Sediment transport to the Laptev Sea—hydrology and geochemistry of the Lena River

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This study focuses on the fluvial sediment input to the Laptev Sea and concentrates on the hydrology of the Lena basin and the geochemistry of the suspended particulate material. The paper presents data on annual water discharge, sediment transport and seasonal variations of sediment transport. The data are based on daily measurements of hydrometeorological stations and additional analyses of the SPM concentrations carried out during expeditions from 1975 to 1981. Samples of the SPM collected during an expedition in 1994 were analysed for major, trace, and rare earth elements by ICP-OES and ICP-MS. Approximately 700 km^3 freshwater and 27×10^6 tons of sediment per year are supplied to the Laptev Sea by Siberian rivers, mainly by the Lena River. Due to the climatic situation of the drainage area, almost the entire material is transported between June and September. However, only a minor part of the sediments transported by the Lena River enters the Laptev Sea shelf through the main channels of the delta, while the rest is dispersed within the network of the Lena Delta. Because the Lena River drains a large basin of 2.5×10^6 km^2, the chemical composition of the SPM shows a very uniform composition. In contrast, smaller rivers with more restricted catchment areas exhibit significant differences.

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Introduction

The extent, thickness and drift patterns of arctic sea-ice cover control the heat and gas exchange between ocean and atmosphere and effect ocean circulation and the global climatic system (Aagaard et al. 1985; Clark 1990). One of the major goals of paleoclimate research is therefore to understand the variations in arctic sea ice distribution and circulation during the climate cycles of the past.

Today large amounts of sea ice are formed in the broad and shallow Eurasian shelf regions. As the Laptev Sea is the main source area for sea ice feeding the Transpolar Drift (Dethleff et al. 1993; Wollenburg 1993; Kassens & Karpij 1994; Nürnberg et al. 1994; Eicken et al. 1995; Reimnitz et al. 1995), it is considered to be one of the key areas in the entire Arctic Ocean.

The Laptev Sea is strongly influenced by continental runoff. The main portion of water and sediments is transported through the Lena River which is the second largest river in Russia and the eighth largest in the world in terms of water discharge (Milliman & Meade 1983). Other rivers—the Jana, the Chatanga, the Olenëk, the Omoloi and the Anabar—play a minor role in the Laptev Sea water mass formation.

The sediments supplied by rivers are partly incorporated into sea ice and transported from the Laptev Sea shelf across the Arctic Ocean and through the Fram Strait via the Transpolar drift (Bischof et al. 1990; Eggertsson 1994; Reimnitz et al. 1994; Stein & Korolev 1994). For that reason the characterisation and quantification of recent sediment transport from the Eurasian continent to the Arctic Ocean and its variations between glacial and interglacial stages reveal important information on the paleoclimate of Eurasia and the history of ice cover and drift patterns in the Arctic Ocean.

This study focuses on the sediment transport of Siberian rivers which drain into the Laptev Sea. The aims are to quantify the sediment transport and to characterise the material being transported through means of chemical and mineralogical methods. The research objectives are to distinguish material transported by different rivers and to find characteristic signatures that allow the identification of this material in the marine sediments of the Laptev Sea shelf and the Arctic Ocean. The present article concentrates on hydrological characteristics of the Lena basin and on the inorganic geochemistry of the suspended particulate material (SPM).

Investigation area

The Lena River originates near Lake Baikal, crosses East Siberia from south to north, and has a length of 4400 km. The Lena basin extends throughout almost all of East Siberia (Jakutia) with an area of 2.5×10^6 km^2.

The main part of the Lena basin is build up by the Siberian platform, which is bordered by the Baikal folded region in the south, the Ochotsk-Čukotski volcanogenic belt in the southeast, and the Verchojano-Kolymean folded region in the northeast.

The Siberian Platform is formed of plateaus, tablelands and plains. The most extensive units are the Prilenskoe plateau which embraces the valley of the middle Lena and the Central Jakutian plain including the middle Lena River with the lower reaches of its tributaries-the Aldan and the Viljuy Rivers. The Prilenskoe plateau is mainly composed of limestones and limestone–terrigenic sediments. The Central Jakutian plain was an area of subsidence in the Mesozoic consisting of terrigenic sediments of Jurassic to Cretaceous age as well as Quaternary alluvial deposits. The Olenëk-Viljuy tableland in the northwest is formed of Triassic volcanic rocks while the Aldan highland is composed of Archean and Proterozoic crystalline and metamorphic rocks.

Ranges and mountains of the Baikal folded region consist of gneiss, shist, quartzite and marbleised limestone of Proterozoic age. In the Verchojano-Kolymean folded region Permian and Carboneous terrigenous sediments, volcanic rocks and granitoids of Triassic and Jurassic age are more common.

The climate in the Lena basin is characterised by a long and cold winter with temperatures down to –45 to –50°C during three months and a short hot summer (up to +30 to +35°C) during two months). The average annual precipitation in the Lena basin is 330 mm with 70 to 80% occurring during summer (Gordeev & Sidorov 1993). Almost the entire basin is located within the permafrost zone. Unfrozen sediments (taliks) underlie the main channel of the Lena River due to warming of the large water mass.

Samples and Methods

Hydrology

Regular hydrological measurements in this region were started between 1925 and 1935. Today a sum of 340 hydrometeorological stations, which are randomly scattered over the drainage area, are in operation. At several of these stations water discharge and total SPM concentrations are measured daily. The data are available through publications of the Leningrad Hydrometeorological Service. The upper and middle reaches of the Lena River are relatively well explored; hydrological data cover the last 30 to 40 years (Leningrad Hydrometeorological Service 1987).

From 1969 to 1994 the Research Laboratory of Soil Erosion and Channel Processes of the Geographical Faculty, Moscow State University, investigated the hydrological and geomorphological features of basins, channels, confluences and deltas of the Viljuy, the Aldan, the Kirenga, the Vitim, the Lena, the Omoloi and the Jana rivers. The seasonal variations in SPM concentrations in the Lena River and its tributaries, as well as in the different channels of the Lena Delta, were studied from 1975 to 1981. During the ice-free periods, daily measurements were carried out. Integrated water samples from the surface to the bottom were obtained by a special river water sampler. The SPM was separated by pressure filtration. The concentration of total SPM was calculated from the weight difference between the pure and the sediment loaded filters.

The data on the annual water discharge, sediment transport and the seasonal variations presented in this study are based on daily measurements from the hydrometeorological stations and additional analyses of SPM concentrations carried out during expeditions between 1975 and 1981. Since hydrological data from the last 30 years are available at most stations, our estimates must be regarded as long-term average values.

To calculate the sediment distribution along the different channels of the Lena Delta, we used the water discharge data measured at the hydrometeorological station of Stolb Island (Fig. 1) and those reported by Ivanov et al. (1983). Total SPM concentrations of the main channels between Stolb Island and the mouths were analysed during the ice-free periods from 1975 to 1977.

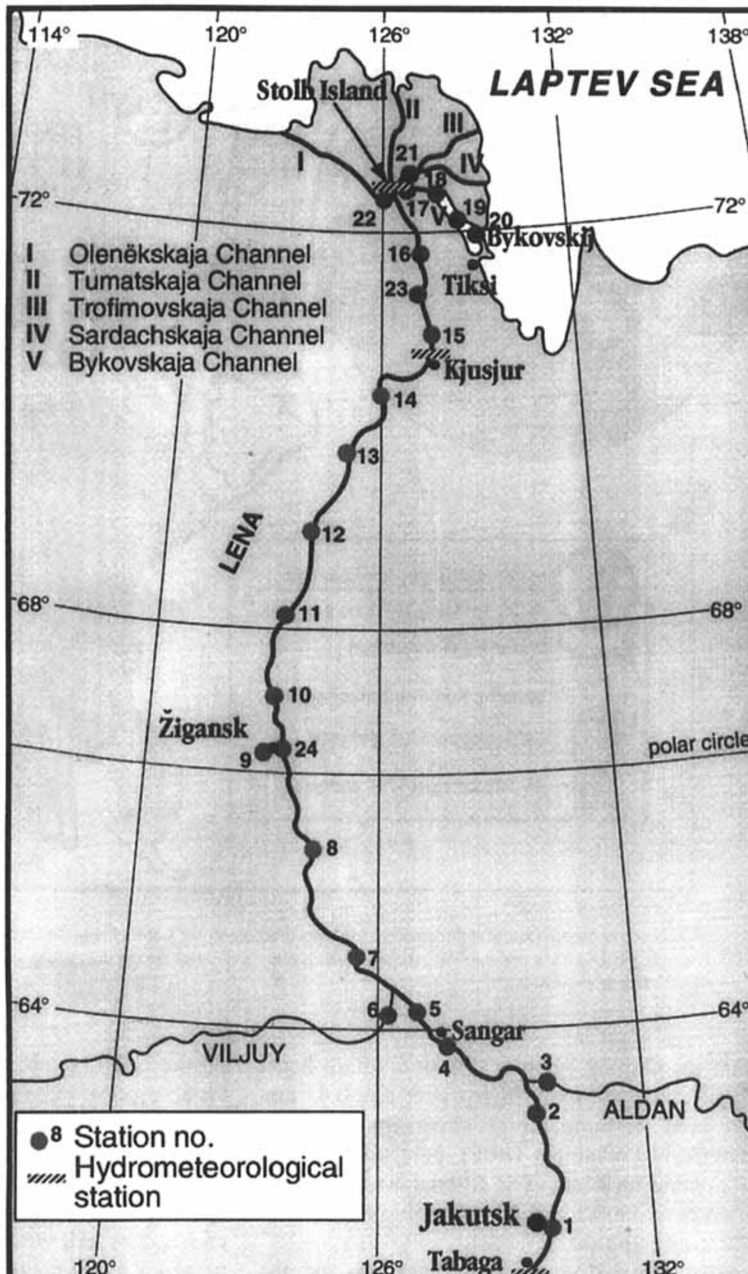

Fig. 1. Location map of the 1994 Lena expedition. Station numbers and positions of hydrometeorological stations are indicated.

Geochemistry

Sampling was performed during an expedition to the Lena River carried out by the Alfred Wegener Institute and the Moscow State University in July and August 1994 (Rachold et al. 1995). Samples of surface sediments, water and SPM were taken along the way from Jakutsk to the Lena Delta with the research vessel PROFESSOR MAKKAVEEV at 24 stations (Fig. 1). Additional samples were retrieved from the major tributaries, the Aldan and the Viljuy Rivers.

Integrated water samples were obtained by a river water sampler. The water was filtered on

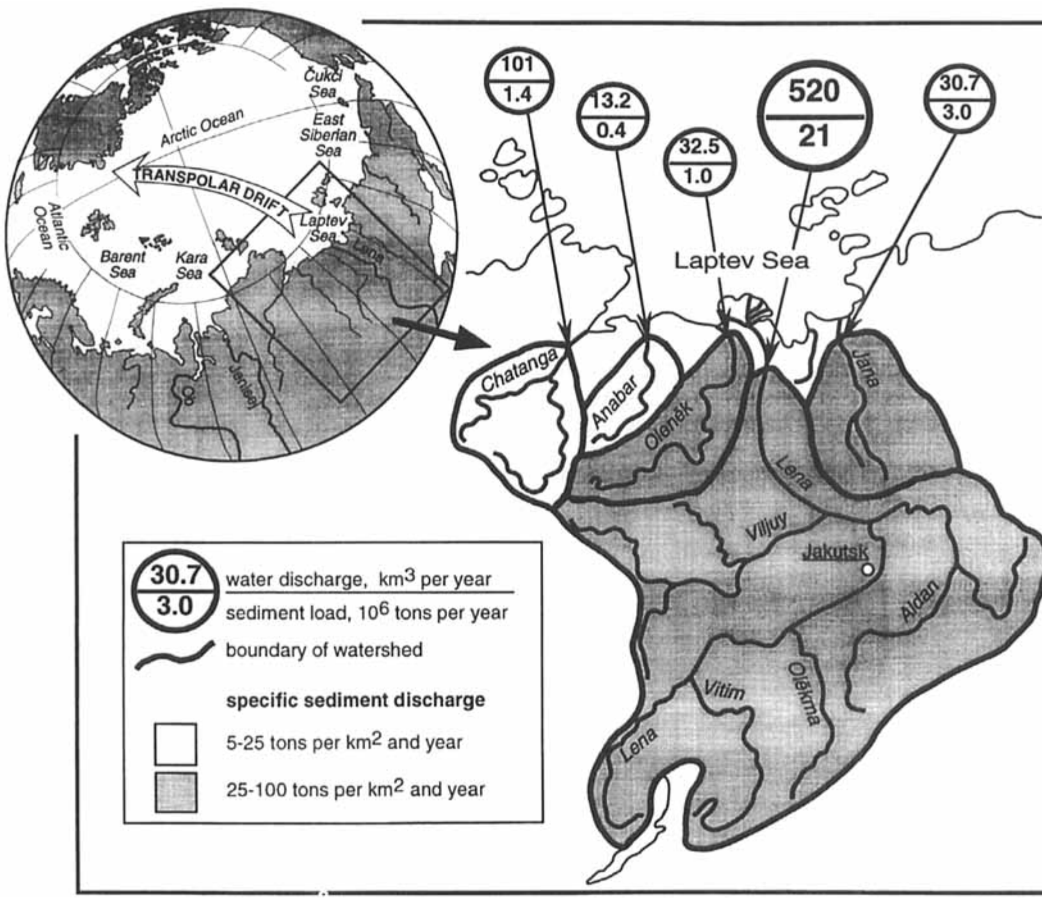

Fig. 2. Annual water discharge and sediment load of rivers draining to the Laptev Sea. The data are based on daily measurements of hydrometeorological stations in the lower reaches of the rivers carried out during the last 30 years. The specific sediment discharge of the river basins is indicated.

board the ship by vacuum filtration within hours of collection. Millipore filters, pore size 0.45 μm, were used for inorganic geochemistry, and glass fiber filters (Whatman GF/F), pore size 0.7 μm, for organic analyses. The filtered water volume varied between 0.5 and 2 l depending on the total SPM concentration.

After freeze-drying, acid digestions of the sediment-loaded filters were performed in Teflon vessels using ultrapure HNO_3, $HClO_4$ and HF. The residues were redissolved in HNO_3 and diluted with H_2O to a final volume of 20 to 50 ml depending on the sediment concentration. Major elements Al, Ti, Fe, Mn, Mg, Ca, Na, and K were analysed by ICP-OES, trace elements and rare earth elements by ICP-MS.

Glass fiber filters were pulverised in an achat pestle. C,-N-, S- concentrations were analysed by IR-absorption (C and S) and temperature conductivity (N) by a Leco element analyser. $d^{13}C$ values of the particulate organic material (POM) were measured by a Finigan MAT Delta S mass spectrometer. Accuracy of the analytical data was checked by international standard reference material for every method.

Results and discussion

Hydrology

Average annual water discharge and sediment load of the major rivers draining to the Laptev Sea

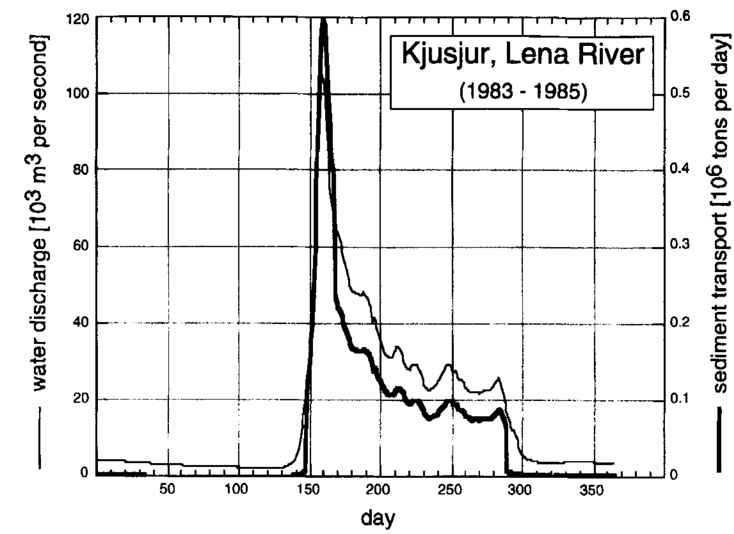

Fig. 3. Seasonal variations in water discharge and sediment transport of the lower Lena River. Daily water discharge (10^3 m^3 per second, left axis) and daily sediment transport (10^6 tons per day, right axis) are presented. The data recorded at the hydrometeorological station Kjusjur (Leningrad Hydrometeorological Service 1987) during 1983 to 1985 represent the typical seasonal pattern.

are presented in Fig. 2. The estimates for the Lena River (520 $km^3 \times a^{-1}$ and 21×10^6 $t \times a^{-1}$) are based on daily water discharge data and total SPM concentrations measured at the lowest hydrometeorological station Kjusjur (145 km south of the delta, Fig. 1) during the last 30 years (Leningrad Hydrometeorological Service 1987). Values for the other rivers are calculated from water discharge data and SPM concentrations presented by the hydrometeorological stations in the lower reaches of those rivers. The total annual water discharge and sediment transport to the Laptev Sea calculated on the basis of these values accounts for ca. 700 km^3 and ca. 27×10^6 tons, respectively. The specific sediment discharge of the river basins varies between 5 and 100 tons per km^2. The lowest values can be observed in the Chatanga and Anabar basins (Fig. 2). Rivers draining to the Laptev Sea are generally characterised by significantly lower specific sediment discharge than for example the Ob River with 100 to 200 tons per km^2 (Snischenko 1992).

Rivers of the Lena basin are characterised by the typical East-Siberian water regime. The main features are long and high, ridge-like summer floods and very low water flow in winter. This is a reflection of the sources and behaviour of water supply. For the lower Lena, 50% of the water is formed from snow melting, 35% from rain and 15% from groundwater. About 75 to 95% of the water discharge occurs during warm seasons. The maximum can take place both in spring and summer depending on latitude and altitude of the sub-basin. For the Lena itself, the maximum flow appears in April in the upper reaches, in May in the middle reaches and in June in the lower reaches. Average water discharge data measured at the hydrometeorological station Kjusjur from 1983 to 1985, which represents the typical pattern for the lower Lena River, are presented in Fig. 3.

The variability of sediment concentration from season to season is very pronounced. Sediment concentration amounts to 60 to 80 mg/l during spring flood and falls to 5 mg/l and lower in winter. Summer rain floods only result in an increase of turbidity up to 20 to 40 mg/l, so that the main portion of the sediment load of the Lena is transported during spring floods (at Kjusjur more than 50% during one month). The daily sediment transport calculated from the water discharge data and total SPM concentrations is presented in Fig. 3.

The downstream accretion of the water mass and sediment load in the Lena River is not uniform. The Lena confluences twice with tributaries having water discharges comparable to that of the main river, the Vitim and the Aldan rivers. According to the position of these tributaries, the Lena is traditionally subdivided into the upper reach (upstream the Vitim), the middle reach (from the Vitim to the Aldan) and the lower reach (downstream of the Aldan). The Aldan supplies 35% of the Lena discharge, the

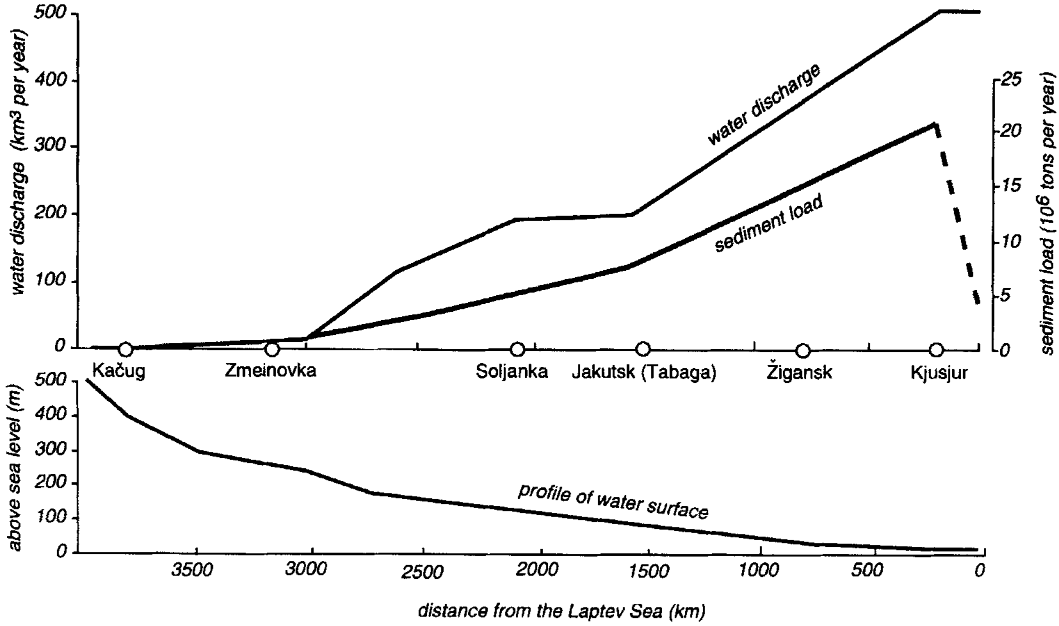

Fig. 4. Downstream accretion of water discharge (left axis) and sediment load (right axis) along the channel of the Lena River. Average data of the last 30 years recorded at hydrometeorological stations and total SPM concentrations measured during 1975 to 1981 form the basis of the calculated values. The profile of the water surface is indicated at the bottom.

Vitim 20%, the Olëkma 15%, and the single important west tributary—the Viljuy—not more than 10%. The sediment discharge of the Lena River increases approximately proportionally with water discharge (from 0.1×10^6 tons per year at Kačug to 9.9×10^6 tons at Tabaga, and 21×10^6 tons at Kjusjur). Fig. 4 shows the profile of the water surface, water discharge and sediment load along the Lena River. The data were calculated from total SPM concentrations analysed during 1975 to 1981 and daily water discharge data as well as SPM concentrations reported by the hydrometeorological stations.

Human influence on the sediment load in the Lena basin is connected with mining industry. Because systematic monitoring of sediment load began at the same time or later than mining, however, it is difficult to determine the natural background of river turbidity. In the tributaries of the Vitim River, gold exploration started at the end of the 19 century, and regular monitoring of the sediment load was initiated in 1930.

The regular channel dredging of the Lena River and its main tributaries to maintain navigation is another source of technogenic sediments. Dredging resuspends fine particles and activates bottom load movement. The mining of the channel alluvium for construction purposes has the same effect. For example, near the city of Jakutsk the volume of channel dredging was 4×10^6 tons per year, and 2×10^6 tons of sediments were removed from the channel. This is almost comparable with the natural sediment transport, which is about 8×10^6 tons at this place (Zaitsev & Čalov 1989).

The distribution of water and sediment discharge along the different branches of the Lena Delta controls the sediment transport to the Laptev Sea (Korotaev 1984; Korotaev et al. 1990). Fig. 5 shows a schematic map of the Lena Delta and the water and sediment discharge of the main channels. According to data of the hydrometeorological station near Stolb Island, the Bykovskaja channel receives 25%, the Trofimovskaja channel 61%, the Tumatskaja channel 7% and the Olenëkskaja channel 7% of the annual water volume. However, only a minor portion of the water discharge is transferred to the Laptev Sea through the main channels of the delta (Ivanov et al. 1983). In the eastern main delta branch, the Bykovskaja channel, water discharge gradually decreases along the main channel. Only

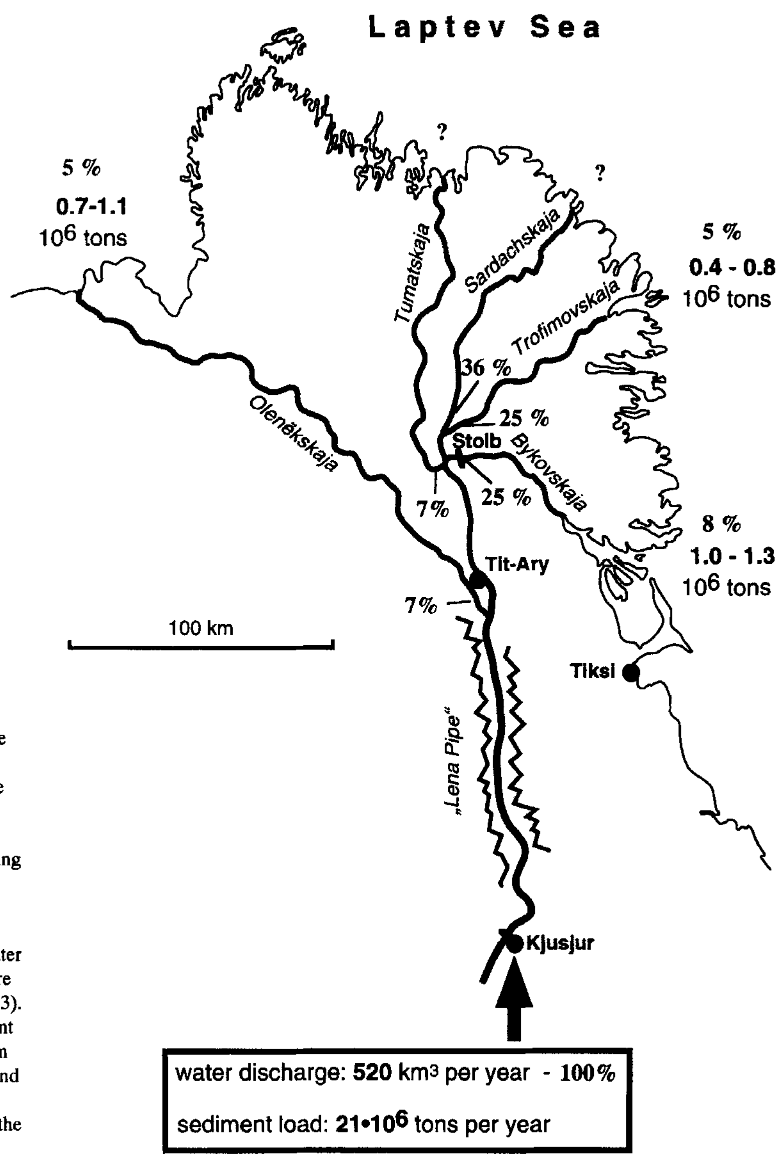

Fig. 5. Schematic map of the Lena Delta. Water and sediment discharge along the main delta branches are displayed. Initial water discharge data at the beginning of the main channels were measured at the hydrometeorological station Stolb Island. The data on water outflow to the Laptev Sea are taken from Ivanov et al. (1983). Sediment load of the different channels was calculated from those water discharge data and measurements of the concentration of SPM along the main channels.

about 30% of the initial discharge reaches the sea through the main channel. The hydrographical network of the Trofimovskaja and the Sardachskaja channels have complicated structures and contain several different regional sub-delta systems. Therefore the changes in water discharge along these channels are very pronounced. Only 7 to 8% of the initial water volume reach the mouth barr of the Trofimovskaja channel. The opposite situation in water discharge dynamics characterises the western delta branch—the Olenëkskaja channel. Its water discharge does not exhibit significant changes along the 145 km of channel length.

Based on those water discharge data and total SPM concentrations measured along the main channels of the Lena Delta, the annual sediment transport through the main channels can be calculated. The results are presented in Fig. 5. The annual sediment transport through the Trofimovskaja channel does not exceed 0.4 to 0.8×10^6 tons. The sediment transport of the

Table 1. Chemical composition of SPM of the Lena River and its major tributaries.

Station	Al_2O_3	TiO_2	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	C	Ba	Bi	Cd	Co	Cr	Cs	Cu	Ga	Hf	Li	Mo	Nb	Ni	Pb	Rb
1	12.86	0.605	5.26	0.185	2.93	3.70	2.15	2.53	5.15	747	0.40	0.98	18.0	76	3.63	83	17.0	3.04	36	1.79	12.1	75	673	99
2	13.68	0.626	5.83	0.207	2.87	3.44	1.96	2.57	8.83	892	0.80	6.65	18.9	80	3.88	338	18.6	3.04	41	1.98	11.9	170	1539	100
3	14.06	0.614	5.84	0.122	2.17	2.12	1.79	2.77	1.03	742	0.75	1.99	15.3	60	4.79	102	17.9	3.39	41	1.37	11.4	69	1513	99
4	13.83	0.621	5.51	0.151	2.27	2.33	2.07	2.79	4.08	709	0.33	0.97	16.8	56	4.83	92	18.7	3.57	42	1.74	12.5	74	576	105
6	13.22	0.684	4.49	0.169	1.49	1.97	1.37	2.80	4.12	752	0.35	4.94	18.4	55	2.63	161	16.3	3.43	25	1.03	10.4	145	914	87
7	15.79	0.682	6.05	0.117	1.83	0.94	1.90	3.09	3.09	784	0.26	1.15	16.0	62	7.00	67	21.9	4.43	43	1.66	14.4	46	47	129
8	15.43	0.682	5.81	0.128	1.90	1.24	2.00	3.07	2.84	762	0.24	0.86	16.3	60	6.25	94	21.4	4.03	42	1.56	15.2	59	79	126
10	14.55	0.669	5.47	0.115	1.94	1.50	1.96	3.11	3.14	759	0.24	3.71	15.3	62	5.82	53	20.2	3.92	41	1.33	13.1	54	52	115
11	14.76	0.684	5.43	0.128	2.19	2.21	1.96	2.79	2.52	738	0.21	0.77	17.1	58	4.58	80	20.2	3.69	40	0.94	12.9	59	33	110
12	15.85	0.709	6.25	0.141	2.09	1.27	1.99	3.12	3.05	791	0.24	0.73	17.6	61	6.49	50	22.2	4.31	48	1.63	14.5	50	56	126
13	15.62	0.729	6.18	0.155	2.14	1.64	2.25	2.97	3.27	727	0.26	0.78	17.4	60	5.69	57	21.2	4.09	48	1.38	13.7	48	41	114
14	11.43	0.457	3.32	0.075	1.31	1.50	1.98	2.50	3.03	694	0.11	0.31	11.4	38	2.73	24	15.5	2.61	27	0.55	10.4	26	19	94
15	14.21	0.664	5.43	0.150	2.08	1.93	2.02	2.66	3.88	703	0.22	0.90	17.9	62	4.49	126	20.2	3.63	41	1.03	13.6	88	83	103
16	15.02	0.712	6.16	0.220	2.20	1.89	2.15	2.86	4.26	723	0.18	0.80	17.8	59	4.47	121	21.0	3.77	43	1.02	12.6	71	70	98
17	14.43	0.691	6.07	0.232	2.13	1.90	2.11	2.78	4.40	760	0.23	3.30	19.4	75	5.00	207	22.2	3.90	43	1.74	14.8	135	84	126
18	15.62	0.752	6.72	0.271	2.36	2.03	2.07	2.66	5.14	814	0.25	1.54	20.7	86	5.46	135	23.6	4.13	48	1.79	14.7	116	229	134
20	14.81	0.639	6.19	0.272	2.05	1.60	2.22	3.03	5.73	801	0.29	7.50	20.1	91	5.72	226	22.8	3.60	48	2.21	13.7	133	356	134
21	14.35	0.689	5.53	0.161	2.13	1.83	2.18	2.69	3.73	728	0.21	0.74	17.1	76	4.99	102	20.2	3.64	45	0.97	12.9	60	154	107
22	12.64	0.589	4.69	0.134	1.94	1.97	2.10	2.54	4.49	621	0.41	0.74	15.5	67	3.97	143	17.7	3.27	36	0.89	12.1	62	76	98

Station	Sb	Sn	Sr	Ta	Th	Tl	U	V	W	Y	Zn	Zr	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
1	0.85	336	274	0.77	13.8	0.52	4.01	83	1.61	23.2	365	98	47.1	97	10.7	39.7	6.94	1.45	6.58	0.85	4.84	0.84	2.63	0.26	2.52	0.32
2	2.70	862	266	0.66	14.4	0.58	4.43	101	1.62	22.8	1019	96	53.8	114	12.3	44.6	7.74	1.60	7.16	0.88	4.80	0.90	2.68	0.35	2.46	0.34
3	2.28	1083	162	0.62	10.0	0.61	2.91	104	1.56	20.4	573	111	35.0	77	8.2	30.6	5.92	1.24	5.44	0.73	4.09	0.81	2.30	0.32	2.32	0.33
4	0.95	186	187	0.91	13.7	0.60	3.45	92	1.60	21.6	324	118	43.9	96	10.3	38.0	6.78	1.48	6.25	0.80	4.42	0.83	2.45	0.34	2.45	0.34
6	2.46	460	209	0.73	7.3	0.46	1.93	83	1.08	16.8	533	115	29.4	65	6.9	25.1	4.83	1.26	4.32	0.59	3.39	0.66	1.88	0.26	1.92	0.26
7	0.75	5	135	1.01	12.9	0.67	3.49	126	1.54	24.9	343	158	41.7	92	9.8	35.3	6.60	1.50	6.33	0.87	4.91	0.97	2.80	0.40	2.84	0.40
8	0.62	15	150	1.05	13.0	0.65	3.56	108	1.53	24.2	306	150	44.4	96	10.3	37.3	6.70	1.53	6.34	0.89	4.82	0.91	2.71	0.39	2.75	0.38
10	0.79	6	159	1.01	12.2	0.66	3.08	90	1.51	22.8	399	137	43.3	94	10.0	36.8	6.62	1.47	6.13	0.81	4.59	0.90	2.69	0.37	2.71	0.36
11	0.42	7	217	0.87	11.5	0.58	3.03	90	1.41	22.0	381	129	43.7	94	10.1	36.5	6.71	1.52	6.13	0.79	4.53	0.85	2.50	0.33	2.48	0.33
12	0.71	7	159	1.01	12.4	0.68	3.25	96	1.58	24.6	329	149	42.3	92	9.8	35.9	6.67	1.53	6.16	0.84	4.86	0.94	2.71	0.40	2.86	0.40
13	0.60	4	187	0.93	12.0	0.66	2.90	116	1.60	23.8	321	138	43.7	94	10.0	37.2	6.73	1.49	6.34	0.82	4.67	0.92	2.62	0.36	2.66	0.36
14	0.27	3	221	0.60	7.1	0.47	2.00	58	0.94	15.5	144	100	29.1	64	6.8	24.8	4.46	1.15	4.18	0.55	3.00	0.57	1.68	0.23	1.66	0.24
15	0.50	43	219	0.70	11.5	0.55	2.92	104	1.54	22.4	356	132	43.7	95	10.0	36.5	6.63	1.51	6.19	0.80	4.39	0.83	2.41	0.33	2.40	0.33
16	0.68	20	202	0.86	11.5	0.42	2.92	98	1.44	22.6	394	122	42.5	96	10.1	36.9	6.46	1.48	6.15	0.82	4.53	0.84	2.58	0.25	2.43	0.27
17	1.01	11	192	1.02	12.8	0.49	3.29	113	1.65	25.2	696	130	48.0	110	11.6	42.8	7.60	1.74	7.15	0.96	5.09	0.95	2.88	0.33	2.73	0.33
18	1.02	17	202	1.04	13.5	0.50	3.52	108	1.65	25.5	490	137	52.1	116	12.2	44.0	7.62	1.78	7.23	0.97	5.20	1.00	2.99	0.29	2.73	0.34
20	1.33	41	179	0.72	13.2	0.54	3.44	129	1.71	26.3	1020	127	54.0	124	12.8	45.4	7.44	1.67	7.71	0.95	5.14	0.98	2.93	0.32	2.60	0.31
21	0.88	31	191	0.88	11.8	0.47	3.07	93	1.47	21.6	536	129	43.3	97	10.3	36.6	6.57	1.57	6.26	0.81	4.27	0.81	2.51	0.28	2.33	0.28
22	0.54	20	187	0.74	10.6	0.43	2.75	102	1.38	19.8	480	108	40.2	88	9.3	34.3	6.06	1.38	5.92	0.74	3.94	0.72	2.23	0.24	2.04	0.23

major elements [wt. %]

trace elements [mg/kg]

Bykovskaja channel is 1.0 to 1.3 × 10^6 tons per year, that of the Olenëkskaja channel varies from 0.7 to 1.1 × 10^6 tons per year. There are no data available of the Tumatskaja and Sardachskaja channels. With the present data set we cannot provide a complete picture of the sediment distribution within the Lena Delta. However, it can be stated that from 21 × 10^6 tons of SPM coming into the sub-delta section (at Kjusjur), only 2.1 to 3.5 × 10^6 tons (10 to 17% of this value) reach the shore of the Laptev Sea through the main channels of the delta (Fig. 5). The major portion of the sediment is dispersed in vast delta plains and second order distributors.

Geochemistry of the suspended particulate material

During our sampling in July 1994, the sediment concentration varied between 10 mg/l and more than 100 mg/l, with high values between Žigansk and Kjusjur and low values near Jakutsk and in the delta. The average sediment concentration of 40 mg/l is in general agreement with the typical

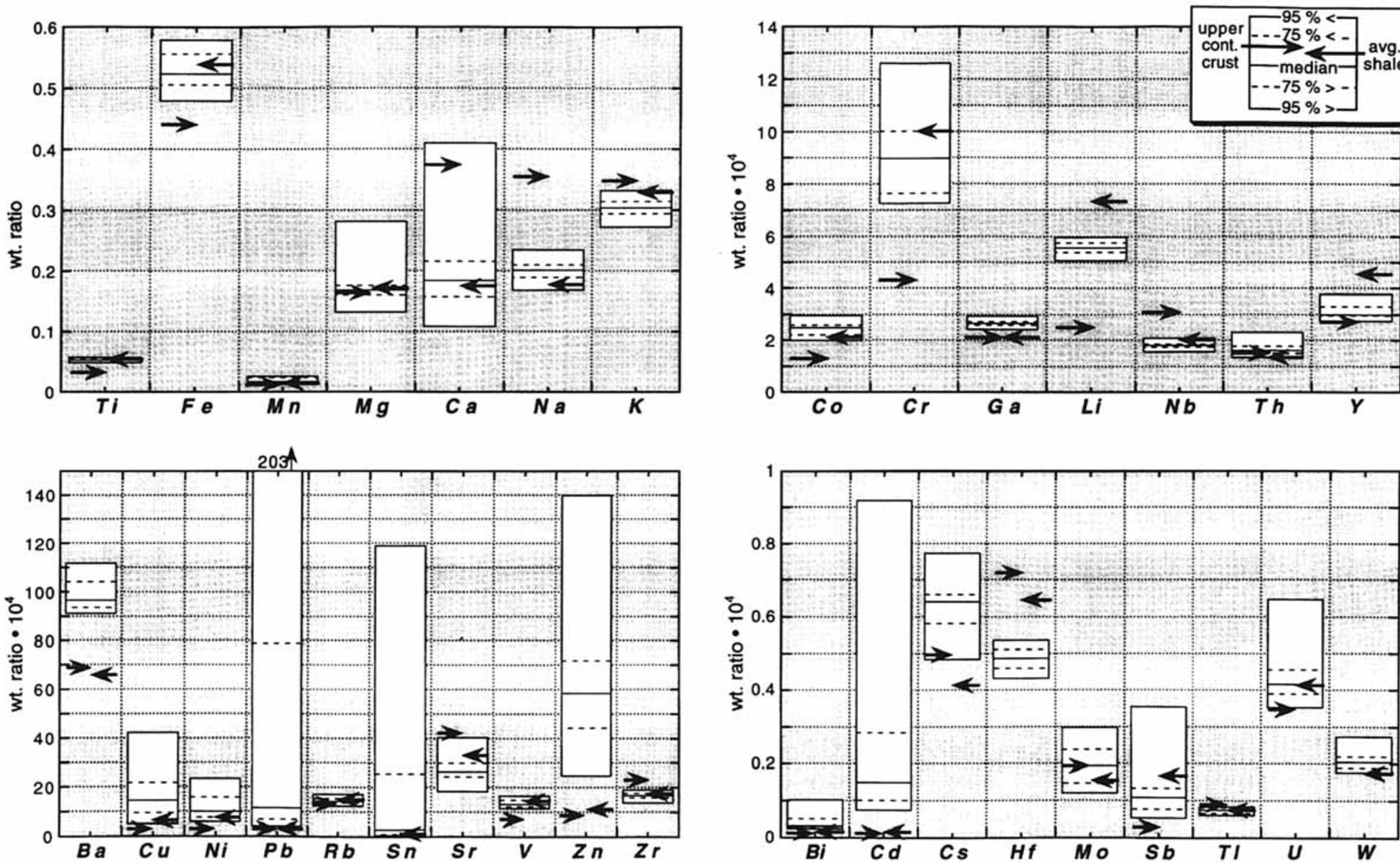

Fig. 6. Major and minor element composition of SPM of the Lena River. Aluminum normalised concentrations are based on weight ratios and multiplied by 10^4 for trace elements. Median values, 75% and 95% percentiles are displayed. Upper continental crust composition (black arrow, left side) taken from Taylor & McLennan (1985) and average shale data (black arrow, right side) from Wedepohl (1971) and Wedepohl (1991) are shown for comparison.

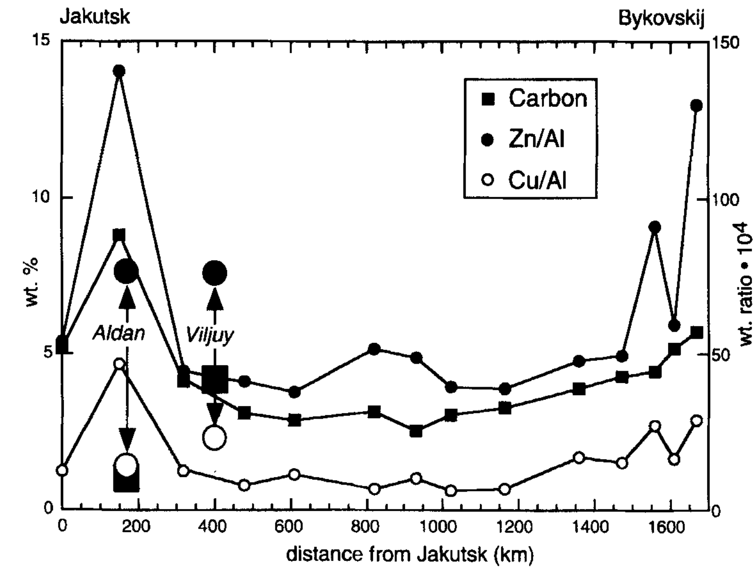

Fig. 7. Al normalised Cu and Zn (y-axis, right side) concentrations and carbon content (y-axis, left side) of particulate material of the Lena River. The figure displays a long section of the Lena River between Jakutsk and Cape Bykovskij in the Lena Delta. The scale on the x-axis corresponds to the distance of the station from Jakutsk in km. The main tributaries the Aldan and the Viljuy Rivers are shown.

summer values of the last years measured at the hydrometeorological stations.

The major and minor element composition of the SPM sampled between Jakutsk and the Lena Delta is presented in Table 1 and Fig. 6. The values of average shale (Wedepohl 1971, 1991) and upper continental crust (Taylor & McLennan 1985) are shown for comparison. To compensate for different amounts of organic material diluting the mineral fraction, aluminum normalisation was applied. Aluminum is a conservative element and exclusively bound to the mineral component. The carbon concentration analysed from glass fiber filters varies between 1 and 9%. The $d^{13}C$ values of the organic fraction are almost constant throughout the river with an average of –27.0 ± 0.8‰, indicating the dominance of C^3 plants. Very similar values (–26.7 ± 0.4‰) have been analysed in the Congo River SPM (Mariotti et al. 1991).

The elemental composition of the Lena River SPM is very homogenous for all of the major elements. The median values of the Al normalised concentrations compare well with average shale. The upper continental crust composition on the other hand displays significant differences (Fig. 6).

In general, average shale can be regarded as the weathering product of the upper continental crust after subtracting the "soluble" elements. For this reason average shale is characterised by a depletion in Na and Ca and an enrichment in Fe and Ti compared to the upper crust. The correspondence of the median composition of the Lena River SPM and that of average shale therefore suggests that (1) the average major element composition of all lithologies in the Lena basin is comparable to that of the upper continental crust, and (2) that the rate of chemical weathering in the drainage area is similar to the world-wide average.

As the Lena River drains a large basin, the agreement of the average composition of the rocks in this area and the upper crust is not surprising. The same holds true for other major rivers (Gaillardet et al. 1995).

The chemical data of the Lena River SPM analysed in the present study do not reflect the reduced denudation rate reported for polar regions (Ugolini 1986). In the Lena basin weathering processes should be furthermore decelerated because of scarce precipitation. Gordeev & Sidorov (1993) reported that the annual chemical denudation rate in the Lena basin is about half of the world average. However, to study weathering processes in detail, which is not the purpose of this study, data on the dissolved load are essential.

Most of the trace elements show a similar behaviour. In particular the aluminum normalised concentrations of Co, Cr, Ga, Mo, Nb, Rb, Sb, Th, Tl, U, V, W and Zr are constant throughout the river and the median values are similar to that of average shale.

However, some differences are visible: (1) Al

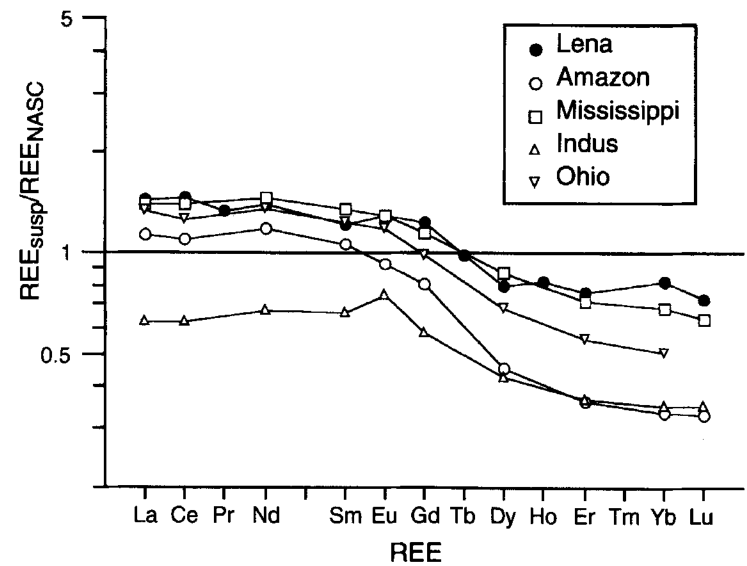

Fig. 8. Shale normalised REE pattern of the Lena River and other major rivers. Data for Amazon, Mississippi, Indus and Ohio have been presented by Goldstein and Jacobsen (1988). Shale Data (North American Shale Composite = NASC) are taken from Condie (1993).

normalised Ba, Cs, and Hf concentrations are also constant but Ba and Cs concentrations are higher and Hf concentrations are lower than that of average shale and upper continental crust; (2) Cd, Cu, Pb, Sn and Zn display a strong scatter with high values in some samples.

For the elements Ba, Cs and Hf, the differences can be interpreted by deviations of the average source rock concentration in the Lena basin from that of average shale. High Cd, Cu, Pb, Sn and Zn concentrations on the other hand cannot be explained by the lithology of the drainage area.

Fig. 7 displays the carbon content and the Al normalised concentrations of Cu and Zn analysed along the Lena River between Jakutsk and Cape Bykovskij in the Lena Delta. Note that the scale on the x-axis is the distance of the station form Jakutsk in km. The positions of the Aldan and the Viljuy data points correspond to the distances of their mouths from Jakutsk. A correlation between carbon content and Cu, Zn and Cd concentrations can be observed. Obviously the concentrations of these elements in the particulate material are linked to absorption to organic material. Dai et al. (1995) pointed out that in river water Cd, Cu and Ni are associated with colloidal organic carbon.

The elements Pb and Sn are highly correlated and exhibit high values in the area of Jakutsk including the Aldan and the Viljuy Rivers. Bi and Sb show a similar but less pronounced behaviour. The enrichment of these trace metals in the particulate material cannot be explained at the moment. The association of Bi, Pb, Sb and Sn suggests pollution from mining. However, there are no ore deposits in this area, and cassiterite only occurs in the Jana basin.

The composition of the SPM of the Aldan River, which is the major tributary of the Lena River, does not exhibit strong deviations from that of the Lena River because the Aldan River drains very similar lithologies. For most of the major and minor elements the differences do not exceed the variations within the Lena River itself. The Viljuy River particulate material on the other hand can be clearly distinguished from that of the Lena River. The Ti/Al ratios of the Viljuy River are higher and the Fe/Al ratios evidently lower than that of the Lena River: Lena River: Ti/Al = 0.052 ± 0.002, Fe/Al = 0.518 ± 0.040 (n = 17); Viljuy River: Ti/Al = 0.059, Fe/Al = 0.448 (n = 1).

Furthermore, the SPM of the Viljuy River can be distinguished from that of the Lena River by most of the trace elements. While the normalised concentrations of Cs, Li, Rb, Th, U, W and Y are lower, the concentration of Co is higher than that of the Lena River SPM.

Fig. 8 displays REE patterns of the SPM of the Lena River and some other major rivers. The concentrations are normalised to the North American Shale Composite (NASC, Condie 1993). The REE pattern of the Lena River SPM

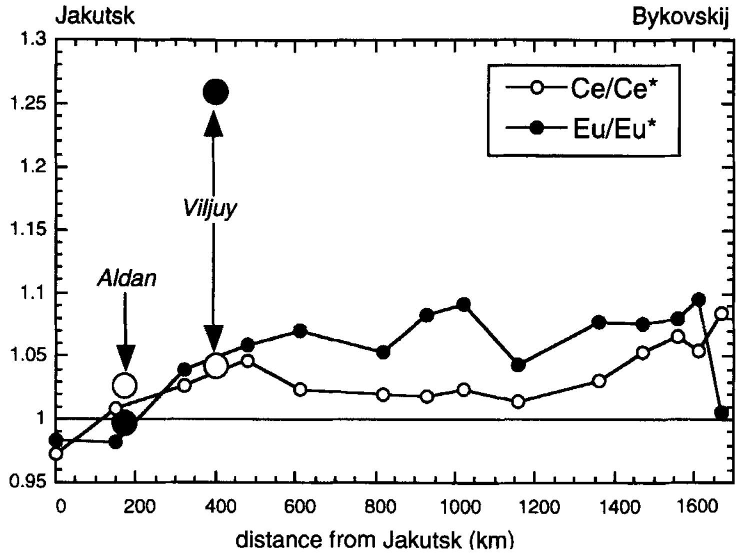

Fig. 9. Eu and Ce anomalies in the SPM of the Lena River (long section between Jakutsk and Bykovskij in the Lena Delta) and its main tributaries the Aldan and the Viljuy Rivers. See text for explanation.

material proves to be very similar to that of other major rivers, which are generally characterised by a slight enrichment of the LREE and a deficiency of the HREE (Martin et al. 1976; Goldstein & Jacobsen 1988). The Lena River SPM, for example, displays almost the same distribution as that of the Mississippi River.

The REE patterns of river SPM are sensitive to the drainage basin geology (Goldstein & Jacobsen 1988). However, if the drainage basin is large enough the REE pattern of the SPM represents the weathered upper continental crust. For that reason the SPM of major rivers display similar REE patterns.

As has been pointed out earlier, the Viljuy River shows some differences. Eu and Ce anomalies of the particulate material are displayed in Fig. 9. The figure shows a long section of the Lena River including the Aldan and the Viljuy Rivers. While the Lena and the Aldan Rivers are characterised by the absence of any Ce and Eu anomalies, the Viljuy River SPM exhibits a pronounced positive Eu anomaly (Fig. 9). The catchment area of the upper Viljuy River consists of Triassic volcanic rocks. The series is mainly formed from basaltic tuffs and tuffitic rocks as well as Trap basalts. Due to the magmatic fractionation of Ca rich feldspars upper continental crust and average shale are characterised by a negative Eu anomaly relative to the primitive earth mantle or chondrite, respectively. Continental flood basalts on the other hand do not exhibit this pronounced Eu anomaly since they are less fractionated. Therefore the average shale normalised REE patterns of material derived from basaltic rocks displays a positive Eu anomaly. Chemical data of Siberian Trap basalts from the Noril'sk district have been published by Lightfoot et al. (1993). These basalts are located west of the Viljuy catchment area but belong to the same sequence like the basaltic rocks in the Viljuy basin. The NASC normalised REE distribution of the Noril'sk Trap basalts displays Eu anomalies of +1.3 to +1.5. The positive Eu anomaly of the SPM of the Viljuy River accounting for 1.25 reflects the influence of the Trap basalts (Fig. 9).

Conclusions

The material transport of the Siberian rivers mainly by the Lena River strongly influences the sedimentation in the Laptev Sea shelf and the Arctic Ocean. Due to the climatic situation in the drainage area, the main portion of the material is transported during spring flood. However, it has to be taken into account that only 10–17% of the material entering the Lena Delta reach the Laptev Sea through the main branches while the rest is dispersed in the delta.

It is difficult to determine the quantity of natural sediment transport of the Lena River because systematic hydrological monitoring in Jakutia began at the same time as mining. Additional sediment is transported due to channel dredging for navigation purposes. Near the city of Jakutsk the volume of dredging almost equals the natural sediment transport.

The SPM of the Lena River shows a uniform major element composition that generally compares well with that of average shale. This also holds true for most of the trace elements with the exceptions Cd, Cu and Zn. These elements are obviously associated with the organic fraction. High concentrations of Pb and Sn in the area of Jakutsk cannot be explained at this moment.

Since average shale can be regarded as the weathering product of the upper continental crust after dissolution of "soluble" elements, we conclude that the average composition of the rocks in the Lena basin is similar to that of the upper continental crust. Furthermore our data reflect the influence of chemical weathering on the SPM composition.

While the chemical composition of the SPM of the Aldan River is similar to that of the Lena River, the Viljuy River can be clearly distinguished. In particular the REE pattern of the SPM of the Viljuy is characterised by a positive Eu anomaly relative to average shale resulting from the occurrence of basaltic rocks in the catchment area.

Rivers which drain a large basin in the order of 10^6 km^2, as does the Lena River, integrate a variety of lithologies. For that reason the SPM of the Lena River does not exhibit specific geochemical signals. In contrast, the SPM of smaller rivers such as the Viljuy River clearly reflects the geology of the more restricted drainage area and displays typical chemical signatures.

Further analyses are required to obtain more information about the material transport by Siberian rivers to the Laptev Sea shelf and the Arctic Ocean. At the moment, Sr isotopic composition of the SPM and heavy mineral distribution of the sediments are studied.

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