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GEOCHEMISTRY

Uranium in the Mineralized Lakes of Altai Krai

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Abstract—Data on the physicochemical properties (pH, Eh, salinity) and content of U and other trace elements (As, Li, B, Br, I, Sr) are provided for the mineralized lakes of the Kulundinskaya steppe of Altai Krai. The sodic lakes of the region are characterized by higher U^{238} contents (up to 4 mg/l). The U contents in the lake waters are positively correlated with the sum of carbonate and hydrocarbonate ions and the pH of waters and are negatively correlated with salinity. These data confirm the presence of an economic U-bearing zone of the ground reservoir oxidation located along the eastern slope of the Platovskoe uplift in the northwestern direction along the boundary with Kazakhstan.

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The demand for uranium by the atomic industry has stimulated interest in hydromineral materials. Among hydromineral sources, salt lakes are of interest worldwide [1–5]. Study of the U content of lakes is interesting not only from the point of view of their ore-generating potential, but they also provide information on the U potential of the rocks that occur in the drainage area of the lakes. Our aim is to determine the U potential of the salt lakes of the Kulundinskaya valley that has not been studied yet.

The data on the U content were collected during the expeditions of 2013 and 2014. The sampling places are shown in the figure. The major components of water samples were analyzed at the "Voda" Accredited Center of Tomsk Polytechnical University (Tomsk) following the methods described in the literature. The contents of U and other trace elements were analyzed on an Agilent 7500a ICP MS at the Institute of Solid State Chemistry and Mechanochemistry, Siberian Branch, Russian Academy of Sciences; Li was determined using a Varian AA 280 FS spectrometer.

The lakes studied occur in the forest steppe and steppe landscape–climatic zones of Altai Krai. They vary in size, source of water–salt supply, chemical composition, degree of salinity, and the hydrogeological conditions of their location. They are often endorheic, isometric, and from 8–10 (Bolshoe Yarovoe, Burlinskoe) to 35 (Kulundinskoe) km in diameter. The lakes are shallow (1–6 m deep), and the oscillations of their levels reach 1 m [6]. Evaporation, the value of which from the lake surface is 350–600 mm during the open water period, significantly exceeds the amount of atmospheric precipitates (250–300 mm). The salinity of the lake waters varies from $n \cdot 1$ to 325 g/l, and pH ranges from 7.2 to 9.9 (table). The CO_3^{2-} and HCO_3^- contents are <0.003–25.8 and 0.49–8.8 g/l, respectively. The contents of Cl and SO_4^{2-} ions reach 155 and 97 g/l, respectively. Na^+ is the dominant cation, and locally, higher Mg^{2+} contents are observed. The lake waters are characterized by higher contents of (up to, mg/l) B (78), Br (820), Li (3.6), I (6.3), and As (0.6). The U content varies widely from 9.2×10^{-4} to 4.1 mg/l (0.3 mg/l, on average). The U content correlates with the sum of CO_3^{2-} and HCO_3^- ions (Pearson correlation coefficients of 0.675_{2014} and 0.516_{2013}, respectively). The U content has a positive correlation with the pH of lake waters (0.528_{2014} and 0.439_{2013}) and a negative correlation with salinity (-0.155_{2014} and -0.520_{2013}). The presence of a positive correlation between the contents of the carbonate ions and U indicates its accumulation in the form of carbonate complexes of the uranyl ion.

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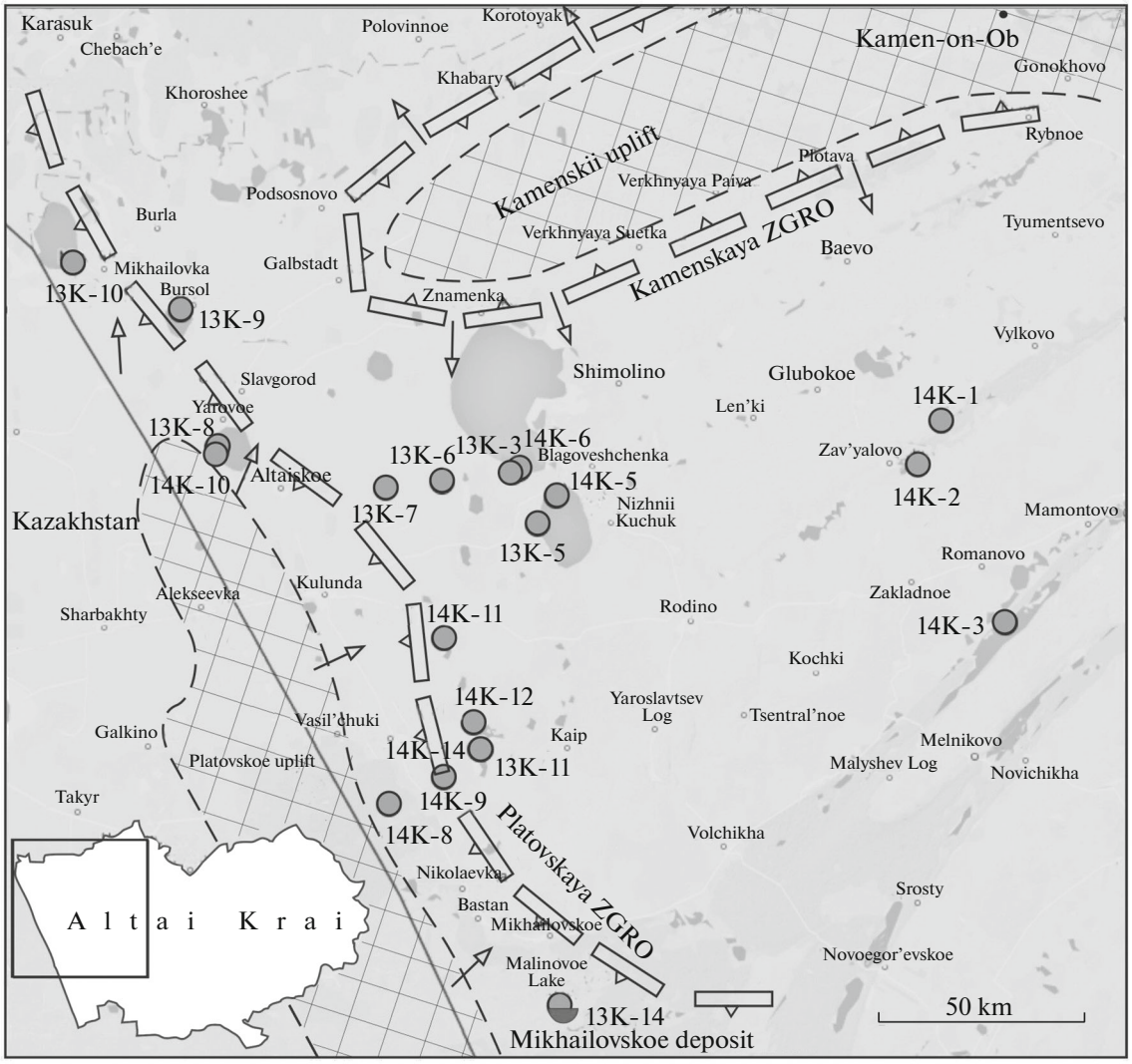

Map of sampling in the mineralized lakes of Altai Krai.

Uranium in the lakes of the Kulundinskaya steppe derives from the discharge of the underground U-bearing waters. The rocks of the provenances (Altai, Tomsk–Kolyvan fold area, Kamenskii uplift) and underlying basement with U-bearing (3–4 ppm) granitic rocks are the U source for the underground waters. The activity of waters infiltrating into the hydrodynamic zones of free and hampered water exchange of the S–N directed paleo-riverbed flow along the Irtysh shear zone resulting in accumulation of U in the Meso-Cenozoic cover of the Kulundinskaya depression (Mikhailovskoe deposit, Ramadan occurrence) [7]. They form an ore-controlling epigenetic zoning of the oxidation type in the water-bearing horizons. The U deposits of the infiltration type were formed at the pinch out of the regional zone of the ground reservoir oxidation. Due to erosion windows in the waterproof clayey sediments of the paleo-

Physicochemical characteristics of the lake waters of salt lakes of Altai Krai

Lake	Year	Number on map	Sampling site coordinates	pH	Eh, mV	U, mg/l	HCO_3^-, g/l	CO_3^{2-}, g/l	Salinity, g/l
Kulundinskoe	2013	13K-3	N-52°49′27″ E-79°35′18″	8.7	58	0.0020	1.9	0.23	144
	2014	14K-6	N-52°49′41″ E-79°36′46″	8.4	14	$<5.7 \times 10^{-3}$	1.4	0.06	148
Kuchuk	2013	13K-5	N-52°42′46″ E-79°40′36″	8.2	83	0.0040	0.57	<0.003	324
	2014	14K-5	N-52°46′26″ E-79°44′43″	7.6	–27	0.018	0.74	<0.003	325
Bolshoe Yarovoe	2013	13K-8	N-52°52′27″ E-78°33′03″	8.4	33	0.010	0.61	0.18	133
	2014	14K-10	N-52°52′06″ E-78°33′00″	8.0	72	0.024	0.56	<0.003	138
Kurich'e	2013	13K-11	N-52°13′47″ E-79°28′43″	8.5	74	0.027	0.61	0.12	94
	2014	14K-14	N-52°13′49″ E-79°28′24″	7.2	20	0.055	0.86	<0.003	323
Malinovoe	2013	13K-14	N-51°40′37″ E-79°45′16″	8.4	25	0.0037	0.49	<0.003	329
Burlinskoe	2013	13K-9	N-53°09′54″ E-78°25′32″	8.1	51	0.0021	0.49	<0.003	315
Bolshoe Topol'noe	2013	13K-10	N-53°15′54″ E-78°02′54″	9.7	18	0.011	3.1	1.1	22
Shoshkaraly	2013	13K-6	N-52°48′15″ E-79°20′28″	9.6	102	0.0055	1.025	0.108	3.3
Dzhemansor	2013	13K-7	N-52°47′03″ E-79°08′43″	9.7	88	0.037	3.538	0.744	41
Baklan'e	2014	14K-1	N-52°55′54″ E-81°05′51″	9.1	58	0.0010	0.51	0.06	2
Krivoe	2014	14K-2	N-52°50′15″ E-81°00′40″	8.0	83	9.2×10^{-4}	0.52	0.02	1.5
Gor'koe	2014	14K-3	N-52°30′08″ E-81°19′20″	9.4	–44	0.0040	1.7	0.78	14
Petukhovo	2014	14K-8	N-52°06′42″ E-79°09′28″	9.9	–359	1.0	7.32	25.8	69
Zheltyr	2014	14K-9	N-52°10′08″ E-79°20′52″	9.6	1.8	4.1	8.84	11.1	100
Krivaya Puchina	2014	14K-11	N-52°28′15″ E-79°20′49″	7.5	–1.0	0.066	1.04	<0.003	220
Petukhovo 2	2014	14K-12	N-52°17′23″ E-79°27′08″	7.6	–33	0.18	1.06	<0.003	369

riverbed structure, the zones of the ground reservoir oxidation have a complex configuration because of the waters overflowing the underlying sediments and, in places of hidden discharge vents, to the upper horizons. This was favorable for lateral and vertical dispersion of the U deposits. The waters of the oxidation conditions transform easily soluble sulfate and carbonate compounds of U into a solution, particularly in the upper part of the section, where the sodic waters are formed due to insufficient and moderate moistening. For example, according to the data of the PGO Berezovgeologiya, the U content in waters of the Paleogene complex in the area of the settlement of Malinovoe Lake reaches 0.02 mg/l. The U content in

the hydrocarbonate sodium waters of the Neogene–Quaternary complex with pH >8 is 0.08–0.11 mg/l. The Mikhailovskoe U deposit of hydrogenic type 2 km wide extending 100 km along the mountainous–fold framework was discovered in Meso-Cenozoic rocks [8]. Thus, the U-rich infiltration waters could have formed economic U deposits under favorable strongly reducing conditions in the areas of hidden regional discharge (area of Kulundinskoe Lake) under conditions similar to the Chu–Sarysu U province. The conclusions on the economic U potential of the Meso-Cenozoic rocks of the Kulundinskaya depression are supported by the high U contents in Petukhovskoe, Kurich'e, and Zheltyr lakes, among others, which indicates the discharge of the underground U-bearing waters to these lakes. This is also evident from the salinity-normalized U contents of the lake waters: 15 and 40 ppm for Petukhovskoe and Zheltyr lakes, respectively, which are higher in comparison with other lakes studied (<1 ppm). The suggested U-bearing zone of the ground reservoir oxidation extends for more than 300 km along the eastern slope of the Platovskoe uplift in the northwesterly direction along the border with Kazakhstan.

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