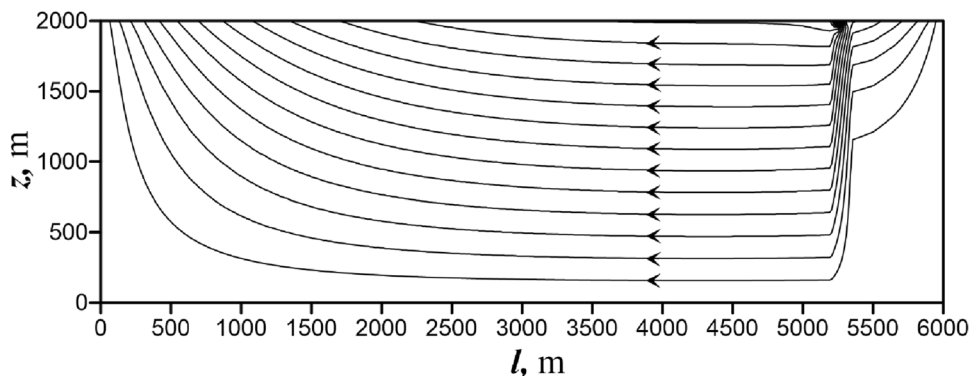
Fig. 7 Position of the contaminant plume 5000 years after repository loading ($l_s = 5700$ m, $z_s = 1500$ m, $l_f = 5200$ m, $\delta_f = 100$ m)

a

b
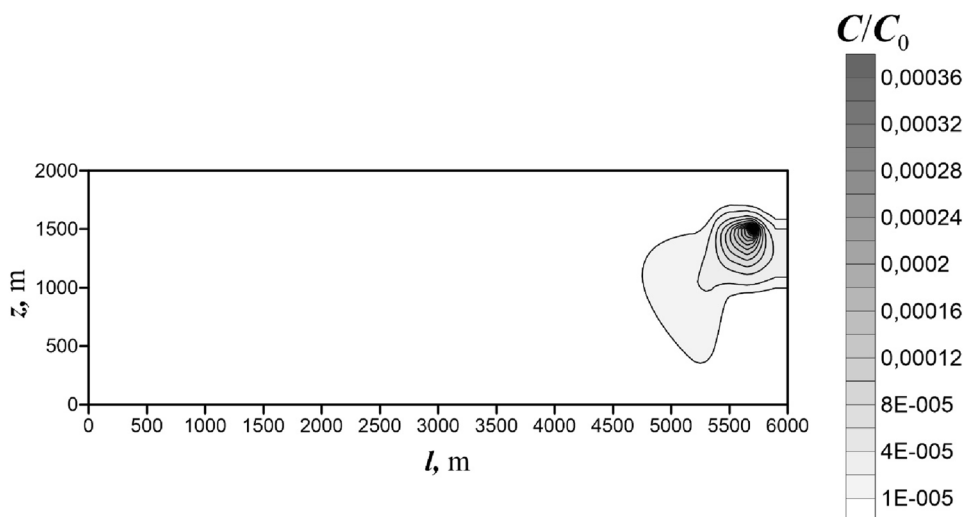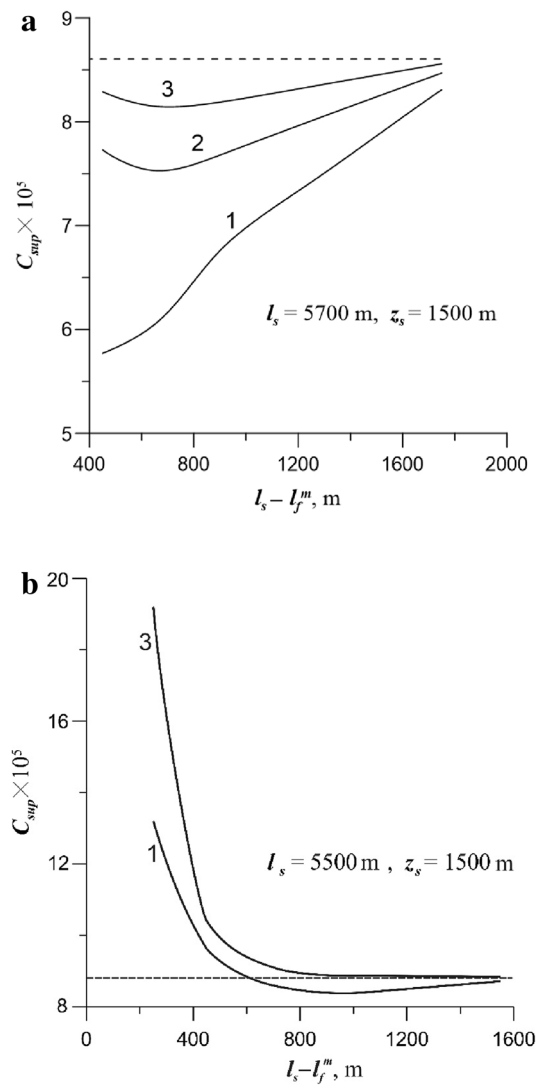
Fig. 8 Dependence of the maximum concentration of the radionuclide in the groundwater at the surface on the distance between the repository and the fault plane (l_f^m) **a** $l_s = 5700$ m; **b** $l_s = 5500$ m. (1) the fault emerges immediately after repository loading; (2) in 500 years; (3) in 1000 years; dashed line denotes C_{sup}^0, i.e. the maximum concentration in absence of the fault

of the fault is denoted as C_{sup}^0. Plots of C_{sup} against $l_s - l_f^m$ (where $l_f^m = l_f + \delta_f/2$) at $l_s = 5700$ m and different t_f are presented in Fig. 8a. One can see that $C_{sup} < C_{sup}^0$ for any t_f at $l_s - l_f^m > 400$ m. However, the difference $C_{sup} - C_{sup}^0$ decreases and tends to zero as $l_s - l_f^m$ increase. The reason is that vertical component of the pressure gradient in the near-fault domain decreases with growth of $l_s - l_f^m$ which leads to a decrease of groundwater focusing by the fault. It is worth noticing that the minimum of the curve 1 corresponds to its left end whereas minima of curves 2 and 3 are shifted to the right. This can be explained by an analysis of Fig. 6. The interaction of RAW with groundwater leads to

the formation of a pollution plume that moves due to advection and expands under the action of hydraulic dispersion. As a result, the front of the plume reaches the fault zone. If by this time the fault already exists, the focused stream carries the plume downward to the domain of the longest streamlines, which leads to an increase in time of radionuclide migration and hence to a decrease of radionuclide concentration in the discharge zone due to radioactive decay. This case corresponds to curve 1 in Fig. 8a. If the fault does not exist yet (curves 2 and 3) and the distance between the repository and the fault is small (400–450 m), the front of the plume passes through the zone where the fault will eventually appear. If the distance between the repository and the fault is large ($\cong 700$ m), the time between plume formation and fault emergence can be insufficient for the passage of the main part of the plume through the future fault zone. As a result, the main plume is carried by the focused stream down the fault to the long travel passes. That is why the local minima of curves 2 and 3 are shifted to the right. The same analysis is valid for analogous plots in Fig. 8b at an increased distance between the repository and the water divide ($l_s = 5500$ m).

Actual water table

The actual water table can differ substantially from its linear approximation. A representative water table of the YS is illustrated in Fig. 9. The center of the repository site (contaminant source) corresponds to $l_s \cong 4700$ m. Streamlines of the groundwater in the cross-section are shown in Fig. 10. One can see that the contaminant source is located outside a domain of active water exchange in a practically stagnant zone. A special feature of water table position in the cross-section shown in Fig. 1 is the presence of weak local maxima and minima of the water table elevations between the repository position and the water divide. The role of these heterogeneities of the water table in absence of tectonic faults is not significant. However, they exert a substantial influence on the streamlines in the presence of a fault (Fig. 11). This elongated highly permeable structural unit feeds the groundwater stream which discharges partially into the river and to a much less extent to the depressions in the water table between the fault and the water divide. The repository is located just in the domain of the flow which discharges to these depressions. As a result, the radionuclides from the repository can be carried by the groundwater partially downward into the fault, while the ascending branch of the flow carries a part of them upward. In this case, the length of the travel path of the radionuclides to the surface is less than in absence of the fault. Therefore, radioactive decay decreases radionuclides concentration in the groundwater during their migration from the repository to the biosphere to a much lower extent. As a result, C_{sup} can substantially
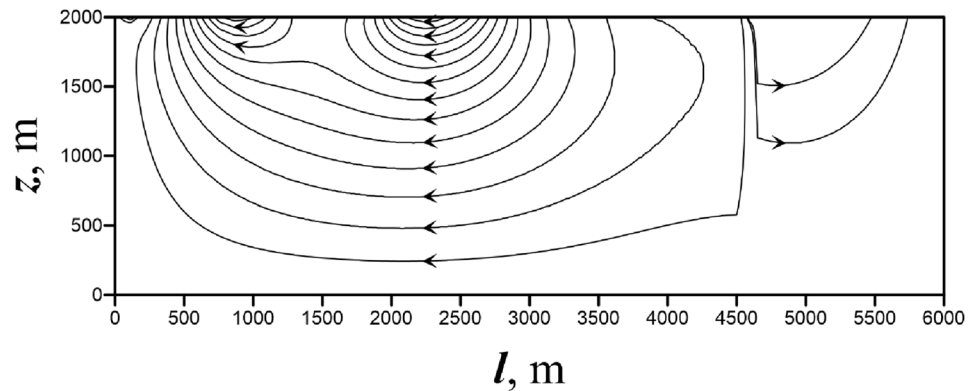
Fig. 9 Position of the water table at the YS along the cross-section A–A shown in Fig. 1
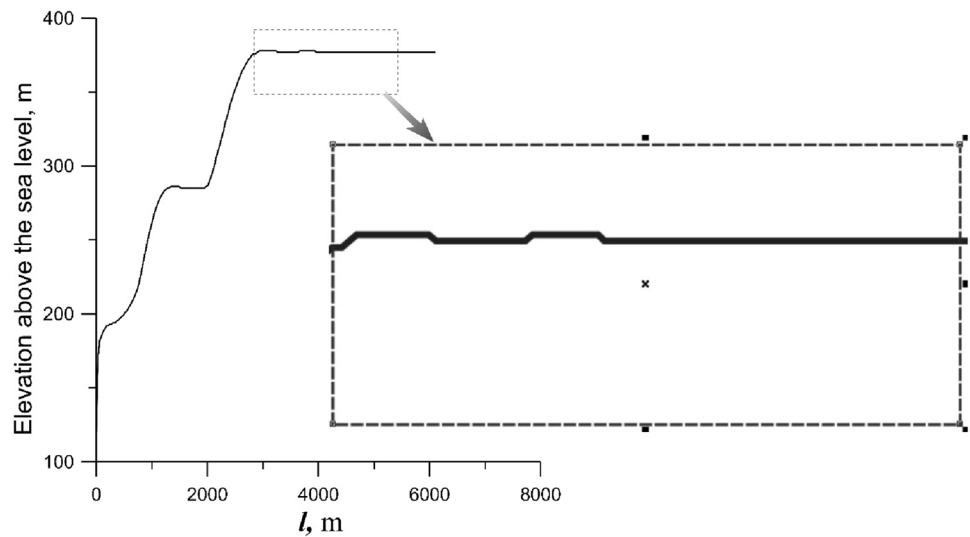
Fig. 10 Streamlines in cross-section at the YS in absence of a fault accounting for a realistic water table as illustrated in Fig. 9
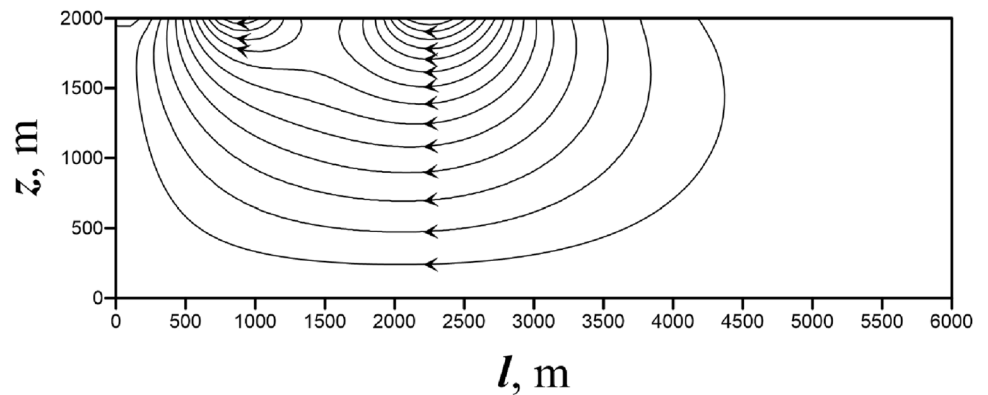

**Fig. 11** Streamlines in cross-section at the YS in presence of the fault ($l_f = 4500$ m, $\delta_f = 100$ m)

increase in presence of the fault (Fig. 12). The shape of the water table corresponds to the current topography. Hence local depressions of the relief between the repository and the water divide can substantially increase the negative influence of future tectonic activity on the repository safety.

We considered an artesian basin with a thickness of 1500–2000 m which is confined from the bottom by tight basement rocks. Since a real dimensions of the basin are substantially larger than its thickness (as, for example, this takes place at YS), one can expect that the fault, which can emerge due to tectonic activity, should be steeply dipping.
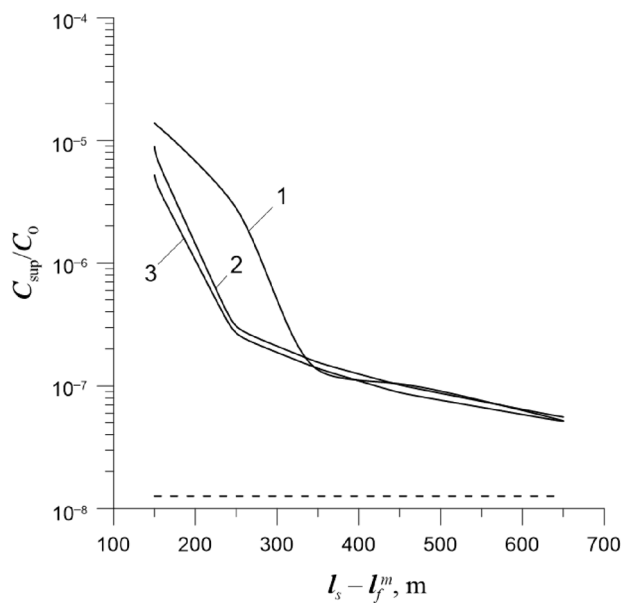
Fig. 12 Dependence of the maximum radionuclides concentration in the groundwater at the surface on the distance between the repository (ls) and the fault plane (l_f^m) at the YS $l_s = 4700$ m; $z_s = 1500$ m. (1) the fault emerges immediately after repository loading; (2) in 500 years; (3) in 1000 years; dashed line denotes maximum concentration in absence of the fault
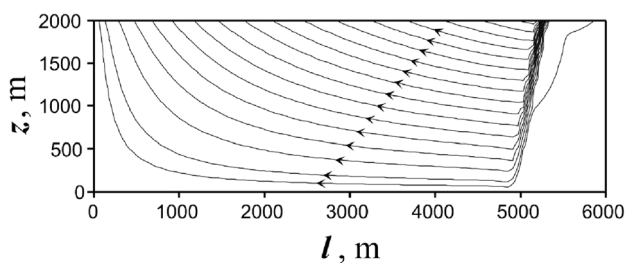
Fig. 13 Groundwater streamlines in presence of the fault ($l_f = 5200$ m at $z = 2000$ m; the angle between the fault and the vertical is 10°)

We considered the vertical fault in the model through an actual fault can be slightly inclined. Nevertheless, the vertical orientation of the fault is a reasonable approximation, because the inclined fault also focuses descending flow of the groundwater, and the streamlines in the case of the slightly inclined fault are similar to streamlines in the case of the vertical fault (Fig. 13).

We considered fault zones of constant thickness and permeability. Evolution of an actual fault can induce consequent perturbations of enclosing rocks and extension of the fault zone. We assumed as a conservative approximation that the emergence of the fault leads to the immediate formation of the final fault zone with a thickness of approximately 100 m according to Achtziger-Zupan et al. (2016) and Vidal and Genter (2018).

Conclusions

Deep-mined repositories for underground disposal of solid radioactive waste can be developed in a massif of low-fractured crystalline rocks. The rock massif plays an important role in the isolation of hazardous radioactive substances from the biosphere. The main mechanism of propagation of radioactive pollution from the repository through the rocks in case of radionuclide mobilization and failure of engineered barriers is the advective transport of radionuclides by groundwater. On one side, its flow is confined by the regional water divide and, on the other side, by the coastline of an open reservoir to which the groundwater discharges. Isolation properties of the rock massif are sufficient if the concentration of radionuclides in the groundwater decreases due to radioactive decay during their migration to the groundwater discharge zone to an ecologically safe level. Any discontinuities of the rocks can lead to a substantial acceleration of the groundwater flow and to a corresponding increase of radionuclides migration velocity. That is why sites for repository development should be selected in tectonically stable regions. However, the rock massif has to isolate radionuclides from the biosphere for thousands of years because of very long half-life periods of some actinides in composition of the waste. One cannot neglect emergence of tectonic perturbations during such time even in tectonically stable regions. It is therefore of great importance to estimate how the influence of the tectonic perturbation depends on the time between loading of the repository and the emergence of the fault as well as on the distance between the fault and the repository. We consider processes of groundwater flow and radionuclides migration in 2-D approximation in a vertical cross-section normal to the water divide. We examine a case where the groundwater discharges into a river, as at the YS which is selected for the development of a regional repository of high-level radioactive waste in the Russian Federation. The tectonic history of the YS suggests that new faults can be parallel to the river bank (and hence normal to the cross-section).

An ideal case is analyzed first where the position of the water table in the cross-section from the coastline of the reservoir to the water divide is close to its linear approximation (that is local sloping angle of the water table is close to a constant). The following conclusions can be made. The influence of the fault on radionuclides migration can both decrease and increase repository safety as the time of fault emergence increases. If the distance between the fault and the repository exceeds 500 m, the influence of the fault on isolating properties of the rock massif is not significant (in our calculations, the maximum concentration of radionuclides in the groundwater at the surface in presence of the fault changes no more than by 40%). Moreover, if the repository is located close to the water divide (300 m in our calculations), the fault can exert a positive influence on repository safety because its

emergence leads to a decrease of maximum concentration of the radionuclides in the groundwater at the surface.

The role of a realistic water table in the migration of the radionuclides is also considered. The emergence of the fault can cause groundwater to discharge to local water table depressions, in the vicinity of the repository. This local regional flow accelerates the migration of radionuclides to the surface. As a result, the maximum concentration of the radionuclides in the groundwater at the surface can increase by 3 orders of magnitude with respect to the case without fault. However, if the distance between the fault and the repository exceeds 500 m, the maximum concentration increases only by one order of magnitude with respect to the case without fault. Therefore, local depressions of the water table between the repository and the water divide make the repository safety sensitive to the development of tectonic perturbations. It should be taken into account that the position of the water table often correlates with the topographic surface. Hence it is worthwhile to fill in the depressions of the relief between the repository and the water divide with water-retaining rocks to substantially increase the repository safety. At least, this should be done after the emergence of the fault. In the YS, these depressions are relatively shallow, and filling them calls for moderate amount of earthwork.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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