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Lithological–Geochemical Differentiation of Bottom Deposits in the Angara Cascade Reservoirs

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Abstract—A long-term complex study of the Angara cascade reservoirs, the largest artificial reservoirs, showed that the bottom deposits were formed at the predominance of terrigenous influx. The compositional–structural and geochemical characteristics of various lithodynamic types of bottom sediments along a generalized transverse profiles testify that they represent a complex system with varying proportions of sandy, silty, and clayey particles and associations of chemical elements. As is indicated by the composition of the abraded rocks, the sedimentation settings, and the type of the lithological–geochemical differentiation of the bottom deposits, the scattering and differentiation of abrasion fluxes occurred simultaneously with the formation of new types of bottom sediments, whose composition was partially inherited from precursor rocks. It was established that the change in the lithodynamic settings in the Angara cascade reservoirs and the trend of the lithological–geochemical differentiation of the bottom sediments are governed by the same laws as in natural basins.

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INTRODUCTION

Now an urgent problem is the study of modern bottom deposits in water reservoirs in terms of the migration and distribution of the flux of chemical elements from the land. Goldschmidt [1] and Fersman [2, 3] were the first to study the factors and general characteristics of element migration and to reveal the effect of the physicochemical properties of elements on their distribution. The role of the geological environment in geochemical differentiation during sedimentogenesis was first considered by Pustovalov [4–6]. The principles of the modern concepts of the behavior and distribution of chemical elements depending on the combined effect of the aforementioned factors during sedimentation were formulated by Strakhov [7–10]. Subsequent studies significantly contributed to the elucidation of this problem and expanded the concepts of the mechanical differentiation of elements in seas and oceans [11–16].

In large artificial reservoirs, most processes proceed hundreds of times faster than in natural water bodies, and this provokes interest in studying the chemical composition of their waters, bottom sediments, and element migration. The most detailed studies were performed at the Dnieper cascade reservoirs [17]. At the same time, the reservoirs of the Angara cascade, including head Irkutsk, middle Bratsk, and Ust Ilim reservoirs remain studied inadequately poorly (Fig. 1). Therefore, to decipher the geochemical mechanism of sedimentation in the artificial water reservoirs, the following problems were formulated: (1) to quantify the structural and geochemical characteristics of various lithodynamic types of the bottom sediments, (2) to assess the effect of the source material and the geodynamics of the sedimentation environment on the chemical composition of the bottom sediments, and (3) to construct a scheme of lithological–geochemical differentiation of the bottom deposits of the Angara cascade on the basis of original data.

MATERIALS AND TECHNIQUES

Complex investigations, including the study of the lithological, geochemical, hydrochemical, and hydrological parameters of the sedimentation environment, were carried out by the Institute of the Earth's Crust, Siberian Division, Russian Academy of Sciences, in the Angara cascade reservoirs in 1972–2002. During these works, a great amount of factual material was collected on the hydrodynamic conditions, composition, and properties of bottom deposits, rocks from the coastal zone of the reservoirs, and migration and accumulation of chemical elements in these basins. The annual studies of the lithological–geochemical composition included sampling of the bottom deposits (by a PI-27-II corer) and a coastal cliff. Samples were taken along reference coast–reservoir profiles to span most of the sedimentation settings and subwater topographies. The ground survey was accompanied by water sampling with a

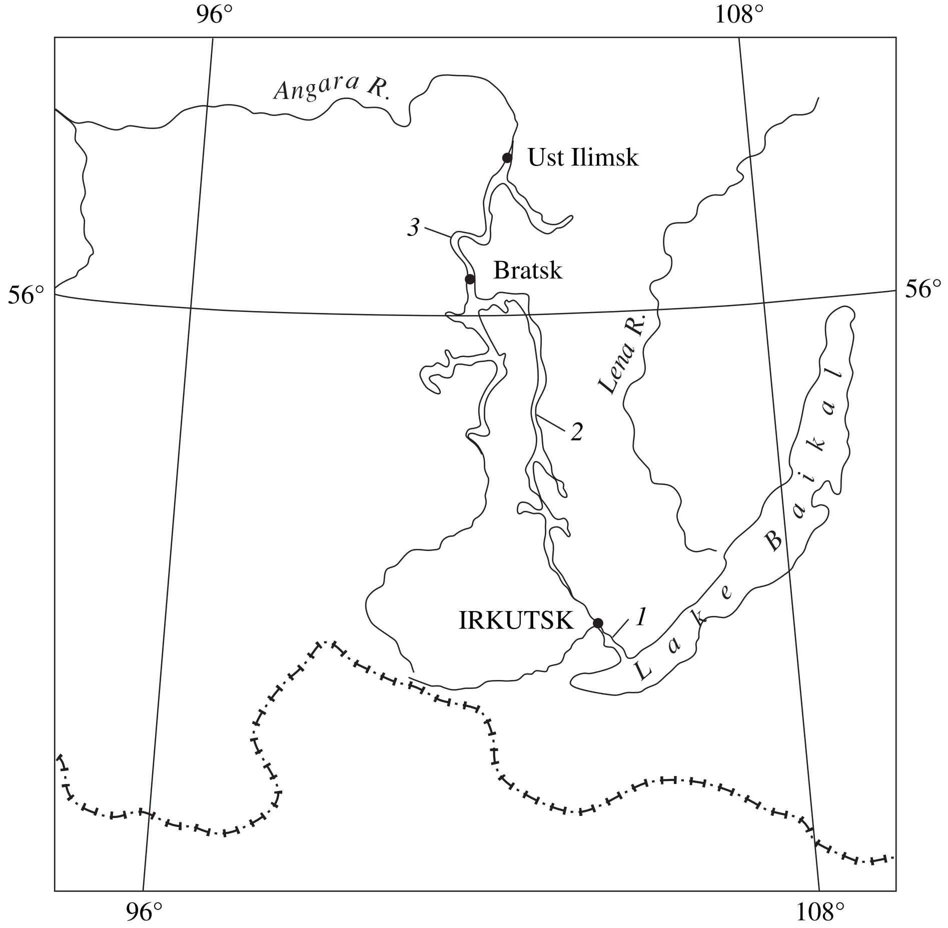

Fig. 1. Location scheme of the Angara Cascade reservoirs. (*1*) Irkutsk reservoir; (*2*) Bratsk reservoir; (*3*) Ust Ilim reservoir.

Molchanov bathymeter and measurement of the flow rates by a VMM marine rotator to examine the lithological–geochemical differentiation of the bottom deposits.

The pH and Eh values were determined by potentiometers with glass and Pt electrodes in bottom sediment columns immediately after their sampling. Using corresponding techniques [18], the volumetric mass, natural moisture in weight and volume units, degree of moisture, porosity, and porosity coefficient were determined. The granulometric composition of the bottom sediments was determined in the laboratory using the technique described in [19]. The chemical composition of the bottom sediments was studied by both traditional wet chemistry and instrumental methods (XRF, emission spectral, atomic absorption). The major elements, main ions, biogenic elements, total OM, organic carbon, trace elements, and the absorption capacity of the sediments were determined. The chemical composition of bottom sediments was determined by conventional chemical and some instrumental techniques at the Analytical Center of the Institute of the Earth's Crust, Siberian Division of the RAS. Emission spectral and ICP analyses were conducted at the analytical laboratories of the Institute of Limnology and Vinogradov Institute of Geochemistry, Siberian Division, Russian Academy of Sciences.

The data were processed with the Statgraphics Plus application. The indication of an anomalous level of element contents in the bottom sediments was assumed to be the concentration coefficient, calculated according to [20], as the ratio of the element content in the sediment to its average background content. Using our data, we constructed a series of 1 : 50000 lithological, facies, and geochemical maps on the basis of bathymetric maps of the Irkustk, Bratsk, and Ust Ilim reservoirs.

RESULTS AND DISCUSSION

The bottom sediments of the Angara cascade reservoir were formed in an environment with the prevalence of a terrigenous influx, intense wave activity during the open-water period, and regional morphological features of the basin floor.

One of the main sources of terrigenous material was the abrasion of coastal cliffs, which extend for more than 2 thousand km and are composed mainly of compositionally heterogeneous sandstones, mudstones, and loams of different age. Erosion is at a maximum in slopes dipping at more than 4°, which are composed of Quaternary deposits, especially talus loam. The most intense abrasion is observed in the widest parts of the Bratsk reservoir, with the most extended coasts consisting of loose Quaternary deposits.

The physicochemical properties of the rocks and the volume of the abraded material determine the flux of elements in the reservoir. The highest contents of the elements in question were observed in mudstones, in particular, in the mudstones of the Cambrian Upper Lena Formation. The sandstones are higher only in Co and contain other elements in lower concentrations than those in the mudstones and loams.

The migration and differentiation of bottom sediments and related accumulation of elements are driven by wave processes, which are different in each of the reservoirs. During wind–wave activity periods, the water mass of the Angara cascade is characterized by mechanical stratification of the currents and the formation of layers corresponding to definite dynamic states of particles of the sedimentary material: layers of stirring, transfer, and sedimentation. The stirring layer corresponds to the depth of wave penetration, with the transfer of suspended material oriented mainly normal to waves. The thickness of these layers depends on the acceleration length of waves having different directions [21]. Winds directed along the water outflow are of short time duration and small rate. However, their influence on the water surface causes the superposition of wind currents on discharge currents and the movement of the entire water mass toward the dam. The rate of the drift current in the 13-m-thick stirring layer can reach 32 cm/s, which is high enough to transfer even fine-sand particles in a suspended state.

The highest repetition rate is shown by winds directed opposite to the natural water outflow in the reservoirs. The turbulence caused by winds of this direction stirs up the top layer to a depth of 5–11 m, with the development of a turbulent whirlwind and highly turbid “clouds” (280 g/m^3) at the stirring–transfer layer interface. The transfer layer that underlies the stirring layer is up to 22 m thick and consists of two parts. The drift currents in the upper part coincide with the wave direction, while the water in the lower parts is transferred by opposite currents toward the dam with a rate of 7–14 cm/s, causing the migration of silt–clay particles [22].

According to the classification of the mechanical transfer mechanisms of the sedimentary material proposed by Murdmaa [23], the transfer and precipitation of sedimentary particles at the coastal banks of the Angara cascade reservoir leads to the formation of the lithodynamic type of deposits precipitated by the near-bottom hydrodynamic flows. During storms, the coasts are strongly affected by waves and provide significant amounts of terrigenous material, which is transferred and accumulated along the banks. The material is supplied to the stirring zone, where it moves as drawn and suspended fluxes, forming banks of sandy and pebbly material. The average transportation velocity of sand fluxes is 30–35% of the current velocity, while the medium- and fine-grained material is transferred with a velocity of 40–41% and about 50%, respectively. The transportation velocity of silt–clay particles practically coincides with that of the water flow. The content of suspended particles varies from the water level to the outer edge of subwater bank depending on the composition of the abraded coastal cliffs as follows: 6.4–0.16 kg/m^3 for loams, eroded 0.6–0.05 kg/m^3 for mudstones, and 0.25–0.1 kg/m^3 for sandstones [24].

Coastal banks are a lithologically–geochemically active type of sedimentation environment. They account for slightly more than 1% of the total reservoir area of the Angara cascade but accumulate much clastic material. During the abrasion of loams, up to 50% of the material remains in the coastal zone to form banks from 20 to 100 m and more wide. An 80-cm thick layer of coarse silt is precipitated from the near-bottom hydrodynamic flow and accumulated annually at the bank. The abrasion of mudstones leads to the precipitation of detritus–sandy material with a pelitic matrix with a rate of 30 cm/yr and to the formation of 10–30 m wide banks. During the abrasion of sandstones, more than 50% of the eroded material is precipitated in the coastal zone, forming sandy banks more than 40 m wide. The depth at the outer edge of the bank corresponds to the lower limit of abrasion caused by the most recurrent waves. In the Angara cascade reservoirs, these depths are 3–10 m.

At the outer edge of the bank, the height of the alluvial layer periodically decreases because of the gravitation transfer of the material to the foot of the subwater slope of the bank, which is also referred to as the depth drop off. The gravitational transportation is facilitated by the high rate of sediment accumulation, the sharp increase in the bottom slope, the grain-size composition, and a weak compaction of the sediment. Waves disturb the stability of the material and its transfer in the form of semiliquid flows and subwater landslides. Poorly sorted but coarser grained sediments are formed at the depth drop off. The abrasion of sandstones produces sands. The abrasion of mudstones and loams near the foot of the subwater slope leads to the formation of coarse silts of variable thickness. A 50-cm layer is formed at the depth drop-off during the transportation of material from coarse silt banks, and a significantly thinner layer is produced by the erosion of sandy banks [25]. The lower boundary of the bottom of the subwater slope is outlined by a 20-m isobath for all the reservoirs, because this depth is the maximum possible penetration depth for waves caused by winds blowing with a speed of more than 15 m/s for a few days, i.e., during strong autumn storms.

Beyond the bank, the suspended material is transferred in the stirring and transfer layers by drift, compensation, and sink flows. In terms of the lithodynamic conditions, the flooded terraces and the riverbed belong to

Table 1. Average contents of trace elements in the coastal zone, ppm

Area, abraded rock	Fe	Ti	Mn	Cr	Ni	Zn	Cu	Pb	V	Co
Rassvet area, mudstones	29000	9000	1400	116	11	86	65	17	167	5
Zaslavsk area, deluvial loam	22000	7000	1060	135	87	76	50	12	110	15

the sedimentation area that is not affected by waves and has low current velocities, occasionally as low as zero. The high-velocity regime is favorable for the aggregation of particles and the precipitation of terrigenous material from the suspensions. The bottom deposits at the flooded terraces are poorly sorted and consist mainly of coarse silt and fine silty muds. The height of the sedimentary layer varies from 1 to 10–25 cm.

In the transition zones between the looded terrace and the old channel of the Angara River, a sharp change in the bottom slope causes an increase in the thickness of the highly turbid flow owing to the ascent of the suspension in the overlying water layer. A 2–5 m nepheloid layer with up to 400 g/m^3 suspensions is formed above flooded terraces and riverbed [22]. The flooded riverbed is characterized by the precipitation of scattered suspension material transferred by weak currents or, if the latter are absent, by the direct precipitation of terrigenous suspension. This produces bottom deposits of coarse silt, fine silt, and silt–clay mud, which are the precipitation products of sedimentation flows. The thickness is 1.5–17 cm for coarse silts, 1–25 cm for fine silty muds, and 5–10 cm for silt–clay muds, with the latter containing 51–58% pelite. The sorting coefficient is 2.28–5.00 and higher.

A change in the lithodynamic settings and structural features of the rocks in the coastal zone of the Angara cascade reservoirs is expressed in the lithological–geochemical differentiation of the bottom deposits. We constructed generalized lithological–facies profiles that characterize the areas with the most abraded coasts composed of mudstones and sandstones. The profile passes across the main subwater topographies (coastal bank, foot of the subwater slope of the coastal bank (depth drop-off), flooded Angara terrace, and the old Angara riverbed) and shows anomalies of the accumulation and removal of chemical elements.

The distribution of bottom deposits and the contents of chemical elements in them were considered using the example of the Rassvet (Fig. 2) and Zaslavsk (Fig. 3) areas of the Bratsk reservoir, which was repeatedly studied by a 1 : 50000 ground survey. Owing to the regional geological and geomorphological specifics of the coastal zone of the reservoir, the element distribution can locally deviate from the general scheme of the lithological–geochemical differentiation of the bottom deposits.

The abrasion coast of the Rassvet area is composed of mudstones of the Cambrian Upper Lena Formation, which were formed in lagoonal–marine and coastal–deltaic environments. The rocks have a massive or thinly bedded structure and a silty texture with 30–40 vol % carbonate–clayey cement [26]. The mudstones contain 43.63% SiO_2, 8.26% aluminum hydroxide and 2.9% Fe_2O_3 [27]. The Ti, Cu, and Pb contents in the matrix are higher than the regional background values (Table 1).

During the open-water period, NW-trending storm waves with an acceleration distance of 10–20 km attack almost perpendicular to the coast. The average rate of the abrasion-related recession of the coastal cliff edge is 2 m/yr. The mudstones are disintegrated into blocks and detritus, which accumulates near the foot of the coastal cliff. Most of the 100-m wide bank is composed of sands with a silt matrix. The subsequent action of waves and currents causes the abrasion of clastic material, which partially slides along the subwater slope of the bank, accumulating near its foot (depth drop-off) as a 4- to 30- or 35-cm-thick layer of dense, coarse reddish-brown silt with an admixture of fine sandy material. Finely dispersed particles were removed beyond the bank and precipitated in the old Angara riverbed. On the flooded terraces, the upper part of the sedimentary succession consists of coarse silt 5–15 cm thick, which is underlain by a 10- to 30-cm layer of loose–clumpy soil overlaying the gray alluvial sands. In the old riverbed, pebble is overlain by fine silty mud from 4 to 27 cm thick.

The examination of geochemical fields in the bottom deposits along the generalized profile of the Rassvet area allowed us to distinguish the following associations of chemical elements, which are arranged in order of decreasing concentration coefficients:

(1) coastal bank: Cr (2.6) Ti (2.2) Mn (1.7) Zn (1.5), Ni (1.4) V (1.4) Cu (1) Fe (0.9) Co (0.8) Pb (0.7);

(2) depth drop-off: Cu (3.3) Ni (3) Ti (2.6) Zn (2.2) Mn (2.1) Fe (1.4) V (1.2) Cr (1.1) Pb (0.8) Co (0.8);

(3) flooded terrace: Ni (3.4) Ti (3.2) Mn (2.9) Cu (2.8) Zn (2.7) Fe (1.8) Cr (1.6) V (1.6) Co (1.1) Pb (0.7); and

(4) old Angara riverbed: Mn (3.2) Zn (2.4) Ti (2.2) Cu (2.2) Ni (2) V (1.5) Pb (1.2) Cr (1.1) Co (0.9) Fe (0.8).

The minimum accumulation of transition elements (Fe, V, and Cr) was found in the flooded Angara riverbed with bottom sediments composed of fine silty muds. The bank sands show the maximum Cr contents, which decrease inward the reservoir with decreasing grain size. Significant amounts of iron in the clay matrix of mudstones is explained by iron removal from the bank with pelitic particles and its rapid transition into the suspended state. The maximum contents of

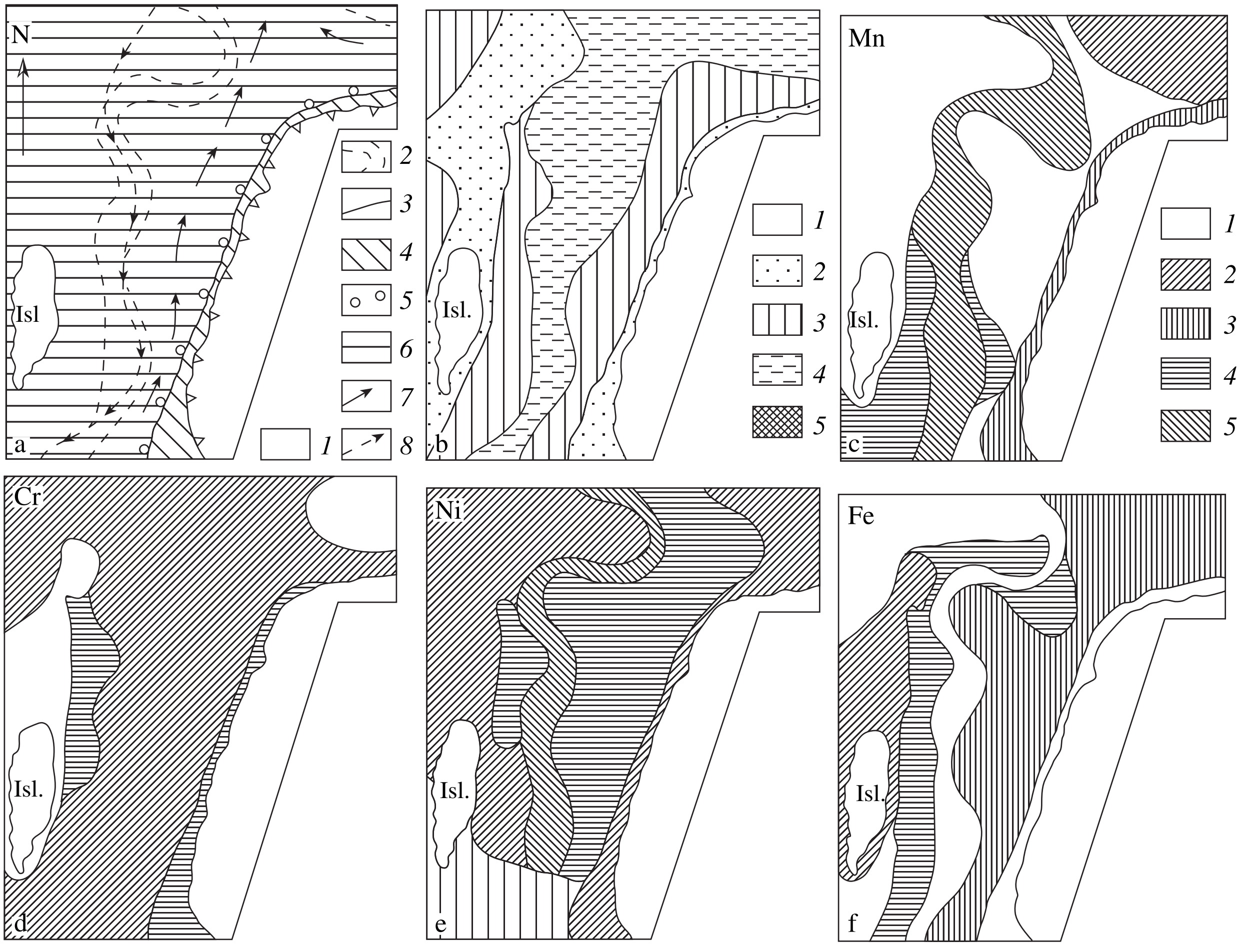

Fig. 2. Schematic 1 : 100000 maps of (a) the lithodynamics; (b) types of bottom deposits; and the distribution of (c) Mn, (d) Cr, (e) Ni, and (f) Fe in the Rassvet area. (a) (*1*) Land; (*2*) flooded Angara riverbed; (*3*) abrasion coast; (*4*) deposits of the bottom hydrodynamic flows; (*5*) gravitation deposits; (*6*) deposits of sedimentation flows; (*7*) drift flows in the stirring layer during the period of high waves of NW direction; (*8*) compensational opposite currents in the transfer layer during period of high waves of NW direction. (b): (*1*) flooded soil; (*2*) sand; (*3*) coarse silts; (*4*) fine silt muds; (*5*) silt–clay muds. (c–f): (*1–5*) Contents of chemical elements: (*1*) low (below the background level); (*2*) average (1–1.5 background values); (*3*) elevated (1.5–2 background values); (*4*) high (*2–3* background values); (*5*) very high (more than 3 background values).

vanadium and iron are found in the bottom deposits of flood terraces, which are unaffected by waves and outflow currents. This area is also characterized by the accumulation of Ti, a hydrolyzate element contained in clastic material.

Among the manganese subgroup, only the manganese content is correlated with the granulometric composition, showing the minimum contents in the sandy deposits and the maximum one in the fine silty muds of the flooded riverbed. The contents of chalcophile lead also demonstrates a correlation with the grain size of the sediment accumulating above the background contents in fine silty muds.

The above succession of elements shows that the coastal banks of the area are transit zones for iron, cobalt, and lead. Lead and cobalt are not retained on the depth drop-off. Sediments deposited in the flooded riverbed display cobalt and iron contents below the background values.

In the Zaslavsk area, the coast is shielded from the most frequent western winds. The length of the wave acceleration for the NW-trending direction can reach 7–11 km, with the stirring layer spanning a water column from the surface to a depth of 5–10 m and underlain by the transfer layer formed by compensational countercurrents at a depth of up to 15–20 m.

The edge of the coastal cliff retreats with a velocity of 5–6 m/yr. The coast is composed of diluvial loams resting on the Upper Cambrian rocks. The diluvial loams have high calcite contents, with carbonates reaching up to 13–20% [28]. The loams are chemically dominated by SiO_2 and contain significant amounts of Al_2O_3 (11.06%) and CaO (7.37%) [27]. Trace elements occur in insignificant amounts only slightly exceeding the background values (Table 1).

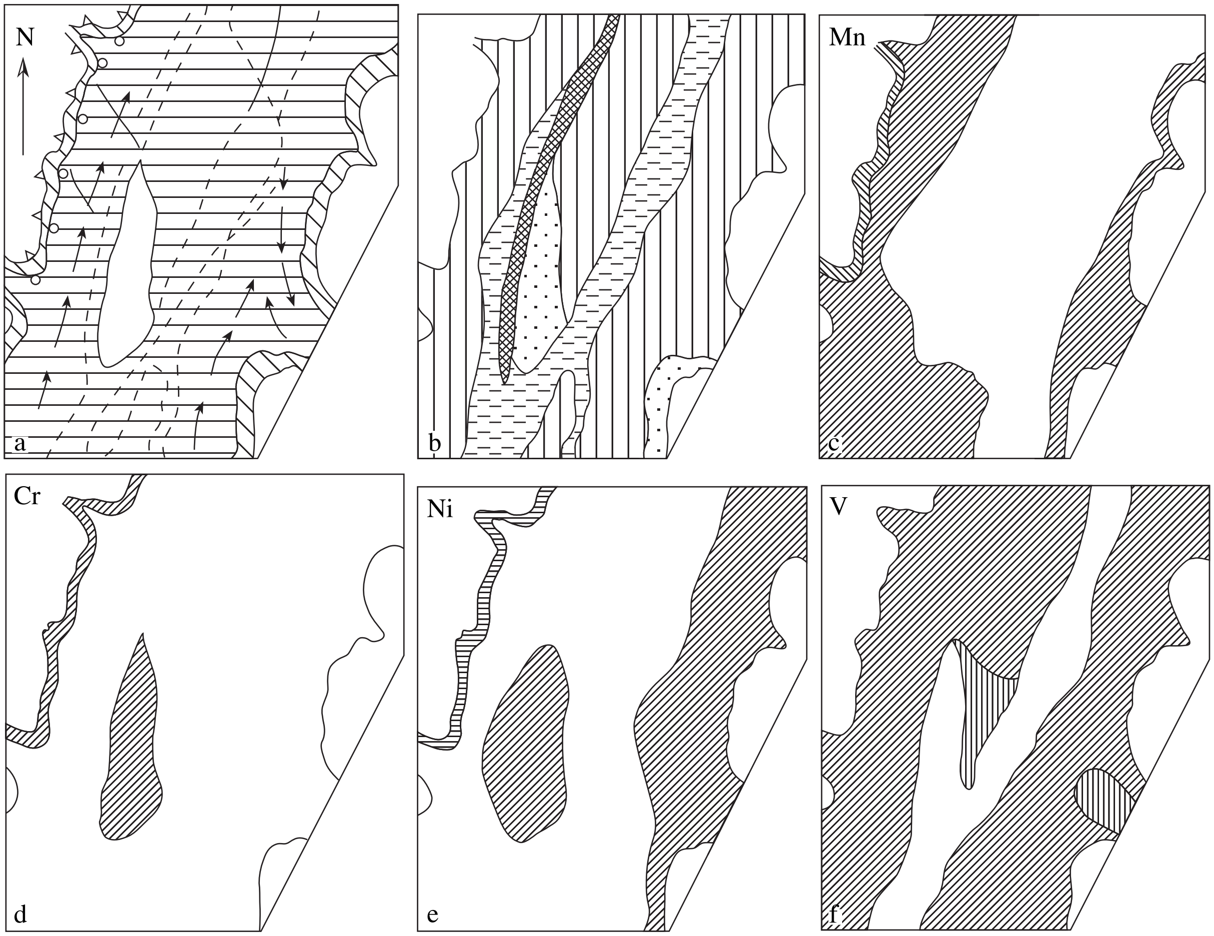

Fig. 3. Schematic 1 : 100000 maps of (a) the lithodynamics; (b) bottom deposits; and the distribution of (c) Mn, (d) Cr, (e) Ni, and (f) V in the Zaslavsk area. The symbols are shown in Fig. 2.

The abrasion of loams results in the formation of a coarse-silt bank about 50 m wide. The dynamic wave impact on the deposits of the outer edge of the bank leads to their liquefying, transportation along the subwater slope to its foot, and the partial transition of particles into the suspended state, thus, producing a 70-cm layer of gravitational bottom sediments of coarse silt on the depth drop-off. The suspended material beyond the bank is transported by drift currents throughout the reservoir and deposited. On the flooded terraces and old islands, the bottom deposits rest on a soil layer, that overlays the terrace alluvium. Coarse silts are 3–4 cm thick, while fine silty muds are 1.5–2 cm thick. The sandy-clayey alluvium in the flooded riverbed is covered by 1.5 cm of fine silty muds with patches of silty–clayey muds.

Within the area, the following series of element distributions can be distinguished in the generalized profile of the bottom deposits:

(1) Coastal bank: Mn (2.3) Fe (2.2) Ni (1.3) Ti (1.2) V (1.2) Zn (1) Cu (1) Pb (1) Cr (0.9) Co (0.5);

(2) Depth drop-off: Ti (1.2) Zn (1.2) Mn (1) Fe (1) Cu (1) Pb (1) V (1) Co (1) Cr (0.9) Ni (0.7);

(3) Flooded terrace: V (1.2) Fe (1) Cu (1) Ni (0.9) Zn (0.9) Ti (0.8) Cr (0.8) Co (0.8) Mn (0.6) Pb (0.6); and

4. old Angara riverbed: Ti (1.1) Zn (1.1) Fe (1) Pb (1) Co (1) Ni (0.9) Cu (0.9) Mn (0.8) Cr (0.8) V (0.7).

The geochemical field of the bottom deposits of the Zaslavsk area shows a weakly contrasting distribution. The only exception is the elevated Mn content in the coastal bank, which decreases inward the reservoir, showing a negative correlation with the granulometric composition. The predominance of fine silt and clay particles in the bottom deposits is not favorable for Cr accumulation (Fig. 2).

Available data on the reservoirs of the Angara cascade attest to the most intense accumulation of elements in the vicinity of the abraded object, i.e., on the coastal bank. This is related to the fact that the geochemical fields of coastal banks are formed by periodical fluxes (during storms) of the sediment-forming material of abraded coastal cliffs that is transported and sorted by waves and currents. The anomalous contents

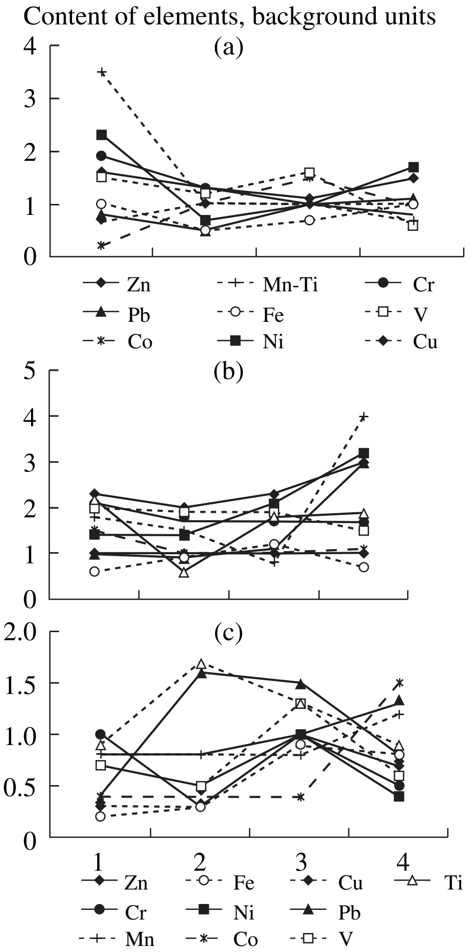

Fig. 4. Distribution of concentration coefficients in the bottom sediments on (1) the bank (2) depth drop-off. (3) flooded terrace, and (4) the flooded riverbed of the reservoirs of the Angara cascade in the areas of abraded coastal cliffs composed of (a) loams, (b) mudstones, and (c) sandstones.

of a wide spectrum of elements (Mn, Ti, Ni, P, Cr, Zn, V, and Fe) are accumulated in coarse silts during loam abrasion. Mn, Ti, and Ni are the first to precipitate from the suspension-carrying flow, while Fe is more resistant to precipitation and is contained in the background concentration. The abrasion of mudstones leads to the removal of Fe and the formation of local anomalies of Zn, Ti, Cr, V, Mn, Co, and Ni and background contents of Cu and Pb. During the abrasion of sandstones, coastal banks are a transit zone for most elements. Fe, Co, Pb, Ni, V, Mn, Ti, and Zn that are accumulated in the matrix of eroded sandstone are removed from the bank. The periodic wave attack of the bank brings about stable background values only of Cr, which is deposited with sandy particles (Fig. 4).

A wide spectrum of elements in concentrations ranging from one to two background values are accumulated beyond the bank on the subwater slope of the bank and depth drop-off, where bottom deposits are precipitated from gravitational flows. In particular, during the abrasion of loams in the coastal cliffs, some elements (Ni, Fe, and Pb) are removed into the open part of the reservoir, while others are precipitated near the foot of the subwater slope of the bank (depth drop-off), yielding anomalous concentrations of Cr, Zn, V, Ti, Mn, Cu, and Co in the coarse-grained silts. The sediments have lower contents of elements that enrich the bank, for example, the contents of Mn, Ti, and Ni decrease by a factor of more than three and that of Fe by a factor of two. Cr, Zn, and V are also partially removed (Table 2). During the abrasion of mudstones near the foot of the subwater slope, the coarse silt bottom deposits retain approximately the same anomalies as the bank with the exception of Fe, Pb, and Ti, which are below the background values. Weakly sorted sands formed by the abrasion of sandstones, as on the bank, show no significant accumulation of elements, with the exception of Pb and Ti, which only insignificantly exceed the background levels.

The distribution of Mn, Co, Ni, and Zn in the low-energy areas, which are distant from the coast and dominated by sedimentation flow deposits, depends mainly on the grain size; i.e., an increase in the amount of pelitic particles leads to an increase in the element contents. For example, the flooded terrace with high contents of pelitic particles shows a weakly contrasting accumulation of many elements. The widest element association is typical of areas whose abraded coasts are composed of loams. This lithodynamic setting is favorable for the insignificant accumulation of adsorbed species of V, Zn, Ni, and Pb, with Mn, Ti, and Cu contents similar to those in the depth drop-off. No elements other than Fe are removed from the bottom deposits on the flooded terraces. The mudstone abrasion areas display more contrasting accumulation of elements (Fig. 4).

In the old Angara riverbed unaffected by waves, the loam and sandstone abrasion areas demonstrate the same weakly contrasting anomalies as on the flooded terraces. The areas of mudstone abrasion strongly differ from them in having relatively high concentration coefficients (more than two regional background values) of Mn, Ni, Pb, and Zn. The Ti, Cr, and Cu contents in the riverbed are similar to those on the flooded terraces.

The bank deposits occupying the narrow bands along the abraded coasts have elevated concentrations of weakly soluble Cr, which is linked to sandy sediments. The highest concentration coefficient of the element was found at the water level and near the outer edge of the bank. Farther along the profile, Cr continues to accumulate in sandy fractions. Cr, Ti, and V are intensely disseminated with increasing distance from the coast and with depth.

Settings with sluggish hydrodynamics are characterized by the efficient precipitation of material from sedimentation flows and the accumulation of fine-silty and silt–clay muds with elevated contents of Mn, Pb, Co, Ni, and Zn, which indicates the leading role of

Table 2. Indicators of the lithological–geochemical differentiation of the bottom deposits of the Angara cascade reservoirs in the generalized profiles

Topographies	Content of element, ppm										Contents of fractions, %			Content, %		pH
	Fe × 10^3	Cr	V	Mn	Co	Ni	Pb	Zn	Cu	Ti	1–0.05 mm	0.05–0.01 mm	<0.01 mm	carbonates	OM	
Areas of loam abrasion																
Coastal cliff	46.7	75	82	325	34	41	11	48	30	4000	40.0	44.0	16.0	21.44	9.25	8.79
Coastal bank	34.5	171	120	1400	4	69	16	64	21	8750	43.1	45.0	11.9	21.88	8.48	7.73
Depth drop-off	6.9	117	56	300	8	21	8	50	9	2500	40.9	48.4	10.7	24.27	10.43	7.76
Flooded terrace	24.15	90	128	400	30	30	20	44	30	2500	33.7	43.9	22.4	8.81	8.06	6.15
Old river bed	34.5	72	48	280	20	51	22	60	30	1750	22.5	41.1	36.4	14.86	12.41	7.16
Areas of mudstone erosion																
Coastal cliff	84	88	11	860	23	79	18	83	30	5400	69.0	19.5	11.5	15.83	7.10	7.00
Coastal bank	20.7	189	160	720	30	42	20	92	30	5500	66.9	20.9	12.2	15.44	6.89	7.65
Depth drop-off	31.05	153	152	600	20	42	18	80	30	1500	39.4	49.5	11.1	28.29	10.69	7.86
Flooded terrace	41.4	153	152	320	20	63	22	92	30	4500	39.2	40.4	20.4	16.84	8.96	5.86
Former river bed	24.15	153	120	1600	22	96	60	120	30	4750	39.2	37.9	22.9	19.13	9.85	6.98
Areas of sandstone abrasion																
Coastal cliff	1.5	50	55	220	37	40	12	55	22	4000	97.7	2.3	0	3.30	3.17	6.87
Coastal bank	6.90	90	56	300	8	21	8	30	9	2250	99.2	0.8	0	15.89	7.00	6.83
Depth drop-off	10.35	27	40	320	10	15	32	32	10	4250	56.1	36.3	7.6	9.58	5.25	5.99
Flooded terrace	31.05	90	104	200	8	30	30	40	30	3250	58.2	35.6	6.2	16.41	11.70	5.23
Old river bed	27.6	45	48	480	30	12	16	52	21	2250	55.9	28.4	15.7	23.81	10.74	6.83

mechanical precipitation of suspension during the migration of elements in the reservoirs. The precipitation of Co and Ni depends, in addition to purely mechanical accumulation, on clay particles and on the chemical specifics of the sedimentation environment. Low Co and Ni content are observed in the organic-rich sediments (Table 2).

Fe and Cu typically have contents below or near the background. Fe shows a high migration ability and is accommodated mostly in the bottom deposits of the reservoirs in the form of carbonate species. The pH and oxygen fugacity of the reservoir ensure favorable conditions for iron sorption by clay minerals, which is expressed in the appearance of an Fe maximum in the fine silt and silt–clay muds [29]. Copper is linked with the pelitic fraction. With decreasing grain size, the Cu content increases, and Cu is accumulated mainly in the deep-water deposits. The abrupt change in the copper content from fine silt muds to silt–clay rocks is related to the high migration ability of the element and its predominant precipitation from the solution.

CONCLUSIONS

Regional features of the Angara cascade reservoirs define the formation and distribution of bottom sediments and the migration and accumulation of trace elements in them. The bottom deposits were formed in a setting of a predominant terrigenous influx. The change in the lithodynamic settings and structural features of the rocks in the coastal zone of the Angara cascade reservoirs maintain the lithological–geochemical differentiation of the bottom deposits.

The transverse profiles along the bottom deposits of the Angara cascade reservoirs vary in the proportions of sandy, silty, and pelitic particles and element associations. The geochemical fields of the coastal banks are formed at repeated fluxes of sediment-forming material from abraded coastal cliffs with subsequent stirring and transportation of particles by waves and currents. In the areas with a calm hydrodynamic setting, the material is efficiently precipitated from sedimentation flows with the accumulation of fine silt and silt–clay muds and the sorption of elements on clay particles.

The examination of the composition of the abraded rocks, the sedimentation setting, and the lithological–geochemical differentiation of the bottom sediments showed that the scattering and differentiation of the material supplied into the reservoir owing to abrasion occurs simultaneously with the formation of new types of bottom sediments, which partially inherit the composition of the precursors. It was established that changes in the lithodynamic settings in the reservoirs of the Angara cascade reservoirs and the trends of the lithological–geochemical differentiation of the bottom sediments are governed by the same laws as in natural basins.

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