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GEOGRAPHY

Particulate Material Composition in the Lena River–Laptev Sea System: Scales of Heterogeneities

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Values of particulate material parameters (VPP) are among the main factors determining the scale of terrigenous material alteration in the river–sea system, because they are extremely sensitive to the specificity of provenance rocks, exogenous transformations, and anthropogenic effects during mobilization and transfer [1–4, 8]. To study in detail the spatiotemporal heterogeneities of the VPP, the interdisciplinary expedition of

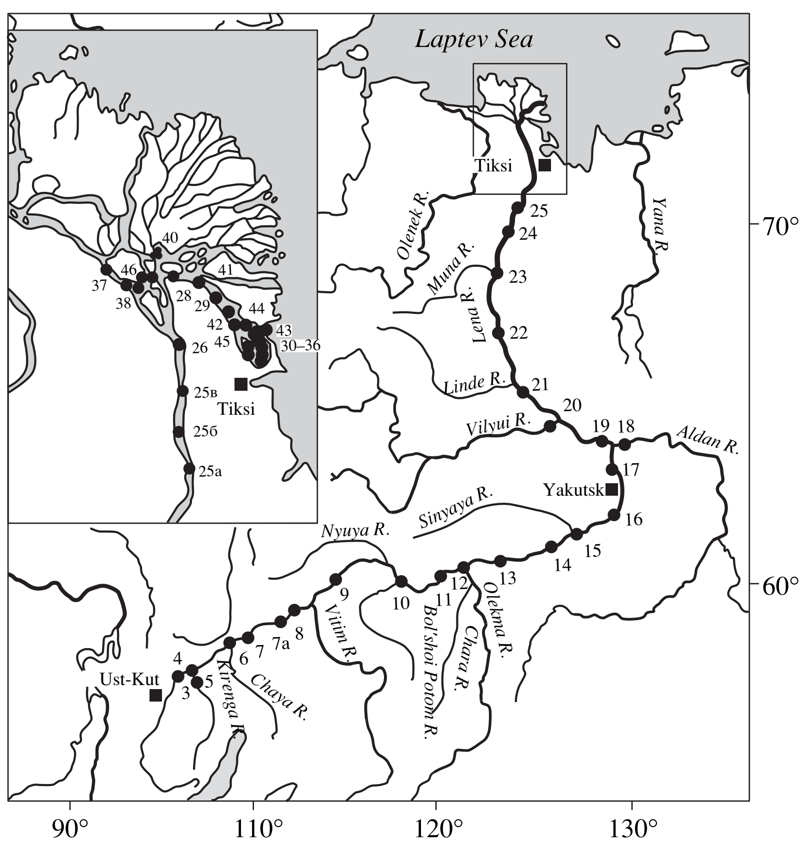

Fig. 1. The expedition route and stations of complex investigations. The inset shows the major channel area of the Lena River in the canyon of the Verkhoyanskii Ridge and delta.

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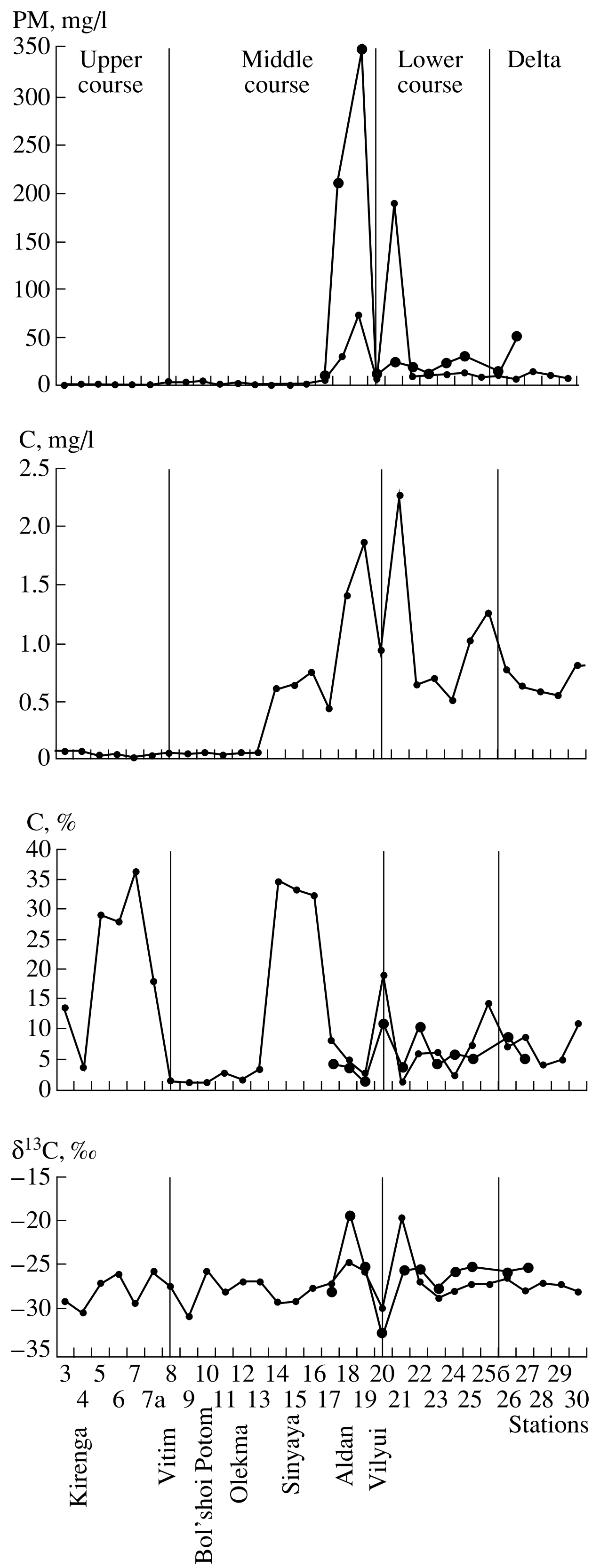

Fig. 2. Spatiotemporal variations in the PM composition across the profile from the upper course of the river to the delta and backward (large dots).

the Vinogradov Institute of Geochemistry (Irkutsk) was carried out in summer 2003. The study region included for the first time a large area of the major course of the Lena River extending from its upper reaches (660th km from the mouth) to the prodelta in the Laptev Sea. Previously, studies of that kind involved only the lower and partially middle courses of this river system [13, 14]. Fifty-eight stations were established (including eleven repeated stations) from onboard the *Moskovskii-11* motor ship during the back route of the expedition (Fig. 1). We studied the following parameters in suspended particulate material (PM): the total PM content, grain size composition (using an Analysette 22 laser analyzer), organic carbon (C), total nitrogen (N), and stable isotopes $\delta^{13}C$ and $\delta^{15}N$ (using a Finnigan MAT Delta Plus mass spectrometer combined with element analyzer). The hydrophysical structure of water was registered by CTD sounding and acoustic Doppler current profiler (ADCP). Hydrochemical characteristics were determined by standard methods.

Spatial variability of the VPP. The Lena River runoff in 2003 was close to the annual mean value. The observation period on the route to the delta (June 25–July 22) coincided with the second wave of the spring–summer flood caused by rains and a continued melting of snow in mountainous catchment regions. According to weather conditions, the summer of that year in the upper course of the river was a low-water season.

Most of the channel in the river upper course (0–1463 km from the mouth) lies in a deeply incised valley across the North Baikal Highland. According to [5], the water surface slope reached 2.7 m/km in some areas, resulting in a high velocity of water flow and erosional mechanism of processes in the channel. Due to the reasons mentioned above, the PM content decreased to 0.2–2.1 mg/l, which is typical of mountain rivers. Heterogeneities of the VPP distribution were revealed after the entry of the Kirenga tributary. Its water was characterized by a still lower PM content, which provoked the PM decrease in the major channel (Figs. 1, 2; Tables 1, 2). In terms of lithogenetic classification, the PM in the main channel can be ascribed to the terrigenous–biogenic type (70% < MC < 50%) in contrast to the biogenic–terrigenous (70% < OC < 50%) and terrigenous (MC > 70%) types before the confluence of the Lena River with the Kirenga River. An increased input of the organic component (OC) due to inflow of the Chaya tributary located 124 km downstream of the Lena River produced the biogenic-type PM (OC > 70%).

An increase in the water content in the major channel downstream of the entry of the Vitim tributary, which marks the middle course of the Lena River (1463–3077 km), was accompanied by the analogous trend of changes in the PM and MC values, as well as the transformation of PM into the terrigenous type. According to [6], the geographic confinement of the region to the area of intense cyclic evolution promoted a high recurrence of atmospheric precipitation over the

Table 1. Spatial VPP variations in the Lena River water

Parameters	Upper course (Sts. 3–7)	Middle course (Sts. 8–19)	Lower course (Sts. 21–25)	Delta (Sts. 26–42)	Prodelta (St. 43)
PM, μg/l[1)]	0.12–2.1/0.83	0.8–77.6/11.4	5.0–190.5/32.1	7.3–85.2/22.1	24.3
C, %[2)]	1.2–36.2/18.5	1.1–33.5/11.7	1.2–18.7/5.3	2.9–11.3/6.3	4.4
C, μg/l[3)]	4–71/41	360–1874/502	509–2275/1053	562–2727/1027	1063
N, %[4)]	0.2–5.3/2.6	0.2–3.37/1.3	0.1–2.1/0.8	0.3–1.4/0.7	0.5
N, μg/l[5)]	3–10/6	5–177/60	58–167/103	58–300/112	120
OC, %[6)]	2.4–72.4/36.0	2.2–67.0/23.4	2.4–37.5/10.6	5.8–22.6/12.7	8.8
MC, %[7)]	27.6–97.6/64.0	33.0–97.8/76.6	62.5–97.6/89.4	77.4–94.2/87.3	91.2
C/N[8)]	6.9–10.3/8.4	7.7–12.1/9.7	8.5–13.2/9.8	8.0–9.1/9.1	8.9
δ^{13}C, ‰[9)]	–31.1…–25.8/–28.3	–30.9…–24.6/–27.9	–30.0…–19.6/–26.8	–30.4…–24.5/–26.7	–25.6
δ^{15}N, ‰[10)]	0.9–3.3/2.7	1.9–5.4/3.1	2.4–5.0/3.6	2.1–6.1/3.9	3.6
Psammite, %[11)]	12.6	1.6–6.2/2.0	1.5–9.5/5.5	4.1–15.6/9.6	1.5
Silt, %[12)]	61.1	27.7–60.4/42.6	55.2–56.8/56.0	30.3–61.4/45.9	23.6
Pelite, %[13)]	26.3	33.4–72.3/55.4	33.7–43.3/38.5	34.5–54.4/44.5	74.9
PM type[14)]	PlS	PlS, SPl, Pl	PlS	PlS, SPl	Pl

Note: The range of values and average value are given to the left and right of the solidus, respectively. (1) Suspended particulate material (PM); (2) organic carbon content in PM; (3) suspended organic carbon concentration in water; (4) total nitrogen content in the PM; (5) total nitrogen concentration in water; (6) contribution of organic component, OC (calculated as C content in PM × 2); (7) contribution of mineral component, MC (100% – OC); (8) C/N ratio; (9) δ^{13}C value; (10) δ^{15}N value. Grain size fractions of the PM: (11) psammite, Ps (1–0.1 mm), (12) silt, S (0.1–0.01 mm); (13) pelite, Pl (0.01–0.001 mm). Dimensional (lithological) types of the PM: pelitic silt (PlS), silty pelite (SPl), pelite (Pl). (Sts.) Stations.

catchment on the left bank of this channel segment. The Aldan River, the largest tributary in its basin, provides a 70%-increase in the water discharge during the spring–summer flood phase. Therefore, the Lena River becomes a powerful river system downstream of the confluence with the Aldan River [5]. The number of aggradation landforms increases due to widening of the channel up to 3–4 km. Small-scale cyclonic circulations, thick accumulations of driftwood, and plant remains on the surface were observed in the frontal zone of the water mixing area. The PM content increased by an order of magnitude and reached 30–77 mg/l. Heterogeneities of the VPP aggravated by floating dredge discharges at the lower course of the Aldan River were indicated by a spotty pale yellow to brown color spectrum of the water. The transitional terrigenous–biogenic and biogenic–terrigenous PMs were transformed into the terrigenous type. The carbon isotopic composition changed from –30.95 to –24.58‰ (Fig. 2; Tables 1, 2).

The last substantial increase in the water content is caused by the water discharge of the Vilyui River. Its entry marks the lower course of the Lena River (3077–4232 km). Although the PM content is low (5 mg/l) in the tributary mouth, the major channel was marked by an apron of dull brown water with PM and C contents equal to 190 mg/l and a C concentration in the water of 2274 μg/l, respectively. The δ^{13}C value increased to –19.6‰ ($\Delta\delta^{13}$C up to 6.2–10.4‰), and the C/N ratio increased to 13.2 (ΔC/N = 2.6). Such values were recorded nowhere in the section from the upper course of the river to the prodelta area. This VPP anomaly can be related to waste discharges from the Lunkhutui and Sangar coal deposits (areas of stations 21 and 19, respectively). The Lena River valley widens up to 40–60 km at 120 km from the confluence with the Vilyui River, and aggradation islands separate the channel into several large branches and tributaries. A decrease in the water surface slope is accompanied by losses in the load capacity of the flow and withdrawal of a significant volume of PM from the water migration system. The decrease in values of some PM parameters is as much as one order of magnitude and remains at that level up to the delta bifurcation area (Fig. 2; Table 3).

The major channel area located between stations 24–26 (Fig. 1) before the delta head lies in the tectonic canyon of the Verkhoyansk Ridge. This area lacks any signs of VPP variation, such as sharp PM increase at the entry of water flow into the canyon [1, 9, 12]. In terms of river hydraulics, this situation accounts for the stability of the hydrodynamic structure of water flow to reconfiguration due to the invariability of the area of its active cross section, because contraction of the major channel is compensated by an increase in depth from 8–12 to 30 m. Along the whole length of the canyon, the PM content varied from 8.7 to 18.6 mg/l. Heterogeneities of other VPPs were also insignificant (Fig. 2).

The lower course of the Lena River terminates at its entry into the delta (4232nd km), one of the world's largest deltas after the Mississippi and Mekong deltas. The water table width increased several times, and the

Table 2. VPP variations in water of upper and middle courses of the Lena River

Parameters	Upper course				Middle course					
	St. 3	St. 4	**St. 5**	St. 7	**St. 8**	St. 9	**St. 10**	St. 11	**St.12**	St. 13
PM, μg/l	0.5	2.1	0.1	0.1	4.1	4.0	5.3	1.3	3.6	2.0
C, %	13.4	3.6	29.2	36.2	1.2	1.1	1.2	2.8	1.7	3.3
C, μg/l	67	71	29	43	48	43	61	36	61	66
N, %	1.8	0.5	3.3	5.3	0.2	0.1	0.1	0.4	0.1	0.3
N, μg/l	9	10	3	6	6	6	7	5	5	6
OC, %	26.8	7.2	58.4	72.4	2.4	2.2	2.4	5.6	3.4	6.6
MC, %	73.2	92.8	41.6	27.6	97.6	97.8	97.6	94.4	96.6	93.4
C/N	7.5	7.4	8.9	6.9	8.0	7.7	9.6	7.5	12.1	11.3
δ^{13}C, ‰	–29.3	–30.6	–29.3	–29.5	–27.7	–30.9	–25.9	–28.3	–26.9	–27.0
δ^{15}N, ‰	3.3	2.6	0.9	4.2	6.5	3.5	5.4	3.5	3.1	1.9
R, km	876	1045	1063	1245	1463	1621	1859	2060	2121	2201
L, km	–	644	–	–	1743	–	505	–	1344	–
S, %	–	1.9	–	–	9.4	–	1.1	–	8.5	–
Psammite, %	–	–	–	–	12.6	–	–	–	–	–
Silt, %	–	–	–	–	61.1	–	–	–	–	–
Pelite, %	–	–	–	–	26.3	–	–	–	–	–
PM type	–	–	–	–	PlS	–	–	–	–	–

Parameters	Middle course								
	St. 14	**St. 15**	St. 16	St. 17		**St.18**		St.19	
				$\rightarrow^{(1)}$	$\leftarrow^{(2)}$	$\rightarrow$	$\leftarrow$	$\rightarrow$	$\leftarrow$
PM, μg/l	0.8	1.9	2.3	5.4	11.1	30.3	21.4	77.0	352.2
C, %	34.6	33.3	32.5	8.0	4.3	4.7	3.8	2.4	1.5
C, μg/l	622	633	761	434	480	1414	817	1874	5133
N, %	3.8	3.7	3.9	0.8	0.5	0.4	0.3	0.2	0.1
N, μg/l	68	71	91	44	56	123	685	177	529
OC, %	69.2	66.6	65.0	16.0	8.6	9.4	7.6	4.8	3.0
MC, %	30.8	33.4	35.0	84.0	91.4	90.6	92.4	95.2	97.0
C/N	9.2	8.9	8.4	9.9	8.7	11.4	11.9	10.6	9.7
δ^{13}C, ‰	–29.4	–29.4	–27.8	–27.5	–28.1	–24.6	–19.4	–25.8	–25.2
δ^{15}N, ‰	2.4	3.1	3.3	2.1	4.8	3.3	4.8	3.3	5.9
R, km	2400	2432	2488	2695		2870		2940	
L, km	–	–	–	–	–	2211		–	–
S, %	–	–	–	–	–	28.9		–	–
Psammite, %	–	6.2	–	–	–	1.6	0.0	–	–
Silt, %	–	60.4	–	–	–	41.9	40.4	–	–
Pelite, %	–	33.4	–	–	–	56.5	59.6	–	–
PM type	–	PlS	–	–	–	SPl		–	–

Note: Station numbers given in bold are located in the estuaries of tributaries: (5) Kirenga, (8) Vitim, (10) Bol'shoi Potom, (12) Olekma, (15) Sinyaya, (18) Aldan. Here and in Table 3, arrows (1) and (2) show stations located downstream and upstream, respectively, of the Lena River. (*R*) Distance from the mouth of the major river; (*L*) length of the tributary; (*S*) catchment area.

Table 3. VPP variations in water of the lower course and delta of the Lena River

Parameters	Lower course									
	St. 20		St. 21		St. 22		St. 23		St. 24	
	→(1)	←(2)	→	←	→	←	→	←	→	←
PM, μg/l	5.0	11.7	190.5	22.9	10.8	17.5	11.5	12.7	12.0	18.5
C, %	18.7	11.3	1.2	3.8	6.0	10.7	6.1	4.7	2.1	6.0
C, μg/l	937	1323	2275	869	652	1877	704	593	509	1104
N, %	2.1	1.3	0.1	0.4	0.5	1.2	0.7	0.5	0.5	0.6
N, μg/l	104	155	167	93	59	205	82	61	58	106
OC, %	37.4	22.6	2.4	7.6	12.0	21.4	12.2	9.4	4.2	12.0
MC, %	62.6	77.4	97.6	92.4	88.0	78.6	77.8	90.6	95.8	88.0
C/N	9.0	8.6	13.2	9.3	11.1	9.2	8.5	9.7	8.7	10.5
$\delta^{13}C$, ‰	–30.0	–32.6	–19.6	–26.4	–26.9	–26.4	–28.7	–28.3	–28.0	–26.5
$\delta^{15}N$, ‰	2.1	2.0	5.0	3.9	2.5	4.9	3.3	3.3	3.4	3.5
R, km	3077		3201		3400		3587		3821	
L, km	2437	–	–	–	–	–	–	–	–	–
S, %	18.2	–	–	–	–	–	–	–	–	–
Psammite, %	0.0	–	9.5	–	–	–	–	–	–	–
Silt, %	27.7	–	56.8	–	–	–	–	–	–	–
Pelite, %	72.3	–	33.7	–	–	–	–	–	–	–
PM type	Pl	–	PlS	–	–	–	–	–	–	–

Parameters	Delta*						
	Head (St. 26)		Stolb Is. (St. 27)		Bykov Branch (Sts. 28–36, 41, 42, 44, 45)	Trofimov Branch (St. 40)	Olenek Branch (Sts. 37–39, 46)
	→	←	→	←			
PM, μg/l	10.6	14.9	7.3	50.1	7.4–44.3/24.1	37.4	7.1–85.2/31.3
C, %	7.3	7.8	8.7	5.4	3.0–11.0/5.1	4.0	2.9–11.3/6.6
C, μg/l	778	1156	636	2693	562–1327/946	1486	633–2727/1290
N, %	0.8	0.8	1.0	0.5	0.3–1.2/0.6	0.4	0.3–1.4/0.8
N, μg/l	82	113	72	271	58–154/102	161	74–300/141
OC, %	14.6	15.6	17.4	10.8	6.0–22.0/10.2	8.0	5.8–22.6/13.2
MC, %	85.4	84.4	82.6	89.2	78.0–94.0/89.8	92.0	77.4–94.2/86.8
C/N	9.5	10.2	8.9	10.0	8.7–9.1/9.4	9.2	8.0–9.1/8.6
$\delta^{13}C$, ‰	–26.6	–26.5	–28.1	–25.6	–28.2…–24.5/–26.4	–24.6	–30.4…–26.7/–27.9
$\delta^{15}N$, ‰	3.9	4.6	3.1	5.0	2.1–6.1/3.8	4.3	3.4–5.7/4.3
R, km	0		5		14–111	18	6–29
L, km	–	–	–	–	–	–	–
S, %	–	–	–	–	–	–	–
Psammite, %	–	–	–	–	4.1–15.6/9.6	–	–
Silt, %	–	–	–	–	30.3–61.4/45.9	–	–
Pelite, %	–	–	–	–	34.5–54.4/44.5	–	–
PM type	–	–	–	–	PlS, SPl	–	–

Note: Station in the mouth of the Vilyui River is given in bold. (*) Distances in the delta are given from its head (4232 km from the mouth of the Lena River or a conditional site at 0 km) across the bifurcation near Stolb Island.

Table 4. Daily mean values of PM flows and its components in the Laptev Sea calculated for the observation period

Parameters	VPP for calculations	Delta branches			Total flux to the sea, t
		Trofimov	Bykov	Olenek	
Water discharge*, m^3/s	–	–	6150.0	–	–
Water discharge distribution between branches**, %	–	75.0	15.0	10.0	100.0
PM, mg/l	7.4	19660.0	3932.0	2621.0	26213.0
C content in PM, %	11.0	2162.5	432.5	288.3	2883.3
OC, %	22.0	4325.0	865.0	576.6	5766.6
MC, %	78.0	15335.0	3067.0	2044.4	20446.4

Note: (*) Data of ADCP measurements by E.B. Karabanov and S. Armstrong; (**) after [5, 10].

water surface slopes decreased to 0.02 m/km [5]. The spreading of the river stream over numerous branches and channels was accompanied by the weakening of its transporting capacity and the withdrawal of PM from the transfer system. As a result, the PM content decreased to 7–11 mg/l. Spatial heterogeneities of this parameter in water of the Trofimov, Bykov, and Olenek branches reflected the lithodynamic trend of channel processes. Over washed-out crests of channel bars, the PM content is an order of magnitude higher relative to areas over pools. The erosion of lower shores of delta islands composed of loam with peat and ice interlayers promoted the additional concentration of PM. The terrigenous-type PM was retained everywhere in the delta water. The $\delta^{13}C$ value varied from –24.5 to –30.4‰; the $\delta^{15}N$ value, from 2.1 to 6.1‰, and the C/N ratio, from 8.7 to 10.3 (Fig. 2; Table 3).

Prodelta. During the investigation period, freshwater (salinity <0.009‰) also spread beyond the delta over its underwater part in the Laptev Sea. The PM composition in the drainage receiver basin begins to transform above the shallow zone of the prodelta. The transformation stage includes the concentration of PM in the backwater zone, as well as destabilization of riverine colloids and clay minerals due to the neutralization of their negative charges by seawater cations at early stages of mixing [15]. The resultant effect of SM transformation was manifested as an increase in the PM content of more than three times only at the 15-km segment located between the Bykov channel mouth and the shallow zone. The C content in the PM decreased threefold due to the gravitational sedimentation of hydraulically large organomineral aggregates formed under the influence of flocculation and coagulation. The terrigenous nature of the PM composition remained consistent with a slight variation in $\delta^{13}C$, $\delta^{15}N$, and C/N values.

Flows of mineral and organic PMs to the sea. Daily flows of PM, C, and MC from the delta were estimated at 26 213, 2883, and 20 446 t, respectively. They reflect the characteristic level of the runoff phase following the flood stage (Table 4). The analysis of monthly mean PM discharges indicates that they can substantially increase during the flood peak.

Short-period VPP variations. The discharge of rain and melt water from the Aldan River basin continued during the back route of the expedition (July 23–August 1). The passage of a new portion of floodwater across the delta bifurcation area provoked a sevenfold increase in the PM content as compared to the head of the delta and the lower course of the Lena River. The concentrations of C and N in the PM increased nearly four times. The C and N isotopic compositions became heavier. An apron of dull brown water with a high PM content (214–352 mg/l), which corresponds to the PM content in tropical estuarine waters of the Mekong River [2, 4], was observed at that time between the mouths of the Vilyui and Aldan rivers. The water surface area covered with land plant debris made up 5%, while the concentrations of C and N in the PM increased three times. The $\delta^{13}C$ and $\delta^{15}N$ values drastically increased to –19.4‰ and 4.8‰, respectively (Tables 2, 3; Fig. 2).

Specific features of the grain size composition of the PM. During both surveys, the dispersed structure of the PM remained stable along the entire pathway of the major channel. The grain size composition was predominated by pelite, Pl (particle diameter <0.01 mm; content 26.3–74.9%, average 48.9%) and silt, S (0.1–0.01 mm; 23.3–61.4%, average 45.9%). The psammite, Ps (1–0.1 mm) content in different areas of the Lena River was 0–15.2%, averaging 5.2% (Tables 1–3). Variations in the ratio of PM-forming fractions reflected peculiarities of particle size differentiation in accord with (1) the initial grain size composition of the provenance and (2) variations in hydraulic characteristics of the channel flow. Increase in the Ps content did not necessarily reflect the cumulative effect of the factors cited above. This was established for the PM of the Aldan River characterized by a stronger correlation with the first factor, although the Ps fraction is reduced to 0% and the flows are subjected to substantial turbulent fluctuations.

CONCLUSIONS

The Lena River–Laptev Sea system is characterized by two types of heterogeneities of the VPP composition: (1) heterogeneities formed without the anthropogenic influence and (2) heterogeneities stipulated by the anthropogenic influence.

Peculiarities of **type I** heterogeneities are caused by their natural zonality, which reflects the relation with the following factors: (a) the geological–tectonic and altitude position of the channel and catchment areas; (b) the water runoff regime and the character of lithodynamic processes in the channel; (c) the extent of readiness and stability of soil and weathering crust to mobilization; and (d) the bioproductivity of water, biomass of land vegetation, and conditions of biochemical transformation. The increase in water volume in the Lena River with the confluence of tributaries did not necessarily mean increase in the PM content, since the latter is mostly controlled by conditions of matter mobilization in the provenance rather than the value of water inflow. Accumulation is the major type of lithodynamic process in the 900-km-long channel zone of the lower course of the river before the delta head, in the delta, and at hydrological fronts, the appearance of which is determined by the interaction of waters between the major channel and tributaries. Trends toward increase in the average concentrations of C (25 times) and N (19 times) in water, as well as decrease in C, N, and OC contents in the PM (3–4 times), were recorded from the upper course of the Lena River to its delta.

Heterogeneities of **type II** are related to anthropogenic discharges. Upon overcoming natural barriers, they distort the natural order of VPP variation and grade to background values. They have been distinguished in the Lena River for the first time (other researchers did not detect them anywhere [13, 14]). Along the route to the delta, the heterogeneities of the VPP were found to extend from the Aldan River mouth, where the intrinsic inflow signal was intensified by anthropogenic pollution, over 330 km downstream. On the back route to the upper course of the Lena River, such waters were identified 210 km from the Aldan River confluence area. Variations in the range of the polluted water apron probably indicate different volumes of discharges and the injection nature of their inflow.

The indications of anthropogenic pollution are the following: (a) sharp increase in PM content (77–352 mg/l); (b) heavier isotopic composition of PM (δ^{13}C from –19.6 to –19.4‰, δ^{15}N = 5.0‰) due to the possible fractionation of isotopes under the influence of inorganic processes during the mineralization of organic material [7]; (c) increase in the C concentration in water by several times (2275–5133 μg/l); (d) decrease in the C content (up to 1%); (e) growth of the MC input (up to 98%), (f) variations in parameters of the water carbonate system (increase in pH, dissolved inorganic C concentration, carbonate and bicarbonate ions, and decrease in the carbon dioxide concentration); and (g) decrease in the concentration of dissolved oxygen and silicon.

Waters with the properties indicated above should be attributed to hydrochemical halos capable of self-purification at natural barriers (usually, biogeochemical– sedimentation barriers) under the influence of the settling of mineral particles and complex organomineral compounds absorbed by colloids and clay minerals.

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