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Selecting the rational parameters for restoring filtration characteristics of ores during borehole mining of uranium deposits

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Abstract

Purpose. The research purpose is to increase the efficiency of borehole uranium mining by selecting special decolmating solutions and rational parameters of the technology for influencing the seam near-filter zone of geotechnological boreholes, as well as improving the filtration characteristics of the seam, depending on the mineralogical composition of ores and the structure of sediment-forming materials.

Methods. The method of X-ray phase analysis was used to study the powders. The core material samples were studied on transparent sections using a LEICA DM 2500 P microscope. The content of the elemental composition of the ores and host rocks in the samples of the productive horizon was controlled using an atomic emission spectrometer.

Findings. Based on the research results, quantitative-qualitative characteristics of the host rocks in the productive horizon, sedimentary formations from technological boreholes have been determined, revealing various levels in the productive horizon. It has been found that in the Campanian horizon boreholes, ores have a complex structure and multicomponent sedimentary formations, representing a mixture of sediments of mechanical-chemical origin.

Originality. The results of quantitative-qualitative, microscopic, thermal research methods of the characteristics of ore-bearing rocks from various horizons at the Syr Darya depression uranium deposit have been studied and comparatively analyzed. The sedimentary formations of technological boreholes in the productive Santonian, Maastrichtian, Campanian horizons of the Northern Kharasan field, Syr Darya depression, have also been sampled and studied. The choice of the most appropriate composition of chemical reagents for dissolution and prevention of sedimentary formation in porous media has been substantiated by the microscopic research method.

Practical implications. A detailed study and comparative analysis of the characteristics of ores and host rocks in various productive horizons makes it possible to more accurately plan the mining of blocks, minimizing emerging risks. Using the developed combined technology for intensifying borehole uranium mining, it is possible to increase the efficiency of borehole uranium mining and reduce its operating costs. At the same time, the ecological and industrial safety of the work of intensifying the leaching uranium ores increases.

Keywords: *uranium, borehole uranium, mining, sedimentary formation, X-ray phase method, decolmating, thermal analysis, uranium leaching*

1. Introduction

Uranium plays an important role in nuclear energy production. Uranium, as a key material for the production of fuel for nuclear reactors and the most common element of the earth's crust, contained in rocks, soil, rivers and ocean waters should be extracted from raw materials in a complex hydrometallurgical process that includes many stages of separation. The uranium in the ore is often accompanied by other rare metals that can be recovered during the technological process to increase the profitability of the entire enterprise [1]-[3]. Uranium is the most representative element of the actinides and is of fundamental importance in the nuclear fuel cycle. The nuclear energy market is expected to grow substantially over the next 20 years. For example, in the United States alone, growth of 50% is predicted by 2030. According to the Ministry of Energy of the Republic of Kazakhstan, global electricity consumption will double by 2030 [4], [5].

In combination with the expected growth of nuclear energy, the demand for uranium will also increase sharply in the future, and the uranium industry of Kazakhstan, based on progressive, highly efficient borehole uranium ore mining, can make a worthy contribution to solving the problem [6], [7]. Data on explored natural uranium reserves are presented in Figure 1, while Figure 2 shows data on the share of uranium concentrate production by countries of the world.

The practice of operating systems of geotechnological boreholes during the exploitation of uranium deposits by underground uranium leaching method shows that over time, a decrease in their productivity is observed [8].

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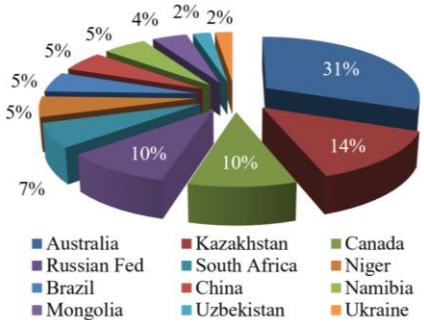


Figure 1. Uranium reserves explored by countries

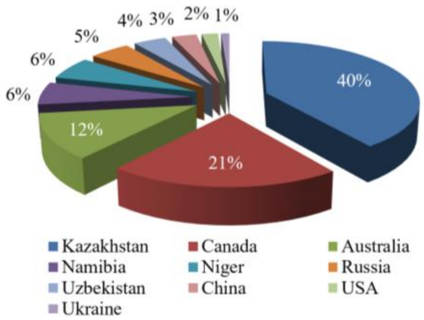


Figure 2. Share production of uranium by countries of the world

One of the main reasons for the decrease in the throughput ability of technological boreholes is an increase in hydraulic resistance and a decrease in the filtration characteristics of the seam due to the formation of colmatation. The latter is caused by settling-out of substances dissolved in technological solutions, or mechanical displacement of particles in the ore-bearing horizon, as well as gas release [9], [10]. Hardly soluble sediments and displaced clay particles in the productive horizon increase the hydraulic resistance and form impermeable areas of geochemical barriers that block the flow lines of solutions. As a rule, a decrease in the filtration characteristics of a productive horizon leads to a decrease in the uranium content in the productive solution, a decrease in the yield and the duration of the uninterrupted operation of boreholes. This extends the period of mining the technological blocks, thereby increasing the consumption of sulphuric acid, electricity and other operating components [11], [12].

Sulphuric acid, used as a leaching agent at the enterprises of borehole uranium mining in Kazakhstan, is conditioned by the low cost, availability, the possibility of relatively complete conversion of uranium into solution [13]. However, the high kinetics of sulphuric acid interaction with carbonate minerals of ore-bearing rocks causes sedimentary formation in the form of a geochemical barrier that impedes the leaching process [14]. The study of the mineralogical characteristics of ore-bearing rocks will make it possible to identify the causes of sedimentary formation and solve the issues of the efficiency of borehole uranium mining technology. The use of special declamation solutions based on ammonium fluoride with the addition of sulphuric acid and surfactants in accordance with the developed methodology makes it possible to effectively destroy and prevent sedimentary formations in the productive horizon of borehole uranium ore mining [15], [16]. This technology can restore the filtration characteristics of the productive horizon and reduce labor costs, electricity and other operating costs for mining.

Real changes in the supply chains of chemical reagents and spare parts for technological equipment increase the importance of improving the filtration characteristics of ores in various mining-geological conditions. The use of traditional methods for restoring the productivity of technological boreholes in difficult conditions of ores with a high content of carbonate and clay minerals does not give a positive result [17]. Studying the structure of ores and composition of sediment-forming components leads to developing rational parameters for restoring the filtration characteristics of ores in various productive horizons [18].

The research purpose is to increase the efficiency of borehole uranium mining in difficult mining-geological conditions by restoring the filtration characteristics of ores during borehole uranium mining, depending on the mineralogical peculiarities and structure of the ore-bearing rocks in the productive horizon. At the same time, this provides an increase in productivity and an increase in the period of uninterrupted operation of geotechnological boreholes, as well as a reduction in electricity costs, labor costs, and other operating costs for mining.

The research objectives are to determine the structure of host rock ores and the composition of sediment-forming components to reveal the causes of the productive horizon ore colmatation in order to select the most optimal composition of chemical reagents for dissolution and prevention of sediment formation. Laboratory experiments should be conducted on the selection of rational parameters of decolmating solutions for the destruction of sediments and prevention of colmatation processes in the pore space of ore-bearing rocks in various productive horizons. It is necessary to develop effective parameters for improving the filtration characteristics of ores from borehole uranium mining, depending on the composition and structure of ores and sediment formations.

2. Research methods

2.1. Studying the quantitative-qualitative characteristics of host rocks

When solving the issues of the filtration characteristics of the host rocks in the productive horizon, first of all, it is necessary to determine the structure of ore-bearing rocks and the type of colmatation (colmatants) of boreholes, and then, treat both the filter and the near-filter zone by selecting the most suitable chemical regents [19], [20]. To determine the structure and composition of ore-bearing rocks, core material is sampled from the Santonian, Campanian and Maastrichtian ore intervals at the Syr Darya depression uranium deposit. The data obtained make it possible to determine the causes of sedimentary formations and a decrease in the filtration characteristics of ores and host rocks in the productive horizon.

The X-ray diffraction analysis is performed using a DRON-3 automated diffractometer with $Cu_{K\alpha}$ – radiation and β-filter. Conditions for obtaining diffraction patterns: $U = 35$ kV; $I = 20$ mA; surveying θ-2θ; detector 2 deg/min. The X-ray diffraction analysis on a semi-quantitative basis is performed using diffraction patterns of powder samples using the equal weight method and artificial mixtures. The quantitative ratios of the crystalline phases are determined. The interpretation of the diffraction patterns is carried out using the data of the ICDD card file: database of powder diffraction patterns PDF2 (Powder Diffraction File) and diffraction patterns of minerals free from impurities [21], [22].

2.2. Microscopic analysis of core samples from productive seams

The microscopic analysis purpose is to study the mineralogical composition of core samples and determine the spatial content of core samples from the productive horizons in the Santonian, Campanian and Maastrichtian horizons. The obtained data analysis makes it possible to determine the dependences of decreasing filtration characteristics and sedimentary formations on the composition and ore crystal size of host rocks in the productive horizon. The bulk material of the samples is examined using a LEICA DM 2500 P microscope in immersion liquids and transparent thin sections made from it [23], [24].

2.3. Differential thermal and thermogravimetric studies

The purpose of thermal analysis is to determine the quantitative-qualitative characteristics of the composition of carbonate and clay minerals in core material samples. Thermal analysis was performed using a Q-1000/D derivatograph system by F. Paulik, J. Paulik and L. Erdey of the MOM Company (Budapest). The method is based on registration by the device of changes in the thermochemical and physical parameters of a substance that can be caused by its heating. The thermochemical state of a sample is described by the curves: T (temperature), DTA (differential thermoanalytical), TG (thermogravimetric) and DTG (differential thermogravimetric). The last of the presented curves is a derivative of the TG-function. The surveying is performed in the air, in the temperature range of 20-1000°C. The heating mode is dynamic $\frac{dT}{dt} = 10\ \frac{\text{deg}}{\text{min}}$ standard substance – calcined Al_2O_3, sample weight – 500 mg, balance sensitivity – 100 mg per 200 mm scale. The sensitivity of measuring systems: DTA – 250 μv, DTG – and TG – 500 μv.

The thermal behavior of sample powders is studied based on the morphologies of thermal curves and numerical values of the intensities of endo- and exothermic effects using thermogravimetric trajectories of TG-lines associated with them.

The analysis results are compared with the data of atlases of thermal curves of minerals and rocks, as well as with the descriptions of the thermal behavior of substances presented in other reference sources and accumulated in the database of the laboratory that conducted these studies.

2.4. Quantitative-qualitative studies of sedimentary formations during uranium mining

The main purpose of X-ray phase analysis is to determine and compare, under laboratory conditions, the quantitative-qualitative characteristics of sedimentary formations depen-ding on the ore-bearing horizon during sulphuric acid lea-ching of uranium. Determining the quantitative-qualitative characteristics of colmatants makes it possible to select effective approaches to their destruction, dispersion, removal and further prevention of sedimentary formation for a long period.

The X-ray diffraction analysis is performed using a DRON-3 automated diffractometer with $Cu_{K\alpha}$ – radiation and β-filter. Conditions for obtaining diffraction patterns: $U = 35$ kV; $I = 20$ mA; surveying θ-2θ; detector 2 deg/min. The X-ray diffraction analysis on a semi-quantitative basis is performed using diffraction patterns of powder samples using the equal weight method and artificial mixtures. The quantitative ratios of the crystalline phases are determined [25].

The interpretation of the diffraction patterns is carried out using the data of the ICDD card file: database of powder diffraction patterns PDF2 (Powder Diffraction File) and diffraction patterns of minerals free from impurities. The composition is calculated for the main phases.

2.5. Studies on the choice of chemical reagents

Based on the study of the mineralogical composition of ores and host rocks in the productive horizon and the analysis of the nature of the sedimentary formation origin, a complex of multifunctional chemical reagents is selected, which intensifies the processes occurring during borehole uranium mining in difficult mining-geological conditions. The effectiveness of a complex of chemical reagents is determined by its composition and is selected depending on the geological peculiarities of the productive horizon and the quantitative-qualitative characteristics of the sediments formed. The chemical reagents included in the complex have the dissolving ability of the main carbonate and secondary sedimentary formations, contribute to the active clay cake removal and the creation of additional water flows in the pore space of the seam, and also have a high oxidizing ability of Fe^{2+} to Fe^{3+} at high pH values to prevent repeated formation of sediments. Intensification of borehole uranium mining with the use of a complex of chemical reagents increases the speed of mining the technological blocks and reduces the cost of the final product.

Experiments on the treatment of sedimentary formations are carried out on samples from the Santonian, Campanian and Maastrichtian horizons with different composition of chemical reagents for decolmating solutions. To determine the effective composition of the solution, the most dissolving properties are selected. For example, experiment No. 1 includes treatment with a solution of hydrofluoric acid (10% by weight) and process water (90%). Experiment No. 2 includes treatment with a solution of hydrofluoric acid (5.0%) and sulphuric acid (10%), surfactant (1%) and process water (84%). Table 1 shows the parameters of decolmating solutions for laboratory studies.

Table 1. Parameters of decolmating solutions

Composition	Hydrofluoric acid (HF), %	Sulphuric acid (H_2SO_4), %	Amidosulfonic acid, %
Experiment 1	10	–	–
Experiment 2	5	10	1

In Experiment 1, the decolmating solution HF (10%) is prepared from process water (90%) and hydrofluoric acid half-finished product. The choice of a half-finished product of hydrofluoric acid is conditioned by its low cost, high reactivity with gypsum, aluminosilicates and siliceous compounds, which are an integral part of ore-bearing rocks and colmation sediments. In Experiment 2, the decolmating solution is prepared on the basis of ammonium bifluoride, sulphuric acid and surfactants at the ratios of HF – 5%, H_2SO_4 – 10%, surfactant – 1%, process water – 84%. The addition of a surfactant provides an increase in the hydrofluoric acid interaction with sediment-forming minerals. In this case, hydrofluoric acid is completely utilized due to the large amount of quartz contained in the sands. Interaction reactions proceed by the formulas:

$$CaSO_4 \cdot 2\,H_2\,O + 2HF = CaF_2 + H_2\,SO_4 + 2H_2O; \tag{1}$$

$$CaAl_2SiO_8 + 16HF = 2AlF_3 + 2SiF_4 + 8H_2O + CaF_2; \tag{2}$$

$$6HF + SiO_2 = SiF_4 + 2\,HF + 2H_2\,O. \tag{3}$$

The choice of sulphuric acid as a reagent-solvent is conditioned by the reactivity with aluminum oxide, iron hydroxide and potassium hydroxide, low cost and availability at mining enterprises. Interaction reactions proceed by the Formula:

$$Al_2O_3 + H_2SO_4 = Al_2(SO_4)_3 \downarrow + H_2O. \quad (4)$$

After performing laboratory experiments with samples treated by the drop method with decolmating solutions of various compositions, sedimentary formations are dried at room temperature. For a detailed study of the sample surface, a scanning electron microscope is used. Comparative analysis of images treated with one or another solution, as well as its comparison with the initial image, makes it possible to visually determine the decolmating solution composition effectiveness.

The images of the sediment surface before and after treatment with various solutions are fixed using a high-resolution analytical scanning electron microscope. It has been produced for a wide range of research tasks and quality control at the submicron level Tescan MIRA 3 FEG-SEM. The SEM TESCAN MIRA electron column and electron source: field emission cathode of the Schottky type. The range of electron-beam energy incident on the sample is from 200 eV to 30 keV (from 50 eV with BDT beam deceleration option). To change the beam current, an electromagnetic lens is used as a device for changing the apertures. Beam current from 2 pA to 400 pA is continuously adjustable. The maximum field of view is more than 8 mm at WD = 10 mm, more than 50 mm at maximum WD. Electron column resolution, high vacuum mode is 1.2 nm at 30 keV, SE detector 3.5 nm at 1 keV, In-Beam SE detector 1.8 nm at 1 keV, BDT beam deceleration option.

3. Results and discussion

In accordance with the methodology given in the previous section, this section presents the main scientific results. Table 2 presents the results of X-ray-graphical studies of core samples.

Table 2. Results of semi-quantitative X-ray phase analysis of core material samples

Mineral	Formula	Santonian horizon, %	Maastrichtian horizon, %	Campanian horizon, %
Quartz	SiO_2	90.8	54.7	66.3
Smectite	$KAl_2(AlSi_3O_{10})(OH)_2$	–	27.0	–
Potassium feldspars	$KAlSi_3O_8$	9.2	10.1	5.7
Kaolinite	$Al_2(Si_2O_5)(OH)_4$	–	6.7	11.6
Gypsum	–	–	–	16.4

The results of X-ray phase analysis of core samples from different ore intervals show the similarity of the mineralogical composition of the Santonian, Maastrichtian and Campanian horizons. However, the presence of various components of kaolinite 6.7% and smectite 27% in the Maastrichtian horizon sample indicates the formation of ion-exchange colmatation caused by swelling of clay minerals as a result of interaction with sulphuric acid solutions. The presence of 11.6% kaolin and 16.4% gypsum in the Campanian horizon core sample indicates the formation of hardly soluble gypsum sedimentary formations and kaolinite swelling. The presence of impermeable areas in the productive horizon leads to a change in the flow of leaching solutions through barren areas and a decrease in the uranium content in the productive solution and, as a result, a slowdown in the uranium recovery from the bowels. Figure 3 shows the surfaces of processed core samples from Santonian, Maastrichtian and Campanian horizons.

(a)

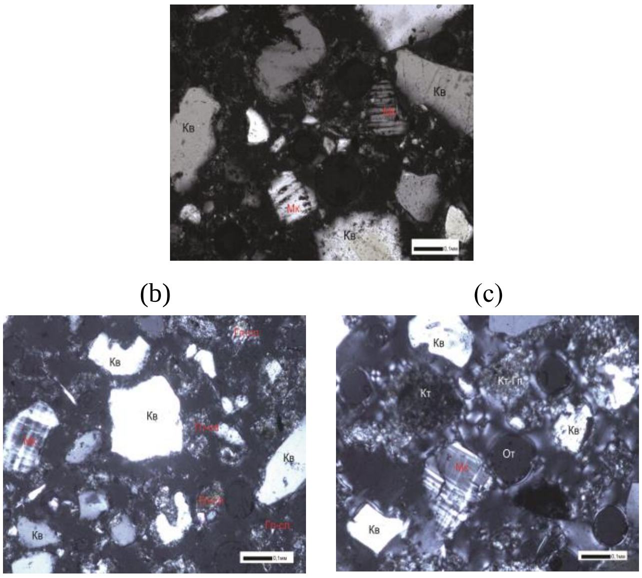


Figure 3. Images of the core material sample surface at 100% magnification from (a) Santonian; (b) Maastrichtian; (c) Campanian horizons

The Santonian horizon sample material (a) is externally light with a slight grayish shade. In the transparent section plane, in the sample composition, the following minerals are identified: quartz, potassium feldspars and cryptocrystalline rocks. Quartz is represented by irregularly-shaped, acute-angled, rounded grains, up to 0.2-0.3 mm in size. Microcline is transparent with a characteristic microcline lattice. Orthoclase is highly pelitized, opaque, brown in color, which is clearly visible both on the thin section and on the immersion sample. The refractive indices are tested in an immersion liquid with a refractive index of 1.525, which corresponds to that of standard potassium feldspars. The rock fragments are fine-grained, cryptocrystalline, transparent or semi-transparent, clouded, pelitized, with quartz and feldspar in composition.

The Maastrichtian horizon sample material (b) is externally similar to sample (a). In the transparent section plane, in the sample composition, the following minerals are identified: quartz, potassium feldspars, cryptocrystalline siliceous, clay-micaceous and K-spar rocks. Quartz is represented by irregularly-shaped, acute-angled, rounded grains, up to 0.2-0.4 mm in size. Microcline is transparent with a characteristic microcline lattice. Orthoclase is highly pelitized, semi-transparent, often opaque, and brown. The refractive indices in the immersion liquid are about 1.525 and below. The rock fragments are fine-grained, cryptocrystalline, transparent or clouded, pelitized, in composition – quartz, feldspar and clayey.

The Campanian horizon sample material (b) is externally similar to samples (a) and (b). It is seen under the microscope that transparent section contains quartz, potassium feldspars – microcline and orthoclase, kaolinite, fine-grained kaolinite aggregates with gypsum. The composition is confirmed in the immersion samples. Quartz is represented by irregularly-shaped, acute-angled, rounded grains, up to 0.2-0.3 mm in size. Microcline is transparent with a characteristic microcline lattice. Orthoclase is highly pelitized, semi-transparent and opaque, brown. By refractive indices determined in immersion liquids, they correspond to standard minerals. Aggregates of kaolinite and gypsum are fine-grained, cryptocrystalline, difficult to diagnose, clouded, pelitized.

Based on the comparative analysis results of core samples from various ore intervals, it can be concluded that the electron microscope images of the Santonian horizon core sample are homogeneous, including quartz with a size of 0.2-0.3 mm and microcline. Electron microscope images of the Maastrichtian horizon core samples show inhomogeneity, that is, along with quartz 0.2-0.4 mm in size, there is a microcline and, in some places, clay-micaceous minerals. The images of the Campanian horizon core samples show the presence of quartz of smaller sizes 0.2-0.3 mm and a number of minerals, including microcline, orthoclase, kaolinite, concentrating everywhere kaolinite and gypsum aggregate. Figure 4 shows the thermal analysis results of core samples from Santonian, Maastrichtian and Campanian horizons (°C).

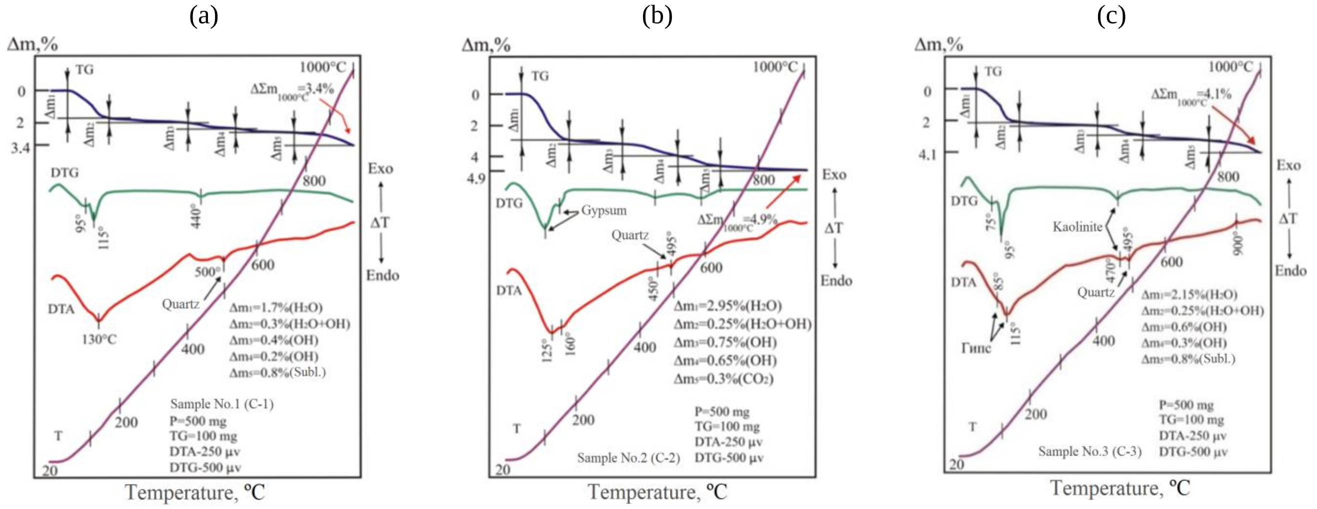


Figure 4. Derivatogram of core samples from (a) Santonian; (b) Maastrichtian; (c) Campanian horizons

Within the used hardware capabilities, the thermal curves of the tested system make it possible to reveal the peculiarities of behavior of the sample components under conditions of its gradient heating in the range of 20-1000°C.

A core sample from the Santonian horizon during dynamic heating gives the manifestations of predominantly endothermic origin on the DTA and DTG-curves (DTA-curve peaks at 130, 500 and 600°C) in Figure 4a. The temperatures of the formation of these thermal effects and their intensity are typical for the thermal destruction of calcium anhydride and clay minerals; a clearly observed peak at 500°C indicates the presence of quartz in the sample. The indicated manifestation is caused by a polymorphic transition of this silicon dioxide from α state to β state (Table 3).

Table 3. Mineral and material composition of core samples according to thermal analysis data

Mineral	Santonian horizon, %	Maastrichtian horizon, %	Campanian horizon, %
Quartz	80	70	70
Smectite	4.6	15.2	10.3
Kaolinite	1.5	2.8	4.3
Gypsum	5.4	2.4	5.4
Potassium feldspars	≤ 10	10	10

The presence of gypsum in the composition of the sample is detected based on the presence of two peaks on the DTG-curve at 95 and 115°C, indicating the development of two dehydration stages of the diagnosed anhydride. Emissions of H_2O into the atmosphere occur together with the dehydration of the sample clay component – smectite, which loses only a third of water in this temperature range. Proceeding from this, the proportion of water ejected by gypsum accounts for $\Delta m_1 \cdot 2/3 = 1.13\%$ of the sample mass. Given the stoichiometric formula $Ca[SO_4] \cdot 2H_2O$, the gypsum content in the sample corresponds to 5.4% (Table 4).

Smectite and kaolinite are identified as clay minerals in the sample composition. According to thermogravimetric data, the amount of smectite corresponds to 4.6% (relative to the sample mass) and kaolinite is 1.5%. According to the results of determining the intensity of the endothermic reaction occurring in the sample at 500°C and according to the residual principle of calculating the system mineral content, the proportion of quartz in the rock composition corresponds to ~80% of the total sample mass. The amount of thermally inert substances in the sample that have not reacted in any way to forced calcination is < 10%. The content of this rock share is also calculated according to the residual principle of diagnostics. Control X-ray phase analysis measurements refer these substances to potassium feldspars.

The Maastrichtian horizon core sample is similar in a number of thermal parameters to the Santonian horizon core sample, but differs from it in a slightly higher intensity of destruction of hydrate-bearing minerals (Fig. 4b). According to the morphologies of thermal curves, these minerals should include all the same impurities that have been found in the Santonian horizon core sample, such as smectite, kaolinite and gypsum. As a result of heating, these inclusions leave on the thermogravimetric curve the corresponding weight loss steps – 3.65, 0.75 and 2.4%. Based on these data, the presence of 15.2% smectite, 2.8% kaolinite and 2.4% gypsum has been determined in the sample (Table 2). The rest of the sample is composed of quartz (~70%) and thermally inert minerals (~10%), which include potassium feldspar.

During dynamic heating, the Campanian horizon core sample leaves on its curves manifestations similar in their properties to those produced by the Maastrichtian horizon sample (Fig. 4c). In particular, a thermal reaction of two-stage dehydration of calcium anhydride in the range of 20-155°C has been detected, and a series of endothermic effects caused by the kaolinite and smectite destruction at higher temperatures has been revealed. The general mineralogical composition determined in the sample is included in Table 2.

Based on the thermal analysis results of core samples from different ore horizons, it can be seen that the mineral composition of the samples is similar to each other, the quartz content varies within 70-80%, and potassium feldspar is within 10-11%. However, at first glance, it has insignificant differences in the content of kaolinite 1.8-2.8-4.3% and gypsum 5.4-2.4-10.3%, which largely determine the efficiency of sulphuric acid leaching of uranium. The presence of more than 10% gypsum indicates the formation of chemical-mechanical sediments in the productive horizon, which confirms the difficulty of restoring permeability and the need for an integrated or combined approach. Tables 4-6 show the thermogravimetric analysis parameters of samples from the Santonian, Maastrichtian and Campanian horizons.

Table 4. Thermogravimetric analysis parameters of core sample from the Santonian horizon within 20-1000°C

Weight loss sequence	Amount of weight lost, %	Volatile components removed from the system	Temperature range of the system decomposition stage, °C
Δm_1	1.7	H_2O	20-160
Δm_2	0.3	OH	160-400
Δm_3	0.4	OH	400-530
Δm_4	0.2	OH	530-750
Δm_5	0.8	Sublimation	750-1000
$\sum \Delta m_{1000°C}$	3.4	H_2O + OH + + Sublimation	20-1000

Table 5. Thermogravimetric analysis parameters of core sample from the Maastrichtian horizon within 20-1000°C

Weight loss sequence	Amount of weight lost, %	Volatile components removed from the system	Temperature range of the system decomposition stage, °C
Δm_1	2.95	H_2O	20-175
Δm_2	0.25	OH	175-345
Δm_3	0.75	OH	345-515
Δm_4	0.65	OH	515-650
Δm_5	0.30	OH	650-1000
$\sum \Delta m_{1000°C}$	3.4	H_2O + OH	20-1000

Table 6. Thermogravimetric analysis parameters of core sample from the Campanian horizon within 20-1000°C

Weight loss sequence	Amount of weight lost, %	Volatile components removed from the system	Temperature range of the system decomposition stage, °C
Δm_1	2.15	H_2O	20-155
Δm_2	0.25	H_2O + OH	155-400
Δm_3	0.60	OH	400-530
Δm_4	0.30	OH	530-750
Δm_5	0.80	Sublimation	750-1000
$\sum \Delta m_{1000°C}$	4.10	H_2O + OH + + Sublimation	20-1000

Figure 5 shows the images of sedimentary formations during borehole uranium mining in Santonian, Maastrichtian and Campanian horizons.

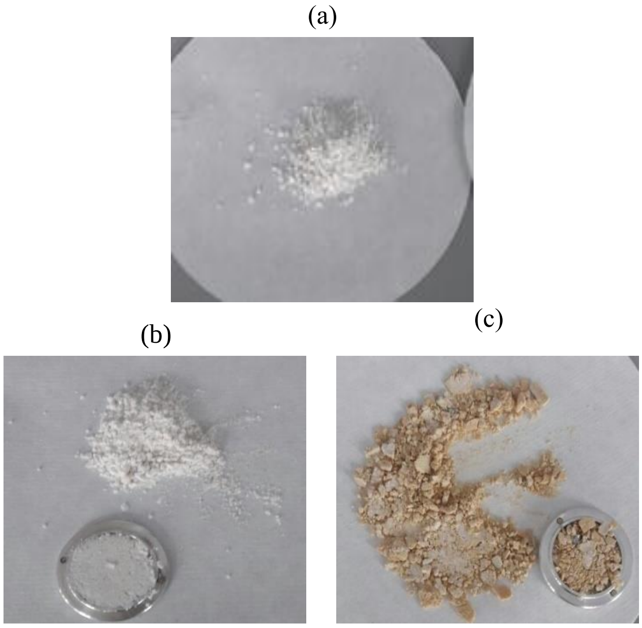


Figure 5. Images of sedimentary formation samples from boreholes of (a) Santonian; (b) Maastrichtian; (c) Campanian horizons

The results of X-ray phase analysis of sedimentary formations of samples from boreholes in the Santonian and Maastrichtian horizons indicate that the sediments are one-component and consist of 100% gypsum, a product of chemical origin. The samples of sedimentary formations from the Campanian horizon boreholes show that the sediments are multicomponent and have a complex structure. The presence of silicon in the amount of 35.6%, albetite 33.9%, microcline 4.9% confirms the predominance of the mechanical type of colmatation. At the same time, the presence of gypsum 16.7% and calcite 8.9% indicates the presence of sediments of chemical origin. Table 7 shows the results of semi-quantitative X-ray phase analysis of sedimentary formation samples.

Table 7. Results of semi-quantitative X-ray phase analysis of crystalline phases of sedimentary formation samples

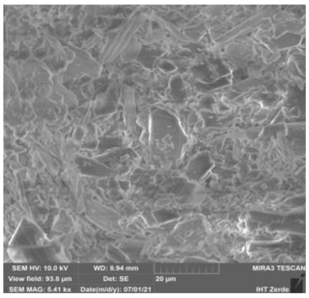
Mineral	Formula	Santonian horizon, %	Maastrichtian horizon, %	Campanian horizon, %
Quartz	SiO_2	–	–	35.6
Gypsum	$Ca(SO_4)(H_2O)_2$	100	100	16.7
Calcite	$Ca(CO_3)$	–	–	8.9
Albite	$(Na_{0.75}Ca_{0.25})(Al_{1.26}Si_{2.74}O_8)$	–	–	33.9
Microcline	$(K_{0.95}Na_{0.5})AlSi_3O_8$	–	–	4.9

The results of X-ray phase analysis of sedimentary formations indicate that in the Campanian horizon boreholes, compared to the Santonian and Maastrichtian horizons, colmatation consists of many components and has a complex structure. In the Campanian ore horizon, the mechanical type of sediments predominates, while in the Santonian and Maastrichtian horizons, sedimentary formations are entirely of chemical origin.

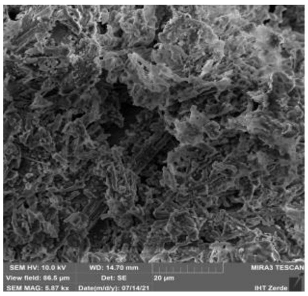
Based on the research results, quantitative-qualitative characteristics of sedimentary formations from technological boreholes have been determined, revealing various levels in the productive horizon. It has been revealed that the sedimentary formations in the Campanian ore horizon boreholes have a multicomponent composition, which is a mixture of sediments of mechanical-chemical origin. It is difficult to eliminate such sedimentary formations and improve the productive horizon filtration characteristics in order to intensify the processes of underground leaching, which requires an integrated approach with a combination of hydrodynamic and reagent methods.

Figure 6 shows images of sedimentary formation samples from the Maastricht horizon of the Syr Darya depression before and after treatment with special solutions.

(a)



(b)



(c)

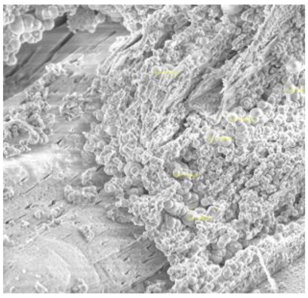
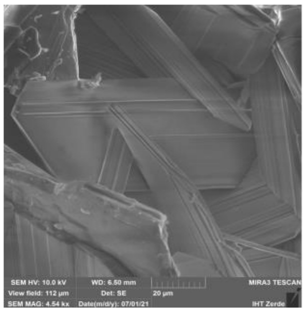


Figure 6. ***Images of sample surfaces from the Maastrichtian horizon: (a) initial sample; (b) Experiment 1 sample; (c) Experiment 2 sample***

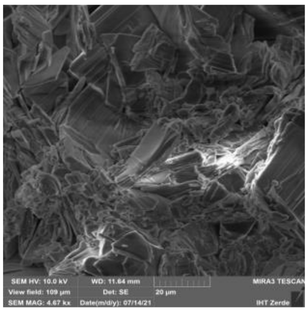
It can be seen from Figure 6a that the initial sample surface is formed by dense lamellar crystals ranging in size from 5 to 20 μm with a characteristic frame structure without ruptures and fractures in the body. The shapes of crystals are elongated with a chaotic arrangement and a uniform surface relief. It can be seen from Figure 6b that after treatment with decolmating solution 1, a noticeable destruction of the structure and a change in the shape of the crystals occur, which is accompanied by a decrease in their sizes and density with the formation of fine loosened flakes. The crystals are arranged less densely with the formation of voids and washouts in the pore space. Partial dissolution of the sample is noticeable and the size of the crystals decreases significantly from 20 to 5 μm. This is caused by the dissolution of a portion of the sample in hydrofluoric acid. It can be seen from Figure 6c, presenting the Experiment 2 data, that the change in the sample structure is similar to the previous experiment with a more obvious character. In addition, the dissolution of sedimentary formation by decolmating solution is noticeable, as well as the formation of washouts and a large fractures along the flow of the solution. Deformed forms of crystals with changed shapes and structure, the sizes of the voids are larger compared to Experiment 1. This is conditioned by the dissolution of sediments in hydrofluoric and sulphuric acids, as well as the action of surfactants.

Figure 7 presents the images of sedimentary formation samples from the Campanian horizon of the Syr Darya depression before and after treatment with special solutions.

(a)



(b)



(c)

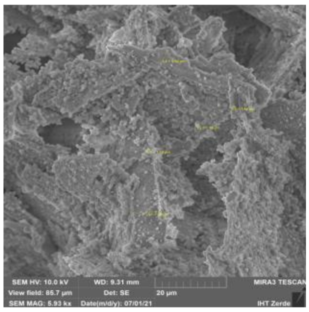


Figure 7. ***Images of sample surfaces from the Campanian horizon: (a) initial sample; (b) Experiment 1 sample; (c) Experiment 2 sample***

It can be seen from Figure 7a that the initial sample surface is formed by dense crystals ranging in size from 20 to 40 μm with a characteristic frame structure without ruptures and fractures in the body. The shapes of crystals are rectangular with a chaotic arrangement and a uniform surface relief. It can be seen from Figure 7b that after treatment with decolmating Solution 1, the structure is destroyed and the shape of the crystals changes, which is accompanied by a decrease in their sizes and formation of fine loosened flakes. The formation of washouts and fractures in the sample body is observed. Partial dissolution of the sample is noticeable and the sizes of the crystals decrease significantly from 40 to 20 μm. These significant changes are caused by the dissolution of sediments by hydrofluoric acid. It can be seen from Figure 7c, presenting the Experiment 2 data, that the sample structure changes more significantly, with a noticeable formation of many deep washouts and fractures along the flow of the solution. Deformed rounded shapes of crystals are noteworthy. Destruction is conditioned by the dissolution of sediments in hydrofluoric and sulphuric acids, and penetration is caused by the action of surfactants.

The decolmating solution should be applied according to a special method using special technological equipment. The innovative method provides for the treatment of the borehole filter zone with a decolmating solution, as well as the prevention of the seam from sedimentation with its maximum destruction. The method provides an increase in the productivity of producing blocks and the completeness of metal recovery from them, due to the removal and prevention of sedimentary formation in a porous medium. In addition, a reduction is achieved in the specific consumption of sulphuric acid, electricity, labor costs and other production costs in the process of borehole uranium mining from various mining-geological blocks.

Figure 8 presents the scheme developed by the authors for intensifying borehole uranium mining.

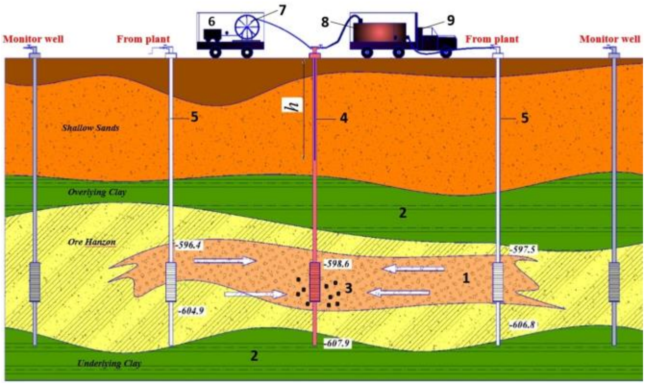


Figure 8. ***Scheme for intensifying the borehole uranium mining: 1 – productive horizon; 2 – impermeable rocks; 3 – sedimentary formations in the BHZ (bottom-hole zone) of the seam; 4 – extraction borehole; 5 – injection borehole; 6 – compressor; 7 – hoisting gear with pressure hose; 8 – container-tank; 9 – transport base***

As can be seen from Figure 8, the bulk of sedimentary formations *3* occur in the productive horizon *1*, directly in the zone of solution discharge and increasing velocity of solution movement from injection boreholes *5* to extraction boreholes *4*. When performing chemical treatment using a complex of chemical reagents, it is possible to provide for the preparation of solutions on special equipment (compressor) *6*, and supply through the pressure hose *7* to the filter zone of the extraction boreholes *4*. In this case, the prepared special solution is supplied from the container of a tank *8* by the transfer pump (transport base) *9*. The supply of decolmating solutions based on 5% hydrofluoric acid, 10% sulphuric acid and 1% surfactant additive directly to the filter zone of technological boreholes reduces the consumption of chemical reagents and increases the penetrating ability for greater destruction and dispersion of sediments.

The calculated area of solutions spreading from the filter through the productive horizon is determined by the Formula:

$$S = \frac{Q_D}{0.22h}, \tag{5}$$

where:

Q_D – volume of decolmating solutions supplied to the borehole, m^3;

0.22 – average porosity coefficient of host rocks in the productive horizon.

The radius of spreading decolmating solutions is determined by the Formula:

$$R = \left(\frac{S}{\pi}\right)^{1/2}. \tag{6}$$

Equipment for the preparation and supply of solutions of chemical reagents consists of a container and a pump, which are made of corrosion-resistant material. This is conditioned by the fact that they contact with sulphuric and hydrofluoric acids.

Upon completion of chemical treatment, it is necessary to conduct airlift pumping of boreholes to remove and bring to the daylight surface the reaction products of interacting chemical reagents and sedimentary formations. The immersion value of the air hose *H* for airlift pumping and removal of the reaction products from the chemical interaction of hydrofluoric acid with sedimentary formations is calculated depending on the static level of process waters by the Formula:

$$H = h \cdot 2.25, \tag{7}$$

where:

h – static process water level;

2.25 – coefficient of the hose immersion to the depth from the static level. With an increase in the depth of the pressure hose immersion into the borehole, the treatment efficiency increases.

The use of this combined technology for borehole uranium mining intensification in particularly difficult mining-geological conditions makes it possible to restore the filtration characteristics of borehole uranium mining and prevent sedimentary formations in a porous medium. This makes it possible to increase the flow rate and the period of uninterrupted operation of technological boreholes, reduce labor costs and other operating costs for production during borehole uranium mining.

When conducting further research on improving the dissolution efficiency and preventing sedimentary formation in the productive horizon under various conditions using physical-chemical methods of influence, it is possible to reduce the cost of finished products and increase labor productivity.

4. Conclusions

For a quantitative-qualitative study of the composition of samples, core material has been taken from the productive Santonian, Maastrichtian, and Campanian ore intervals of the Syr Darya uranium depression. The X-ray phase analysis results show the predominance of quartz 90.8% and the presence of potassium feldspars 9.2% in the Santonian ore interval. It has been determined that in the Maastrichtian horizon, the content of quartz is 54.7%, the presence of smectite is 27.0%, potassium feldspar is 10.1%, and kaolinite is 6.7%. In the Campanian horizon, the content of quartz is 66.3%, the presence of potassium feldspar is 5.7%, kaolinite is 11.6%, and the presence of gypsum is 16.4%.

The results of microscopic analysis of core samples clearly show the grain sizes of crystals and other minerals of the host rocks in the productive horizon. Data analysis allows determining the reasons for the decrease in the filtration characteristics of ores. These samples from the Santonian horizon indicate the presence of fragments of quartz grains of irregular, acute-angled and rounded shapes, on average, up to 0.2-0.3 mm in size, transparent microcline and pelitized orthoclase. The results of the sample analysis from the Maastrichtian horizon indicate the presence of irregularly-shaped fragments of quartz grains with sizes up to 0.2-0.4 mm, the presence of potassium feldspars and clay-micaceous minerals. The Campanian horizon core samples contain fragments of irregularly-shaped quartz grains with an average size of up to 0.2-0.3 mm, the presence of potassium feldspars, microcline, orthoclase, kaolinite, and fine-grained aggregates of kaolinite with gypsum. The presence of fine-grained particles reduces the filtration characteristics of ores and increases the block mining period.

The study and analysis of data on the thermal behavior of sample powders from the Santonian, Maastrichtian and Campanian ore horizons make it possible to determine the quantitative-qualitative characteristics of the samples and confirm the data of X-ray phase and microscopic studies. Analysis of the results of thermal studies of samples shows that the samples are similar in their composition. However, the presence of a greater amount of the mineral smectite (15.2%) and (10.3%), kaolinite (2.8%) and (4.3%), as well as gypsum (2.4%) and (5.4%) in the samples of the Maastrichtian and Campanian horizons confirms the difficulty in the uranium mining, caused by a decrease in filtration characteristics. The minerals of kaolinite, smectite and gypsum, interacting with sulphuric acid solutions, partially swell and form impermeable areas, thereby changing the direction of the flow of technological solutions and reducing the uranium content in the productive solution.

The sedimentary formation samples have been taken from operating technological boreholes penetrating the Santonian, Maastrichtian and Campanian ore horizons. Quantitative-qualitative characteristics and the compositions of sediment-forming materials have been determined. The results of X-ray phase analysis of a sample from the Campanian horizon borehole show that the sediments are multicomponent and have a complex structure. The presence of silicon in the amount of 35.6%, albetite 33.9%, microcline 4.9% confirms the predominance of the mechanical type of colmatation. At the same time, the presence of gypsum 16.7% and calcite 8.9% indicates the chemical type of sedimentary formation origin.

Conducted laboratory experiments on the treatment of sedimentary formation samples, followed by a comparative analysis of microscopic analysis of samples, confirm the effectiveness of the selected chemical reagents. The decolmating solution is prepared on the basis of hydrofluoric acid (5%), sulphuric acid (10%) and surfactants in small amounts, which makes it possible to increase the dissolving ability of the decolmating solution and prevent sedimentary formation in the seam for a longer time.

The developed scheme for restoring the filtration characteristics of a productive horizon based on the treatment of the filter zone of boreholes makes it possible to reduce the specific consumption of chemical reagents and increase the efficiency of the decolmating solution.

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Підбір раціональних параметрів відновлення фільтраційних характеристик руд свердловинної розробки родовищ урану

Ж. Кенжетаєв, К. Тогізов, М. Абдраімова, М. Нурбекова

Мета. Підвищення ефективності свердловинного видобутку урану за рахунок підбору спеціальних декольматуючих розчинів і вибору раціональних параметрів технології впливу на прифільтрову зону пласта геотехнологічних свердловин, підвищення фільтраційних характеристик пласта залежно від мінералогічного складу руд і структури осадоутворюючих матеріалів.

Методика. Порошки були досліджені рентгенофазовим аналізом. Мікроскопічні дослідження проб кернового матеріалу проводилися на прозорих шліфах під мікроскопом марки LEICA DM 2500 P. Вміст елементного складу руд і вміщуючих порід проб продуктивного горизонту контролювався на атомно емісійному спектрометрі.

Результати. В результаті досліджень були встановлені кількісно-якісні характеристики вміщуючих порід продуктивного горизонту, осадоутворень з технологічних свердловин, що розкривають різні яруси продуктивного горизонту. Виявлено, що на свердловинах Кампанського рудного інтервалу руди мають складну структуру, а осадоутворення багатокомпонентні, що представляють суміш опадів механічного та хімічного походження.

Наукова новизна. Вивчено та проаналізовано результати кількісно-якісних, мікроскопічних, термічних методів досліджень характеристик рудовміщуючих порід різних горизонтів родовища урану Сирдар'їнської депресії. Також було відібрано проби та вивчено осадоутворення технологічних свердловин продуктивних горизонтів "Сантон", "Маастріхт", "Кампан" родовища "Північний Харасан" Сирдар'їнської депресії. Мікроскопічним методом дослідження обґрунтовано підбір найбільш відповідного складу хімічних реагентів для розчинення та запобігання осадоутворенню в пористих середовищах.

Практична значимість. Детальне вивчення та порівняльний аналіз характеристик руд і вміщуючих порід різних продуктивних горизонтів дозволить проектувати відпрацювання блоків точніше та мінімізувати ризики, що виникають. Застосування розробленої комбінованої технології інтенсифікації свердловинного видобутку урану дозволяє підвищити ефективність свердловинного видобутку урану та скоротити експлуатаційні витрати на видобуток. При цьому підвищується екологічна та виробнича безпека робіт інтенсифікації вилуговування уранових руд.

Ключові слова: *уран, свердловинний уран, видобуток, осадоутворення, рентгенофозовий аналіз, декольмація, термічний аналіз, вилуговування урану*