

Comparison of the Geochemical Features of Ore-Bearing Horizons at Young and Ancient Hydrogenic Uranium Deposits (Hydrotechnological Aspects)

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Abstract—Geochemical properties of ore-bearing horizons composed of alluvial aluminosilicate terrigenous rocks have been compared at young and ancient hydrogenic uranium deposits. It has been shown that the lithological setting at the young deposit has an elevated neutralization capacity in relation to sulfuric acid of leaching solutions and, in addition, has a rather low reducing capacity. The redox differentiation of ore substance at the deposit is in progress. It ensures an elevated degree of uranium oxidation in ores. Both ore and nonore sandy rocks contain a sufficient amount of natural oxidizer U(IV) in the form of trivalent iron. Ancient deposits, unlike young ones, contain ore-bearing and ore-hosting rocks with a low neutralizing but high reducing capacity and with an elevated degree of uranium and iron reducing, as the reducing environment dominates in all epigenetic geochemical zones. It is suggested that, in this geochemical setting, the process of in situ leaching (ISL) is not effective without addition of artificial oxidizer to the working sulfuric acid solutions.

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INTRODUCTION

Among the methods of uranium ore development, the most profitable and ecologically safe is the in situ leaching (ISL) method (*In situ...*, 1998). The method has been most widely applied for exploring young (Neogene–Quaternary) infiltration stratal uranium deposits (Maksimova and Shmariovich, 1993), often called hydrogenic deposits (*Hydrogenic...*, 1980; Kislyakov and Shchetochkin, 2000), which formed U ore megaprovinces in Central Asia. In Russia, economic uranium deposits of this genetic type are less abundant, and, moreover, they are not lithological–geochemical analogues of those in Central Asia. More similar to young infiltration stratal ore occurrences are ancient (Late Jurassic–Early Cretaceous) hydrogenic deposits, formed by infiltration water at margins of ancient zones of ground stratal oxidation and situated in the Ural region (Khalezov *et al.*, 1982, 1983; Kondrat'eva and Nesterova, 1997; Khalezov, 2003; Konoplev *et al.*, 2004). They are represented by the Dalmatovsk, Khokhlovsk, Dobrovol'noe, and Tobol'sk deposits, located within the West Siberian uranium ore province.

Young and ancient hydrogenic uranium deposits have many features in common that help to determine whether deposits can be mined using the ISL method. They are (1) confinement of ores to loose substantially sandy rocks of aquifers within slopes of artesian basins;

(2) control of ore mineralization by wedging out of areas of young or ancient stratal oxidation zones; (3) formation of U ore mineralization at the reducing geochemical barrier; (4) superposition (epigenesis) of ore mineralization with respect to the enclosing terrigenous lithological environment; (5) a fine-dispersed nature of black ores, uraninite, and coffinite–uraninite ores; (6) low-grade ores (commonly, the U content in ores is 0.0*n*–0.*n* wt %); (7) in most cases, separation of ore-bearing horizons, at the top and bottom, from adjacent aquifer systems by solution-proof sandstones, siltstones, and clays; (8) a thickness of the ore-saturated zone in the section in most cases smaller than the total thickness of permeable rocks in ore-bearing horizons; and (9) predominance of a moderate geothermal environment (*T* 15–25 or, more rarely, up to 45°C) in ore-bearing horizons at present.

However, there are substantial differences between these deposits, variably influencing the dynamics and duration of uranium extraction from ores by H₂SO₄ solutions. In applying in situ sulfuric acid leaching to develop ancient deposits, these parameters are two to five times less effective than when the method is used for developing young ores. To clarify the causes of this phenomenon, a comparison of the main lithological–geochemical features of deposits belonging to these genetic types was carried out using the Bukinai deposit (sometimes referred to in the literature as the Northern Bukinai) in the Kyzyl Kum as an example of a young deposit and the Dalmatovsk deposit in the Ural region as an old deposit.

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METHODS OF COMPARATIVE ANALYSIS

For effective U output from ores by the conventional (in the Commonwealth of Independent States) in situ sulfuric acid leaching method, an appropriate pH–Eh technogenic setting should be created in the ore-bearing horizon, favorable for U output in keeping with the external diffusion mechanism. In this case, the process of U mineral dissolution is restricted by the rate of reagent supply to their surface and withdrawal of the product of reaction, i.e., dissolved uranium. Thus, an ideal process for ISL is one during which the dynamics of uranium extraction from ores is restricted by the speed of the flow of leaching solutions. To ensure such a process in the horizon, the necessary and sufficient acid–alkaline and redox conditions should be provided.

Ideally, oxide ore mineralization in deposits is represented by two U valent forms, U(IV) and U(VI), differing in the capacity to dissolve in H₂SO₄ diluted solutions (commonly 10–25 g/l): an adequate amount of the oxidizer is needed for complete U(IV) oxidization, while U(VI) is easily dissolved in H₂SO₄ solutions in every instance. Commonly, a natural oxidizer for oxide U ores at young deposits is Fe(III), which is involved in the process in minor amounts from gray-colored rocks of the saccate part of the orebody and, in abundant quantities, from yellow and red sands of the stratal oxidation zone, which occurs between the flanks of the ore roll. Our experience suggests that the above-indicated amount of natural oxidizer at young deposits, ore-bearing horizons of which are under the influence of active water exchange, is usually sufficient for complete oxidation of U(IV) in the oxides forming ores. This is why artificial oxidizers are not used for U ISL. In this case, a necessary redox condition is an increase in the oxidation potential with respect to the background potential in natural underground waters of –210 to +150 mV (pH about 7.5) to values of greater than +500 to +550 mV (pH 1.0–2.0). To promote the process of oxidizing–acid dissolution, pH values should be reduced from natural values that are close to neutral to technogenic, below 2, which ensures suppression of hydrolysis of U(VI) and Fe(III).

This general scheme of ideal ISL becomes much more complicated if ores contain appreciable amounts of difficultly soluble silicates and titanates of U(IV); more acid solutions are needed for their decomposition, and even if a sufficient quantity of the oxidizing agent is available, their dissolution occurs according to a compound or kinetic mechanism. In this case, the hydrodynamic factor becomes less significant, while the factor of time of ore–solution contact becomes decisive.

This brief account of the acid–alkaline and redox conditions during ISL suggests that it depends on the following mineralogical and geochemical factors: (1) ore mineral composition; (2) reducing capacity of ore-bearing and ore-free gray-colored host rocks; (3) degree of U reduction and U(IV) percentage in ores; (4) the quantity of acid-dissolvable Fe(III) in ore-bearing

and ore-hosting rocks; (5) the neutralizing capacity; and (6) the pH–Eh setting in the ore-bearing horizon caused by the mentioned factors. These properties should be studied in the entire ore-bearing horizon, which will be under the influence of circulating leaching solutions during the mining of ore lodes.

A correlation of the main geochemical characteristics of ore-bearing horizons within the compared sites has been carried out for most of the indicated parameters.

Studies of sandy deposits in ore-bearing horizons were carried out on samples derived from freshly recovered drill cores of exploratory wells and planned operating wells.

The reducing capacity (RC) of the rocks directly affects the technogenic environment in the ore-bearing horizon within an ore lode under development, and it accounts for the consumption of natural and artificial oxidizing agents of U(IV). The RC, in turn, depends on the quantity of organic and inorganic reducing agents in the rock. RC is a property of rock, not of ore minerals, though a mineral is to some extent part of a rock. The full consumption of the oxidizer by a rock determines the complete RC. However, in practice, this parameter is only partly determined in conventional conditions, according to the time of contact between reagents and the oxidizer concentration, and the reaction is carried out in an acid medium with pH 0. The RC was determined by this method as milligrams of O₂ per gram of rock (Lisitsin, 1996), i.e., by the potentiometric titration of rock by K permanganate solution. This method is used to characterize the RC of rocks that is maintained by the content of organic matter and mobile Fe(II) of aluminosilicates and siderite in the acid; a significant part of sulfides are not oxidized by K permanganate (Solodov *et al.*, 1993).

The neutralizing capacity (NC) determines the acid consumption for U leaching and the time of pH decrease from nearly neutral values in natural underground waters to the required values of pH < 2. The NC was established by the titration of rock by a 10 N solution of H₂SO₄ using the pH stat technique (Solodov *et al.*, 1994, 2001). This technique is adequate to real in situ leaching, in which the acidity of leaching solutions near the entry to the ore-bearing horizon is maintained at a constant level. Experiments were carried out on noncrushed rocks for a period of 200–400 days until a steady state was attained, when fixed pH values (1, 2, 3) did not alter without addition of H₂SO₄. Incidentally, the duration of the experiments is comparable with the duration of in situ leaching; it allows one to obtain an NC value that is close to the value during commercial mining of ore lodes. The results of the NC are given in milligrams of H₂SO₄ per gram of rock. Values of this parameter for pH 1 (NC_{pH1}) are used for comparison.

To determine valent forms of uranium in ores, several methods are used: (1) direct identification of acid-soluble ΣU_{as} and U(IV)_{as} in 6 N HCl over an hour by the colorimetric method with the arsenazo III indicator at

room temperature (the Luk'yanov–Lisitsin method (Lisitsin, 1975)); (2) by the parameter of the crystalline lattice of *a* oxides according to x-ray analysis (Sidorenko, 1978); and (3) by the spectrum structure and power of connection among internal electrons using x-ray photoelectron spectroscopy (Teterin *et al.*, 1980). The results of determination of the ratio of U valent forms in ores by the indicated methods also depend upon uranium oxidation by washing liquid filtrate during core drilling with clay solution (Solodov *et al.*, 2005). It causes an increased content of its hexavalent form. In the latter two methods, analyzed samples are also oxidized during their storage and preparation for the analysis. This disadvantage is avoided in the Luk'yanov–Lisitsin method since from the moment the core is recovered from the core barrel, all operations are performed in an atmosphere of CO₂, i.e., a gas inert to the oxidizing agent. However, this method exhibits another disadvantage in determining the oxygen coefficient of uranium ores. It may be used for analyzing monomineral U oxide ores alone, as, during partial dissolving in 6 N HCl of polymineral ores containing U silicates and titanates, the U(IV) content might notably increase. Therefore, in interpreting the results, it is more appropriate to speak not about determining the oxidizing capacity of U oxides but about identifying the ratio of acid-soluble U valent forms in ores; the latter is a more important characteristic of ores from the point of view of their in situ leaching.

Parallel to determining acid-soluble U valent forms by the Luk'yanov–Lisitsin method, we were also involved in identifying acid-soluble (in 6 N HCl) valent forms of Fe in the same samples (ΣFe_{as} , $Fe(III)_{as}$) in ores and ore-free rocks at room temperature, in a CO₂ flow, using the colorimetric method with the α - α dipyriddy indicator. The content of Fe mobile valent forms obtained by this method does not quite correspond to their real amount in rocks that could be recovered after a long influence of diluted H₂SO₄ solution during ISL. However, a brief (about an hour) influence of strong 6 N HCl at *T* ~ 20°C on rocks is almost equivalent to the influence on them of diluted H₂SO₄ solutions (10–25 g/l).

The acid–alkaline index (pH) and oxidation potential (Eh) were measured by two methods: in water-saturated hermetically sealed pastes (hp) of noncrushed rocks (Lisitsin, 1967) and by the method of hydrogeochemical logging (is) (Solodov *et al.*, 2005).

A YOUNG HYDROGENIC DEPOSIT

The potential of the Tien Shan ore-forming system, which comprises ore lodes of the Bukinai deposit, was generated at the recent stage of tectonic activation (35–40 Ma) (Kislyakov and Shchetochkin, 2000), which reached its peak in the Neogene, and the ore-forming process in the region, which started ~20 Ma, is still in progress. Therefore, the Bukinai deposit is assigned to young hydrogenic deposits.

The deposit district under consideration is an area of Neogene–Quaternary block postplatform tectonic activation that turned a plain into a series of horst–anticlinal and graben–synclinal structures. In the recent relief, they correspond to mountainous rises and flat troughs. The former exhibit rocks of the folded basement and the latter show the presence of preserved non-lithified Mesozoic and Cenozoic deposits. Specific features of the ore-enclosing sedimentary cover are associated with the platform stage of the area's development. A bed of terrigenous deposits accumulated here in the Late Cretaceous and Paleogene time in plain rivers and shallow sea environments. The deposits are lithologically sustained, as the tectonic regime at that time was fairly stable. The Neogene and Quaternary, periods of high tectonic activity, are characterized by continental sediments with notable changes in the composition and thickness (Solodov and Kochkin, 1996).

The deposit is situated on the western periclinal end of the South Nuratinsk rise at the slope of the Karakatinsk depression. Ore lode 1, the main object of investigation, is localized in sandy deposits of the lower rhythm of plain alluvium (Coniacian to Santonian); it is situated between the Kokchinsk and South Muyunkumsk faults. A stratum of Turonian marine and continental deposits 70–80 m thick separates the lower rhythm of the horizon from sedimentary–metamorphic rocks (carbonaceous cherts, sandstones, limestones, and marbles) of the Paleozoic basement. Higher in the section, the lower rhythm gives way to sandy and clayey deposits of the alluvium upper rhythm, which terminates the Late Cretaceous section. These rocks are unconformably overlain by lagoonal carbonate Paleocene deposits replaced by Eocene marine clays. The sedimentary sequence completed by Neogene continental red-colored and variegated terrigenous rocks and Quaternary eolian sediments preserved only in lower parts of the area.

The lower rhythm of the horizon (hereinafter, the ore-bearing horizon) (Fig. 1) is isolated from the underlying aquiferous horizon in Turonian rocks and from the overlying upper rhythm by solutionproof layers of clays, siltstones, and claystones on carbonate cement 2–12 m thick. The base of the ore-bearing horizon within the ore lode occurs at a depth of 130–190 m. The average thickness of the horizon is 21 m.

Underground waters in the horizon are sulfate–chloride potassic–sodic, brackish (M 1.7 g/l), and close to neutral (pH_{is} 7.5). In the lode 1 area, they contain neither hydrogen sulfide nor oxygen. The content of sulfates in the underground waters is about 630 mg/l. The filtration regime is of the pressure type. When the gradient of the piezometric surface inclination is 0.005, the velocity of the underground water movement in the horizon is estimated at several meters per year.

By mineral composition, the deposits of the horizon are essentially sandy alluvial feldspar–quartz with a kaolinite–hydromica intergrain filling. The average

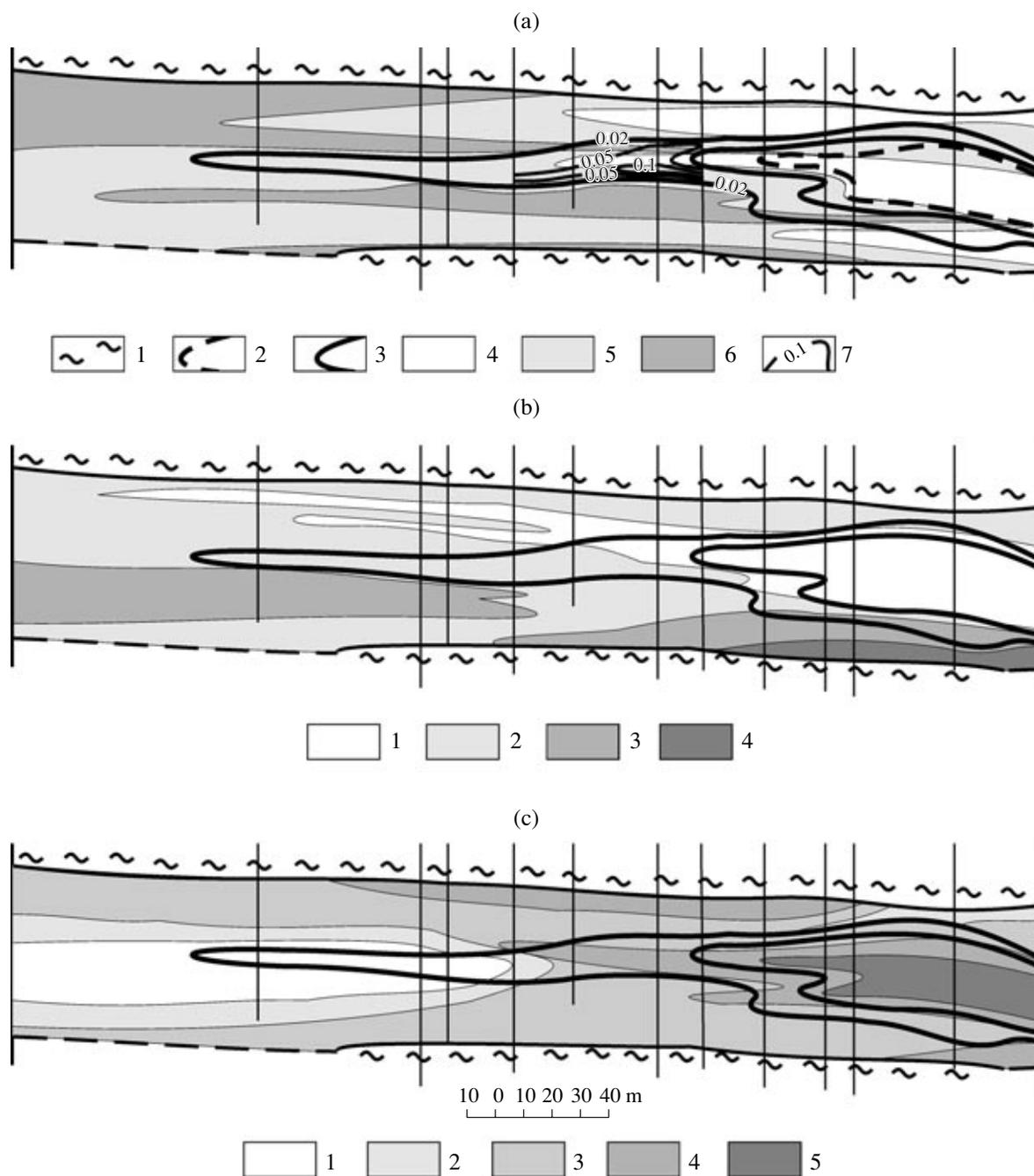


Fig. 1. Epigenetic geochemical zonation of a young hydrogenic deposit characterized by recent processes of oxidation of uranium ores, mobile iron, and dispersed organic matter in rocks. (a) U and C_{org} distribution in the rocks of the horizon: (1) solution-resistant clays, siltstones, and clay sandstones; (2) visually identified frontal boundary of the stratal oxidation zone (yellow sand is within the contour); (3) orebody contour (gray and dark gray sand is within the contour); (4–6) fields of C_{org} distribution (wt %): (4) <0.1, (5) 0.1–0.2, (6) 0.2–0.7; (7) isoline of U content (studied only in the central part of the orebody). (b) Distribution fields of the reducing capacity of sands (mg/g): (1) <0.1; (2) 0.1–0.5; (3) 0.5–1; (4) 1–10. (c) $Fe(III)_{as}$ percentage from summarized ΣFe_{as} : (1) <20; (2) 20–40; (3) 40–60; (4) 60–80; (5) >80.

content of base minerals in gray-colored ore-bearing rocks is as follows (wt %): quartz, 75; albite + orthoclase, 4.6; microcline + oligoclase, 6.3; biotite, 0.1; chlorite, 0.7; sericite, 0.6; muscovite, 1.2; rock fragments, 2.6; hydromica, 2; kaolinite, 1.5; leucoxene, iso-

lated grains; pyrite + marcasite, up to 2; melnikovite, 0.04; chalcopyrite and jordisite, isolated grains; uraninite, up to 1; native sulfur, up to 0.27; and apatite + monazite + xenotime, up to 0.5. Microprobe analysis carried out by L.N. Belova suggests that the ores are

monomineral and represented by nanosize finely dispersed uraninite segregations. Uranium sorbed on titanates is present in subordinate quantity.

By chemical composition, the sands of the horizon are aluminosilicate and acid (wt %): SiO₂, 70.1–83.0; Al, 7.4–12.5; Fe₂O₃, 1.18–2.45; FeO, 0.79–2.39; TiO₂, 0.20–0.78; MnO, 0.02–0.07; CaO, 0.22–3.26; MgO, 0.35–1.17; K₂O, 2.91–4.01; Na₂O, 0.95–1.64; P₂O₅, 0.03–0.09; and CO₂, 0.20–2.33.

According to lithological composition and filtration properties, the horizon has a three-layered structure. The lower level of fine-grained sands (7–11 m), which contains about 10 wt % aleuropelite, has the maximum value of the filtration coefficient (K_f), 5 m/24 h. These rocks contain tiny calcite crystals of dispersed carbonate minerals; carbonate CO₂ makes up on average 0.35 wt %. The low calcite content and relatively small amount of acid-absorbing aluminosilicates (hydromica, chlorite, biotite, and potassic feldspar) account for a low value of $NC_{pHI} = 12.3$ mg/g of these rocks. Coarse-grained and inequigranular sands of the middle layer (5–9 m) contain a small amount of aleuropelitic material (4.7 wt %) and are almost carbonate-free (CO₂ < 0.1 wt %); hence, they are most permeable (maximum K_f 19.4 m/24 h) and have the lowest NC_{pHI} value, 6.2 mg/g. A zone of stratal oxidation, developing in the most permeable sands of the middle layer, is replaced along the underground water flow by high-grade ores located in the saccate section of the orebody (Solodov *et al.*, 2005; Fig. 1a). The upper layer of fine-grained sands (4–8 m) contains the maximum quantity of aleuropelites (18.7 wt %) and the highest amount of finely crystalline calcite (CO₂, about 0.75 wt %), forming in some cases pea-shaped concretions. These parameters determine the lowest permeability of the deposits of the upper layer (maximum K_f , 1.8 m/24 h) and highest NC_{pHI} value, 29.7 mg/g. The weighted average value related to thickness of NC_{pHI} for the whole horizon is 15.2 mg/g.

The orebody, band-shaped in plan, extends for 8 km. Its width ranges from 0.2 to 1 km. The ores in the section are a symmetrically shaped roll. The saccate part of the orebody was deposited by an ore-forming flow in underground waters in the most permeable sands of the middle layer, while the flanks represent poorly permeable upper and lower sandy-clayey layers of the horizon (Solodov *et al.*, 1994, 2005; Fig. 1a).

The assignment of high-grade ores of the saccate part of the orebody to the most permeable rocks of the ore-bearing horizon, the absence of spatial links between the ore-saturated zone and the organic matter contained in rocks (Fig. 1a), the availability of epigenetic reducing gases (hydrogen, methane, and heavy hydrocarbons; Lisitsin *et al.*, 1984), and the epigenetic pyritization of sands (Laverov *et al.*, 2000)—all these features allow us to regard the Bukinai deposit as a subtype of young U infiltration stratal deposits, formed

under the influence of epigenetic reducing gases (*Hydrogenic...*, 1980).

Alterations of the RC of rocks in the horizon, being, on the whole, consistent with the epigenetic geochemical zonation (Fig. 1b), indicate that, at present, a U oxidation process in the ore lode is in progress. The lowest RC values, <0.1 mg/g, are in sands of the stratal oxidation zone (SOZ). A field with such an RC value is superimposed on high-grade ores, adjacent to limonitized sands of the SOZ, whereas ores of the main and frontal parts of the saccate part of the orebody are in an RC field of 0.1–0.5 mg/g. The flanks of the roll are composed of rocks with variable RC: ores of the upper flank are localized in a field with an RC of <0.1–0.5 mg/g, and those of the lower flank are in more reduced rocks with an RC of 0.1–1 mg/g.

The RC distribution in rocks agrees with Eh changes in the middle layer of sands, which crosses all epigenetic zones (Fig. 2). In the oxidized sands of the SOZ, Eh_{is} declines from +450 to +260 mV in the direction of the underground water flow. Positive values of the oxidizing potential embrace a “skip” subzone and partly the rear section of the saccate part of the orebody. Negative values of Eh_{is} are observed in its middle and frontal parts, where they decrease to –210 mV. The continuing U oxidation in ores is well recorded by shifting the equilibrium border of Fe(OH)₃/FeS₂ into mineralized gray-colored sands by 30 m with respect to a visually defined redox boundary. This situation is also confirmed by Eh_{hp} in core samples, obtained from boreholes drilled in various parts of ore lode 1 (Table 1). This suggests that changes in the oxidation potential range from +160 to –180 mV, with the average value equal to –36 mV.

This is consistent with the distribution of acid-soluble Fe(III)_{as} in the considered part of the ore-bearing horizon (Fig. 1c). Its greatest percentage (>80%) from ΣFe_{as} is identified within the SOZ sands, and its lowest (<20%), in the frontal section of the orebody. Incidentally, high Fe(III)_{as} concentrations (60–80 vol %) are in many cases recorded in the oxidizing rear section of the saccate part of the orebody.

This epigenetic geochemical process has led to low U(IV)_{as} contents (the average value is 29%) in ores and relatively high concentrations of Fe(III)_{as} (average, 52%) both in ores and in gray-colored rocks occurring beyond the orebody along the underground water flow (Table 2). The natural process of U ore oxidation, which is continuing at present, prepared the ore lode to be developed by the sulfuric ISL method without addition of artificial oxidizers, as there is a sufficient amount of natural Fe(III)_{as} for complete U(IV) oxidation in ores. The symbiosis of natural aerobic and anaerobic underground microflora in the transitional zone from the oxidizing to the reducing setting played a decisive role in this process (Lisitsin and Kuznetsova, 1967; Vinichenko, 2004). This favorable redox setting at the Bukinai deposit generated a rather high average

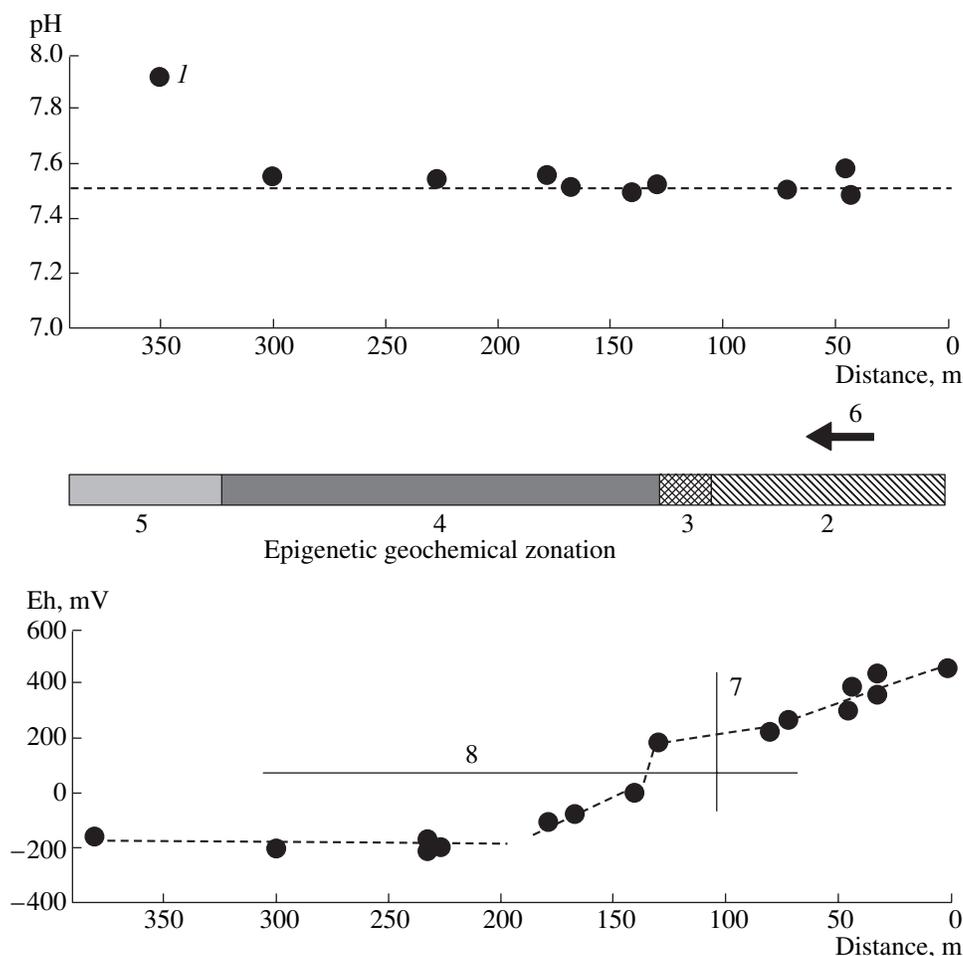


Fig. 2. pH and Eh variations in epigenetic geochemical zonation in the middle layer of the ore-bearing horizon at the Bukinai deposit. (1) Ph and Eh values measured by the hydrogeochemical logging method in water-saturated hermetic pastes; (2) limonitized sands of the stratal oxidation zone; (3) light gray sands of the “skip” subzone; (4) gray and dark gray ore-bearing sands; (5) ore-free reduced gray sands; (6) direction of underground water flow; (7) visually identified redox boundary between gray and yellow sands; (8) theoretical redox equilibrium boundary between Fe(II) sulfides and Fe(III) hydroxides (Lisitsin, 1975).

concentration of dissolved uranium in productive solutions (120 mg/l). The spread of the values of this parameter over the ISL blocks through all of ore lode 1 63–224 mg/l, while the ratio of the liquid phase to the solid phase (L/S) is 1.8–3.1. An analogous process of recent oxidizing transformation of ores and host rocks and similar geotechnological indices obtained as a result of mining ore lodes with the sulfuric ISL method were also established at other deposits of this genetic subtype: South Bukinai (in alluvial ore-bearing deposits), Beshkak in the Kyzyl Kum, and Uvanas in South Kazakhstan (Solodov *et al.*, 1994, 2001, 2004).

AN ANCIENT HYDROGENIC DEPOSIT

The Dalmatovsk deposit is located in the Ural region in Kurgan oblast at the border with Chelyabinsk oblast. Since it was discovered in 1979, it has been comprehensively investigated by traditional techniques

by specialists of NGO Zelenogorskgeologiya (Markov and Poponina, 1984; Luchinin *et al.*, 1992), the All-Russia Institute of Mineral Resources (Khalezov *et al.*, 1982, 1983; Maksimova and Kruglova, 1982; Kochenov *et al.*, 1990; Khalezov, 2003), and IGEM (Kondrat'eva and Nesterova, 1997). However, the literature does not give any information on the geochemical properties of the lithological environment, which could suggest a technological scheme for developing the deposit. Below, against the background of the investigated lithology of rocks and their mineralogical and geochemical properties derived from the papers mentioned above, new evidence is presented on the neutralizing and reducing capacity of rocks and on the uranium and iron valence in ores, along with information about the recent reduction–oxidation and acid–alkaline environment in the ore-bearing horizon.

Tectonically, the deposit is confined to the southwestern margin of the West Siberian plate. Its ore lodes

Table 1. Oxidation–reduction and acid–alkaline environment in the ore-bearing horizon at the Bukinai deposit according to measurements performed in hermetic pastes

Well	Specimen no.	Depth, m	Rock characteristics	pH _{hp}	Eh _{hp} , mV
<i>Preore limonitized sands of the stratal oxidation zone</i>					
5173	1	86	Sand, yellow, irregularly colored	7.20	+40 ± 5
5119	4	103	Sand, reddish yellow, coarse-grained	7.20	+420 ± 0
5173	18	107	Sand, yellow, medium-grained	7.20	+150 ± 30
<i>Sands, gray, ore-bearing</i>					
5173	3	89	Sand, gray, fine-grained, pyritized	7.30	–60 ± 40
5173	4	92	Sand, gray, fine-grained	7.50	–180 ± 20
5173	8	95	Sand, gray, medium-grained	7.20	–140 ± 20
5119	2	98	Sand, gray, fine-grained, clayey	7.80	–140 ± 40
5173	10	99	Sand, light gray, fine-grained	7.80	+20 ± 80
5175	2	100	Sand, gray, fine-grained	7.10	–40 ± 40
5173	13	100	Sand, light gray, fine-grained	7.20	+50 ± 5
5119	3	100	Sand, gray, fine-grained, clayey	7.00	+40 ± 20
5173	16	103	Sand, light gray, fine-grained	7.90	+100 ± 0
5161	7	104	Sand, dark gray, enriched in coalified organic matter	6.90	–100 ± 0
5119	5	109	Sand, gray, fine-grained	7.20	+160 ± 10
5175	21	109	"	7.50	0 ± 20
5119	6	111	Sand, greenish gray, fine-grained, clayey	7.60	–180 ± 0
Average for the ore zone				7.38	–36
<i>Ore-free gray sands</i>					
5175	1	96	Sand, light gray, fine-grained, clayey	7.80	–50 ± 10
5175	2	100	Sand, gray, fine-grained	7.10	–40 ± 40
5175	4	102	"	7.50	–80 ± 50

are localized in Middle–Late Jurassic alluvium, which fills an eroded buried river valley of a basal type. More locally, it is situated in the region of the Uralian monocline of the West Siberian plate. The Middle–Late Jurassic ore-bearing aquiferous horizon is a part of the Tobol'sk artesian basin, one among numerous basins that make up the West Siberian megabasin.

Within the zone of orebody distribution, the buried valley has a southeastern strike; its width is 0.5–2 km and the incision depth is 100–120 m. Middle–Late Jurassic ore-bearing terrigenous rocks rest on pre-Early Jurassic weathering crust (1–100 m thick; on average, about 20 m) formed after crystalline rocks of the Paleozoic folded basement composed of rhyolites, limestones, and schists. Higher, they are overlain by an essentially clayey red-colored Late Cretaceous member consisting of proluvial–lacustrine sediments. Their distribution is wider than that of alluvial sediments, and, hence, they extend beyond the valley borders. Still higher in the section, they are transgressively overlain by platform continental and marine Paleogene, Neo-

gene, and Quaternary sediments. The thickness of the sedimentary cover overlying the Late Jurassic ore-bearing beds is about 300 m.

Uranium ore mineralization along the paleovalley is traced for 10 km. The morphology of orebodies in aerial view is bandlike; in section, it is crescent-shaped and lenticular. Orebodies commonly extend for 400–4500 m; they are 50–700 m wide and 2–12 m thick. They are located at a depth of 360–510 m.

On the basis of paleotectonic, paleoclimatic, and paleohydrochemical reconstructions of the deposit district, A.B. Khalezov has distinguished the major ore-forming epoch; it was the Late Jurassic–Early Cretaceous epoch, associated with the formation of ore deposits at the boundary with an ancient zone of stratal oxidation. This allows us to consider the Dalmatovsk deposit a genetic type of ancient hydrogenic deposits. A number of authors (Khalezov *et al.*, 1983; Markov and Poponina, 1984; Lisitsin *et al.*, 1993; Solodov, 1993) believe that, since the end of the Early Cretaceous, ura-

Table 2. Contents of U and Fe acid-soluble valent forms in ore and ore-free gray-colored sandy rocks in the ore-bearing horizon of the Bukinai deposit

Well	Specimen no.	ΣU_{as} , wt %	$U(IV)_{as}$, wt %	$U(IV)_{as}$ in %% from ΣU_{as}	Fe_{gross} , wt %	ΣFe_{as} , wt %	$Fe(III)_{as}$ in %% from ΣFe_{as}	
1611	1	0.0002				0.019	63	
	2	0.0001				0.015	67	
	3	0.0001				0.016	50	
	4	0.0001				0.016	50	
	9	0.0006				0.016	50	
	10	0.0006				0.027	63	
	11	0.0030				0.012	67	
	15	0.0770	0.037	48		0.024	0	
	16	0.0220	0.007	31		0.005	0	
	18	0.0520	0.021	40		0.021	0	
	20	0.0200	0.004	21		0.009	33	
	22	0.0140	0.002	12		0.031	45	
	23	0.0003				0.032	50	
	24	0.0009				0.008	50	
	25	0.0003				0.022	59	
	26	0.0004				0.064	50	
	27	0.0004				0.079	55	
	1631	1	0.0005			1.32	0.054	80
		2	0.0006			0.84	0.018	67
		3	0.0360	0.027	76	0.62	0.022	41
		9	0.0130	0.002	12	1.10	0.031	74
		10	0.0120	0.001	10	0.70	0.030	60
		11	0.0240	0.002	7	0.53	0.044	77
		12	0.0140	0.001	10	0.44	0.018	61
		13	0.0006			0.66	0.036	70
		14	0.0007			0.69	0.099	62
		15	0.0006			0.77	0.180	55
1651		1	0.0004			3.27	0.008	37
		5	0.0006			0.82	0.006	33
		6	0.0006			0.83	0.041	63
		7	0.0780	0.056	72	0.94	0.038	47
		9	0.0040	0.0004	9	0.95	0.052	58
	11	0.0002			0.44	0.028	64	
	12	0.0001			0.70	0.055	76	
	15	0.0006			0.85	0.079	58	
Average				29			52	

nium mineralization has been conserved, remaining without any substantial changes until the present. This is confirmed by the following data: (1) a fairly slow hydrodynamic regime in the ore-bearing horizon, which, as suggested by studies of radiative defects in quartz and changes in the coefficient of radioactive equilibrium, has existed here since the Late Creta-

ceous;¹ (2) this hydrodynamic regime has led to suppression of biochemical activity of natural underground microflora; (3) in particular, intense growth of sulfate-

¹ The velocity of movement of underground waters has not been reliably defined by hydrogeological methods. Its proposed value is tenths of a meter per year.

Table 3. Contents of U and Fe acid-soluble valent forms in gray-colored ore-bearing and white-colored ore-free sandy rocks of the Middle–Late Jurassic ore-bearing horizon (the central ore lode of the Dalmatovsk deposit)

Well	Specimen no.	ΣU_{tot}^1 wt % ¹	ΣU_{is}^2 wt % ²	ΣU_{as}^3 wt % ³	U_{is} from ΣU_{tot} , rel. %	$U(IV)_{as}$, rel. %	$U(IV)_{as+is}$, wt %	$U(IV)_{as}$ in % from ΣU_{as}	ΣFe_{as} , wt %	$Fe(III)_{as}$ from ΣFe_{as} , rel. %
G-51	4/85 ⁴	0.044	0.023	0.021	52	0.012	0.035	56	0.130	46
706a	4/81 ⁴	1.980	1.750	0.230	88	0.2190	1.969	95	0.025	0
	5/81 ⁴	3.490	1.040	2.450	30	0.7600	1.800	31	0.065	0
730	6/81 ⁴	0.660	0.020	0.640	3	0.4030	0.423	63	0.062	0
	14/81 ⁴	0.055	0.043	0.012	78	0.0110	0.054	90	0.033	0
	15/81 ⁴	0.079	0.036	0.043	47	0.0430	0.079	100	0.036	0
		0.011	0.009	0.002	82	0.0018	0.011	92	0.022	32
	26/81 ⁴	0.015	0.007	0.008	46	0.0054	0.012	67	0.051	18
		0.013	0.010	0.0026	77	0.0017	0.012	67	0.001	0
	27/81 ⁴	0.015	0.006	0.009	40	0.0067	0.013	74	0.002	0
		0.014	0.010	0.0038	71	0.0013	0.011	34	0.006	0
	28/81 ⁴	0.016	0.009	0.007	56	0.0024	0.011	34	0.006	0
		0.012	0.010	0.0023	83	0.0015	0.012	67	0.009	0
	29/81 ⁴	0.012	0.009	0.0028	75	0.0016	0.011	57	0.004	0
		0.006	0.0057	0.0007	89	0.0005	0.006	75	0.002	0
	30/81 ⁴	0.010	0.0056	0.0042	57	0.0033	0.009	79	0.004	0
		0.310	0.220	0.093	71	0.0790	0.299	85	0.120	0
	31/81 ⁴	0.430	0.020	0.410	5	0.2870	0.307	70	0.120	0
		0.007	0.0055	0.001	84	0.0007	0.006	67	0.002	0
35/81 ⁴	0.006	0.0026	0.003	46	0.0025	0.005	83	0.002	0	
	0.013	0.009	0.0042	68	0.0030	0.012	72	0.002	0	
40/81 ⁴	0.018	0.007	0.011	39	0.0050	0.012	47	0.009	0	
	0.006	0.0051	0.0009	85	0.0009	0.006	100	0.007	0	
841	0.008	0.0050	0.0026	66	0.0026	0.008	100	0.006	0	
	49/81 ⁵	0.033	0.020	0.013	60	0.0080	0.028	62	0.320	18
50/81 ⁵	0.033	0.018	0.015	54	0.0009	0.019	6	1.030	33	
	0.032	0.020	0.012	62	0.0054	0.025	45	0.730	27	
51/81 ⁵	0.039	0.022	0.017	56	0.0019	0.024	11	1.830	23	
	0.064	0.043	0.021	67	0.0130	0.056	60	0.034	0	
52/81 ⁵	0.067	0.035	0.032	52	0.0130	0.048	41	0.270	15	
	0.079	0.040	0.039	50	0.0160	0.056	41	0.027	0	
Average	0.083	0.026	0.057	31	0.0370	0.063	65	0.210	38	
				66.7			67		6.8	
3c	23/92 ⁶	0.0001			47.8				0.760	29
	24/92 ⁶	0.0001							0.031	100
	25/92 ⁶	<0.0001							0.069	35
	26/92 ⁶	0.0002							0.002	100
Average										66

Note: ¹ Total uranium content (ΣU_{tot}) was determined in rock specimens in boiling 6 N HCl with hydrogen peroxide.

² Insoluble uranium was determined by the difference between $\Sigma U_{tot} - \Sigma U_{as}$.

³ Acid-soluble (ΣU_{as}) was defined by dissolving a weighed rock portion in 6 N HCl in a CO₂ flow over an hour (figures in the numerator) and 24 h (figures in the denominator).

⁴ Gray and dark gray sands with coalified organic matter, from fine-grained to inequigranular, clayey with gravel and gravel-free.

⁵ Gray fine-grained sands without visible coalified organic matter, clayey.

⁶ White sands.

Table 4. Comparison of the chemical properties of sandy alluvial rocks at the Dalmatovsk and Bukinai deposits

Components, wt %	Dalmatovsk ¹		Bukinai ²	
	lithological–geochemical type			
	whitish	gray-colored	yellow-colored	gray-colored
SiO ₂	81.00	76.60	80.90	79.15
TiO ₂	0.82	1.05	0.30	0.29
Al ₂ O ₃	10.70	14.10	8.38	9.24
Fe ₂ O ₃	0.50	0.60	1.66	1.33
FeO	0.03	0.11	1.47	1.32
MnO	0.03	0.01	0.02	0.02
MgO	<0.20	<0.20	0.43	0.50
CaO	0.07	0.10	0.26	0.26
Na ₂ O	0.10	0.15	1.18	1.34
K ₂ O	0.60	0.85	3.29	3.56
P ₂ O ₅	<0.04	<0.04	0.03	0.04
S _{spd}	<0.01	0.30	<0.01	0.12
CO ₂	0.22	<0.20	0.20	0.20
C _{org}	<0.10	0.60	<0.10	0.25
Number of analyses	48	43	4	7

Note: ¹ The data are from (Khalezov, 2003) and are supplemented by data on Mn and Fe provided by the authors.

Note: ² The comparison was performed for the middle layer of medium- and coarse-grained sands of a channel facies; authors' data.

reducing and denitrifying bacteria, appraised on a four-point scale (0–3), amounts to 0–2 (Solodov *et al.*, 1993); (4) lithological isolation of the ore-bearing horizon, transgressively overlain by a thick cover of interbedded confining and aquiferous rocks; (5) a slightly alkaline, reducing hydrosulfide environment in the ore-bearing aquifer; and (6) an age of ores dated by the Pb isotope method of about 135 Ma. The Late Jurassic–Early Cretaceous ore-forming epoch was characterized by low-amplitude tectonic movements and by a change of humid climatic conditions to arid ones.

Ore host rocks (hereinafter, the ore-bearing horizon) are gray-colored alluvium splitting into upper and lower rhythms, in which gravel–sandy channel deposits give way to clayey siltstone floodplain deposits. Within the rhythms (each is 15–30 m thick), coarse-grained terrigenous deposits are replaced higher up in the section by fine-grained ones, progressively passing into clayey sediments. Large-scale rhythms are complicated by minor ones. Major uranium resources are concentrated in deposits of the upper rhythm. The alluvium is marked by sharp facies changes; therefore, the boundaries between the rhythms are obscure. Deposits of the ore-bearing horizon display all lithological types of ter-

ritigenous rocks, among them, gravelites, sands, clayey sands, siltstones, clays, and thin coal seams. The lithological heterogeneity of rocks in the horizon is also manifested in filtration heterogeneity. Their filtration coefficient ranges from 1 to 13 m/24 h. Gravel–pebbly material is represented by fragments of bedrocks (rhyolites, limestones, schists, and basalts). The sandy and aleurite fractions mainly consist of quartz (75–85%). Clastic aluminosilicates are dominated by potassic feldspar; its content ranges within 5–9 vol %. The clayey fraction is mostly represented by kaolinite and, to a lesser extent, by hydromica.

Kaolinite is present in two forms among sandy grains. One is essentially sedimentogenic. It appeared as a result of reworking of weathering crust during the formation of alluvial deposits; the weathering crust formed in a humid climate. The second variety is authigenic kaolinite intensely replacing biotite fragments. Feldspar fragments are less affected by kaolinization.

Three permeable sandy deposits reveal epigenetic geochemical zonation: bleached (white and white with a greenish shade); gray, and dark gray (in some cases, black). Ore mineralization is confined to gray-colored rocks; it was formed at the boundary with bleached rocks.

Rocks have become gray-colored due to a high content of coalified organic matter (COM), sulfide minerals, and titanates. The color of sands is associated with the amount of C_{org}. The average C_{org} content (wt %) in light gray varieties is 0.26; in gray, 1; in dark gray, 1.8; and in black, 4.7.

Titanates are represented by ilmenite and titanomagnetite, intensely leucogenized. An elevated Ti content in sands, a Uralian specific feature with respect to the compared horizon at the Bukinai deposit, must be the main cause of the appearance of minor amounts of brannerite and davidite in ores, which are poorly soluble in H₂SO₄ solutions. The main ore minerals here are uraninite and coffinite, commonly present in ores in equal quantities. The size of their crystals is in the nano- and micrometer range. However, in some cases, segregations of uranium minerals are large, a few fractions of a millimeter in size. Ore mineralization at the Dalmatovsk deposit is more coarsely crystalline than that at the Bukinai deposit, and, consequently, it has a smaller specific surface and ores are less soluble in diluted H₂SO₄ solutions. Ores are of a higher grade. The U content is 0.01–0.08 wt %. In some cross sections, it reaches 3.5 wt % (Table 3).

Sulfides are more diverse in composition than in the Late Cretaceous sands of the Bukinai deposit. Apart from prevailing pyrite and marcasite, there occur pyrrhotite, melnikovite, arsenopyrite, chalcopyrite, jordisite, linneite, molybdenite, sphalerite, and possibly bismuth sulfide.

Bleached rocks are abundant in the upper part of the paleovalley. The bleaching process affected the greater part of coarse-grained rocks of the lower and partly the upper rhythm. The bleaching mainly affects permeable

Table 5. Oxidation–reduction and acid–alkaline environment in the Middle–Late Jurassic ore-bearing horizon according to data obtained from measurements in hermetic pastes

Well	Specimen no.	Depth, m	Rock characteristics	U, wt %	pH _{hp}	pH _{pr}	Eh _{hp} , mV
706a	7/81	439	Sand, gray, inequigranular, clayey	0.0720	7.20	7.90	-180 ± 80
	8/81	441	Sand, black, coarse-grained, clayey	nd	nd	nd	-220 ± 20
	9/81	442	Sand, whitish, medium-grained, clayey with relicts of Fe(III) hydroxides	0.0110	7.45	8.15	-50 ± 50
	11/81	444	Sand, whitish, fine-grained, clayey	0.0080	8.45	nd	-270 ± 10
	16/81	446	Sand, gray, fine-grained, slightly clayey at the boundary with gray ore sand	0.0120	7.60	7.90	-200 ± 10
730	21/81	433	Sand, whitish, medium-grained, clayey with abundant black detrital grains	0.0054	7.80	8.55	-180 ± 100
	23/81	435	Gravelite, light gray with white clayey cement	0.0012	7.95	8.20	-20 ± 50
	24/81	438	Sand, dark gray, fine-grained, highly clayey	0.0200	7.70	8.35	-200 ± 20
	25/81	440	Sand, dark gray, fine-grained, clayey with coalified organic matter fragments	0.0150	8.50	8.00	-380 ± 0
	32/81	443	Sand, gray, medium-grained, clayey with coalified organic matter fragments	0.0110	7.60	8.05	-100 ± 100
	33/81	446	Sand, gray, coarse-grained, clayey with coalified organic matter fragments	0.0200	7.90	7.90	+60 ± 30
	34/81	448	Sand, dark gray, coarse-grained, clayey with coalified organic matter fragments	0.0100	7.75	7.80	-50 ± 5
	37/81	452	Sand, dark gray, fine-grained, clayey with coalified organic matter fragments	0.0200	8.05	8.60	-220 ± 35
	38/81	453	Sand, light gray, fine-grained, clayey	0.0270	8.35	8.35	-10 ± 30
	40/81	454	Sand enriched in coalified organic matter	0.0100	8.60	8.70	-310 ± 40
841	43/81	429	Sand, whitish, fine-grained, clayey	0.0120	8.45	8.60	-210 ± 20
	44/81	430	"	0.0110	8.50	8.65	-220 ± 50
1c	25/92	460	Sand, light gray, inequigranular, clayey	0.0086	8.10	7.60	-230 ± 50
3c	34/92	464	Sand, light gray, fine-grained, clayey	0.0009	7.20	8.67	-295 ± 30
Average					7.95	8.23	-173

deposits, thus suggesting a significant role in its formation of the underground water flow that at present moves along the paleovalley. Bleaching penetrates into gray-colored rock varieties crossing age and facial boundaries. This proves its epigenetic nature (Khalezov, 2003).

The main difference of bleached rocks from gray-colored rocks is the nearly complete absence of COM in them. The concentration of feldspars is decreased due to secondary kaolinization, whereas the content of titanates increases with a concurrent decline in the content of sulfide minerals.

Middle–Late Jurassic sands of the Dalmatovsk deposit, just like Late Cretaceous deposits of the Bukinai deposit, are aluminosilicate (Table 4). Unlike the latter, the former are impoverished in Fe, Mg, Ca, Na, and K; this confirms their formation under intermittent acid influence. These data show that bleaching of gray-colored rocks was accompanied by removal of Fe(II), while the Fe(III) form did not undergo any substantial

redistribution. This confirms that the formation of the ancient stratal oxidation zone, namely, the decomposition of organic matter and oxidation of sulfides, was accompanied by an acid process, during which the pH could fall to 6 and Fe(II) became mobile, while Fe(III) did not migrate.

The essentially quartz composition of clastic material <0.01 mm in size and the kaolinite composition of the intergrain filling of slightly carbonate sandy rocks with a predominant CO₂ content of 0.02 wt %, rarely reaching 5 wt %, bring about a low NC_{pH1} value. It makes up 6–8 mg/g in white-colored sandy deposits, while in ore-bearing gray to dark gray sand deposits, it increases from 9 to 14 mg/g. The NC_{pH1} value here is much lower than in continental ore-bearing sands, where it ranges from 6 to 40 mg/g. In particular, in the Bukinai deposit, the weighed mean value of this parameter is 15.2 mg/g. That is, ore-bearing deposits of the Dalmatovsk deposit were prepared for artificial sulfuric acid leaching through the influence of natural acid processes occurring at different stages of the formation of

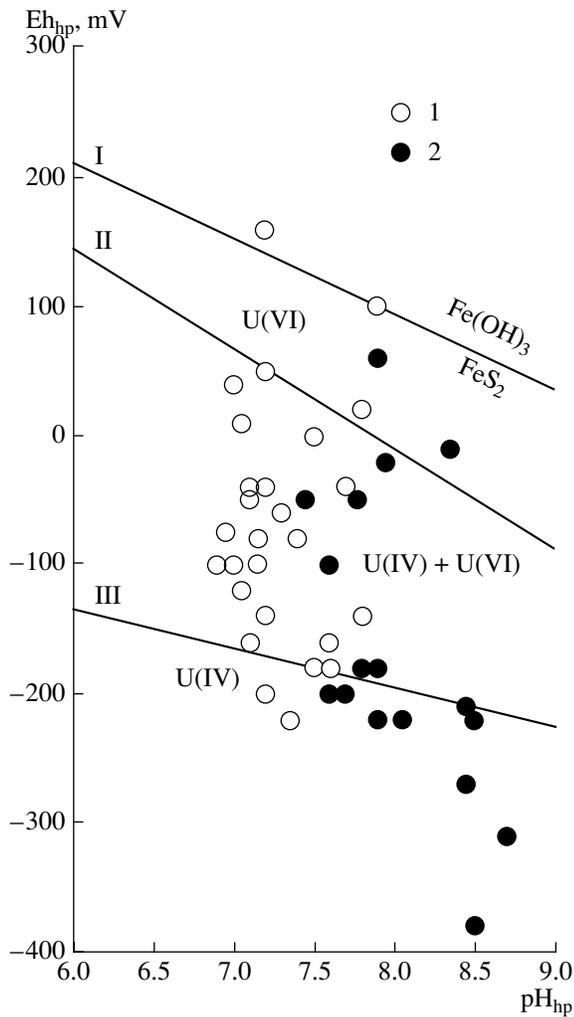


Fig. 3. Comparison of redox environments in the ore-bearing horizons of the described deposits. (1) Data on the Bukinai deposit; (2) data on the Dalmatovsk deposit. (I) Oxidation–reduction boundary— $\text{Fe}(\text{OH})_3/\text{FeS}_2$ equilibrium line; (II) commencement of reducing uranium precipitation as indicated by experimental data; (III) predominance of $\text{U}(\text{IV})$ in oxides.

ore-bearing terrigenous sediments, being accompanied by the leaching of petrogenic components. This lithological–geochemical setting is ideal for applying *in situ* sulfuric acid leaching; in NC_{pH1} value, it is comparable with the geotechnological conditions in ore-bearing quartz sands at the Beshkak, Lyavlyakan, and Kanzhugan deposits in Central Asia.

A major geochemical distinction (influencing the selection of a reagent technological scheme for developing ore deposits by the ISL method) of ancient deposits from their young counterparts is a high reducing capacity of ore-bearing rocks. In gray-colored varieties, it is 1.5 mg/g, and in dark gray and black sands, it increases up to 3.5–4.9 mg/g. In white colored sands RC is close to that of the subzone of partial stratal oxidation on the compared young ore deposit (0.1–0.5 mg/g).

Secondary restoration of the lithological environment, which, most likely, occurred after the hydrodynamic isolation of the ore-bearing horizon (since the beginning of the Late Cretaceous), has brought about hydrogen sulfide contamination of the bed. The nearly sulfate-free chemical composition of hydrocarbonate (50 mg/equiv) chloride (50) sodic (95) underground waters is a specific hydrochemical feature of the deposit under consideration. In this case, hydrogen sulfide is present in minor amounts (0.1 mg/l) in all epigenetic geochemical zones. In ore-bearing lodes, its content increases to a few milligrams per liter.

The presence of hydrogen sulfide brings about low values of the oxidation potential through the entire horizon within the distribution of ore lodes of the deposit (Table 5). Out of 19 measurements, only one gave $\text{Eh} = +60$ mV, which may be related to the core pollution by drilling mud. All other values vary within a broad range (–20 to –380 mV). The average Eh value, equal to –173 mV, is much lower as compared with that in ore-bearing horizon (–36 mV) of a young deposit. Analysis of the pH and Eh measurements in underground waters of the ore-bearing horizons under comparison (Fig. 3) showed that the sodic underground waters of the Dalmatovsk deposit are more alkaline than the underground waters of the Bukinai deposit and that the Eh reducing environment is dominating in the Middle–Late Jurassic horizon.

This reduction–oxidation setting favors a high degree of U reduction in ores (Table 3). The mean content of acid-soluble $\text{U}(\text{IV})_{\text{as}}$ from $\Sigma\text{U}_{\text{as}}$ influenced by a 6 N solution of HCl over an hour amounts to 67%, and over 24 h, 60%. The share of uranium insoluble in HCl without an oxidizer at normal temperature reaches nearly half of its gross content in ore (U_{is} 47.8–66.7% from $\Sigma\text{U}_{\text{tot}}$); i.e., these ores are more resistant to acid solutions.

This also explains a complete absence or low content of acid-soluble $\text{Fe}(\text{III})_{\text{as}}$ (0–33%) from $\Sigma\text{Fe}_{\text{as}}$ in ore and ore-free gray-colored rocks (Table 3). Simultaneously, its content in bleached rocks ranges from 29 to 100% from $\Sigma\text{Fe}_{\text{as}}$. However, the total amount of $\Sigma\text{Fe}_{\text{as}}$ is rather low, reaching 0.002–0.069 wt %. In rare cases, it amounts to 0.76 wt %. The analysis of these data indicates that mobile $\text{Fe}(\text{III})$ is not sufficient for oxidizing $\text{U}(\text{IV})$ in the conditions of the Dalmatovsk deposit.

CONCLUSIONS

The analysis performed suggests that ancient hydrogenic deposits of the Dalmatovsk type have a considerable advantage over young deposits with respect to the NC value of rocks. They are most suitable to be developed by the *in situ* sulfuric acid leaching of uranium. In this geochemical environment, the consumption of H_2SO_4 for the rock mass lower.

Nevertheless, this type of deposits has a serious shortcoming. It is a highly reducing environment,

determined by a high reducing capacity of rocks and the presence, though in small quantities, of hydrogen sulfide, a strong reducing agent, which creates a reducing Eh setting in all epigenetic geochemical zones of the ore-bearing horizon. Its consequence is a high degree of reducing acid-soluble U and Fe forms in rocks. In such a geochemical setting, the recovering of uranium from ores without using artificial oxidizers is not effective. The mining of the deposit that was carried out using the ISL method without applying such reagents is one of the causes of low uranium concentrations in productive solutions.

REFERENCES

1. *Hydrogenic Uranium Deposits*, Ed. by A. I. Perel'man (Atomizdat, Moscow, 1980) [in Russian].
2. *In situ Leaching of Multi-Elements*, Ed. by N. P. Laverov (Izd. Akad. Gornyykh Nauk, Moscow, 1998) [in Russian].
3. A. B. Khalezov, *Dalmatovsk Uranium Deposit* (VIMS, Moscow, 2003) [in Russian].
4. A. B. Khalezov, R. F. Dangovtsev, I. L. Luchinin, *et al.*, "Main Features of the Geological Structure and Conditions of the Formation of the Dalmatovsk Deposit," in *Materials on the Geology of Uranium Deposits* (VIMS, Moscow, 1982), Issue 74, pp. 5–16.
5. A. B. Khalezov *et al.*, "Ore-Controlling Epigenetic Zonation at the Dalmatovsk Deposit," in *Materials on the Geology of Uranium Deposits* (VIMS, Moscow, 1983), Issue 77, pp. 169–176 [in Russian].
6. Ya. M. Kislyakov and V. N. Shchetochkin, *Hydrogenic Ore Formation* (Geoinformmark, Moscow, 2000) [in Russian].
7. A. V. Kochenov, A. B. Khalezov, E. M. Shmariovich, and V. T. Dubinchuk, "Mineralogical–Geochemical Features of Infiltration Uranium Deposits of a "Basal" Type," *Litol. Polezn. Iskop.*, No. 1, 123–132 (1990).
8. I. A. Kondrat'eva and M. V. Nesterova, "Lithological–Geochemical Features of Uranium Deposits in Mesozoic River Paleovalleys," *Litol. Polezn. Iskop.*, No. 6, 577–594 (1997) [*Lithol. Miner. Resources*, No. 6, 505–520 (1997)].
9. A. D. Konoplev, G. A. Tarkhanov, E. V. Konopleva, *et al.*, *Influence of the Lithological Composition of Ores of the Khokhlovsk Deposit on Uranium Output in Laboratory Technological Research* (VIMS, Moscow, 2004) [in Russian].
10. N. P. Laverov, A. K. Lisitsin, and I. N. Solodov, "Uranium-Bearing Multi-Element Exogenic Epigenetic Deposits: Conditions of Formation and Sources of Metals Recovered by In Situ Leaching," *Geol. Rudn. Mestorozhd.* **42** (1), 5–24 (2000) [*Geol. Ore Deposits* **42** (1), 3–19 (2000)].
11. A. K. Lisitsin, "Method of Determining Eh–pH Chemical Equilibrium of Water Solution with Rocks and Minerals," *Geokhimiya*, No. 8, 994–1002 (1967).
12. A. K. Lisitsin, *Hydrogeochemistry of Ore Formation* (Nedra, Moscow, 1975) [in Russian].
13. A. K. Lisitsin, *Protective Geochemical Properties in the Geological Environment* (Geoinformmarka, Moscow, 1996) [in Russian].
14. A. K. Lisitsin and E. T. Kuznetsova, "The Role of Microorganisms in the Formation of Reducing Geochemical Barriers on Wedging out of Zones of Stratal Limonitization," *Izv. Akad. Nauk SSSR, Ser. Geol.*, No. 1, 31–44 (1967).
15. A. K. Lisitsin, A. M. Kireev, I. N. Solodov, *et al.*, "Usage of Well Cores for Detailed Studies of the Composition and Properties of Underground Water Solutions," *Litol. Polezn. Iskop.*, No. 3, 74–87 (1984).
16. A. K. Lisitsin, S. N. Markov, and G. Yu. Poponina, "The Dalmatovsk Deposit in Transuralian Region, as an Instance of a Geological Situation Suitable for Safe Disposal of Radioactive Waste," *Geol. Rudn. Mestorozhd.* **35** (4), 360–368 (1993).
17. I. I. Luchinin, P. A. Peshkov, P. K. Dement'ev, *et al.*, "Uranium Deposits in Paleovalleys of the Transural and Transbaikalian Regions," *Pazved. Okhr. Nedr.*, No. 5, 12–15 (1992).
18. M. F. Maksimova and V. G. Kruglova, "Mineral and Geochemical Features of Ore Mineralization in the Dalmatovsk Deposit," in *Materials on Geology of Uranium Deposits* (VIMS, Moscow, 1982), Issue 74, pp. 84–95 [in Russian].
19. M. F. Maksimova and E. M. Shmariovich, *Stratal-Infiltration Ore Formation* (Nedra, Moscow, 1993) [in Russian].
20. S. M. Markov and G. Yu. Poponina, "Radiological Features of the Dalmatovsk Deposit Ores," in *Materials on Geology of Uranium Deposits* (VIMS, Moscow, 1984), Issue 82, pp. 24–35 [in Russian].
21. G. A. Sidorenko, *Crystallochemistry of Uranium Minerals* (Atomizdat, Moscow, 1978) [in Russian].
22. I. N. Solodov, *Geoecological Record of the Dalmatovsk Uranium Deposit* (IGEM RAS, Moscow, 1993) [in Russian].
23. I. N. Solodov, A. M. Kireev, O. I. Zelenova, and V. A. Umrikhin, "Technogenic Oxidation Changes in Reduced U-Bearing Sandy Deposits of Marine Genesis," *Litol. Polezn. Iskop.*, No. 6, 84–96 (1993).
24. I. N. Solodov and B. T. Kochkin, "Influence of the Geostuctural and Geochemical Factors on the Distribution of Technogenic Sulfate Brines in the Aquifer Enclosing the Bukinai Uranium Ore Lode (Kyzyl Kum Province)," *Geol. Rudn. Mestorozhd.* **38** (1), 87–102 (1996) [*Geol. Ore Deposits* **38** (1), 78–91 (1996)].
25. I. N. Solodov, M. V. Nesterova, G. A. Shugina, *et al.*, "Protective Geochemical Properties of U-Bearing Quartz Sandy Deposits of the Beshkak Deposit (Kyzyl Kum Region)," *Litol. Polezn. Iskop.*, No. 1, 49–70 (2001) [*Lithol. Miner. Resources*, No. 1, 43–61 (2001)].
26. I. N. Solodov, V. I. Velichkin, M. G. Rubtsov, *et al.*, *Hydrogeochemical Logging: Theory and Practice* (URSS Editorial, Moscow, 2005) [in Russian].
27. I. N. Solodov, O. I. Zelenova, and G. A. Shugina, "Technogenic Geochemical Barriers in the Ore-Bearing Horizons of Uranium Hydrogenic Deposits," *Geokhimiya*, No. 3, 415–432 (1994).
28. Yu. A. Teterin, V. M. Kulakov, V. M. Baev, *et al.*, "Studies of Uranium Oxidation Degree in Uraninite by the RES Method," *Dokl. Akad. Nauk SSSR* **255** (2), 434–437 (1980).
29. P. V. Vinichenko, *Theory of Biogenic Ore Formation Illustrated by Uranium Deposits* (Sosnovgeologiya, Irkutsk, 2004).