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Late Quaternary sedimentation history of the Lena Delta

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Abstract

Core and outcrop analysis from Lena mouth deposits have been used to reconstruct the Late Quaternary sedimentation history of the Lena Delta. Sediment properties (heavy mineral composition, grain size characteristics, organic carbon content) and age determinations (^{14}C AMS and IR-OSL) are applied to discriminate the main sedimentary units of the three major geomorphic terraces, which form the delta. The development of the terraces is controlled by complex interactions among the following four factors: (1) *Channel migration*. According to the distribution of ^{14}C and IR-OSL age determinations of Lena mouth sediments, the major river runoff direction shifted from the west during marine isotope stages 5–3 (third terrace deposits) towards the northwest during marine isotope stage 2 and transition to stage 1 (second terrace), to the northeast and east during the Holocene (first terrace deposits). (2) *Eustasy*. Sea level rise from Last Glacial lowstand to the modern sea level position, reached at 6–5 ka BP, resulted in back-filling and flooding of the palaeovalleys. (3) *Neotectonics*. The extension of the Arctic Mid-Ocean Ridge into the Laptev Sea shelf acted as a halfgraben, showing dilatation movements with different subsidence rates. From the continent side, differential neotectonics with uplift and transpression in the Siberian coast ridges are active. Both likely have influenced river behavior by providing sites for preservation, with uplift, in particular, allowing accumulation of deposits in the second terrace in the western sector. The actual delta setting comprises only the eastern sector of the Lena Delta. (4) *Peat formation*. Polygenetic formation of ice-rich peaty sand ("Ice Complex") was most extensive (7–11 m in thickness) in the southern part of the delta area between 43 and 14 ka BP (third terrace deposits). In recent times, alluvial peat (5–6 m in thickness) is accumulated on top of the deltaic sequences in the eastern sector (first terrace).

1. Introduction

The Lena Delta is the largest delta in the Arctic occupying an area of $3.2 \times 10^4\,km^2$ (Gordeev and Shevchenko, 1995). With the second largest river discharge in the Arctic ($525\,km^3/a$), it is the main connection between interacting continental and marine processes within the Laptev Sea (Rachold et al., 1999). The distinctive pattern of upstream and lateral islands surrounded by the delta holds hundreds of river branches. Today four major delta branches carry the bulk of the water. The largest, known as Trofimovskaya branch, is directed toward the east and receives 61% of the annual water discharge (Fig. 1). It is followed by the Bykovskaya branch with 25% towards southeast, by the Tumatskaya branch to the north and the Olenyokskaya branch to the west, each of them with 7% (Alabyan et al., 1995). During the last two decades several studies have been conducted on geomorphology (Korotaev, 1986; Grigoriev, 1993), cryolithology (Kunitsky, 1989), hydrology (Alabyan et al., 1995; Rachold et al., 1996), paleogeography (Fukuda, 1994; Galabala, 1997; Are and Reimnitz, 2000), tectonics (Avetisov, 1999; Franke et al., 2000) and coastal retreat (Are, 1999) in the Lena Delta area. However, the sedimentation history as well as the processes that control the lateral extension of the Lena Delta in total are poorly understood. According to Grigoriev (1993), the Lena Delta can be subdivided into three geomorphological terraces. The first terrace including active floodplains (1–12 m a.s.l.) covers the main part of the eastern delta sector between the Tumatskaya and the Bykovskaya branches (Fig. 1). This terrace is assumed to represent the "active" delta. The western sector between Tumatskaya and Olenyokskaya branches consists of mainly sandy islands, of which Arga Island is the largest. It has a diameter of 110 km and represents a major part of the second terrace (20–30 m a.s.l.). Sandy sequences covered by the so-called "Ice Complex (IC)" form the third terrace

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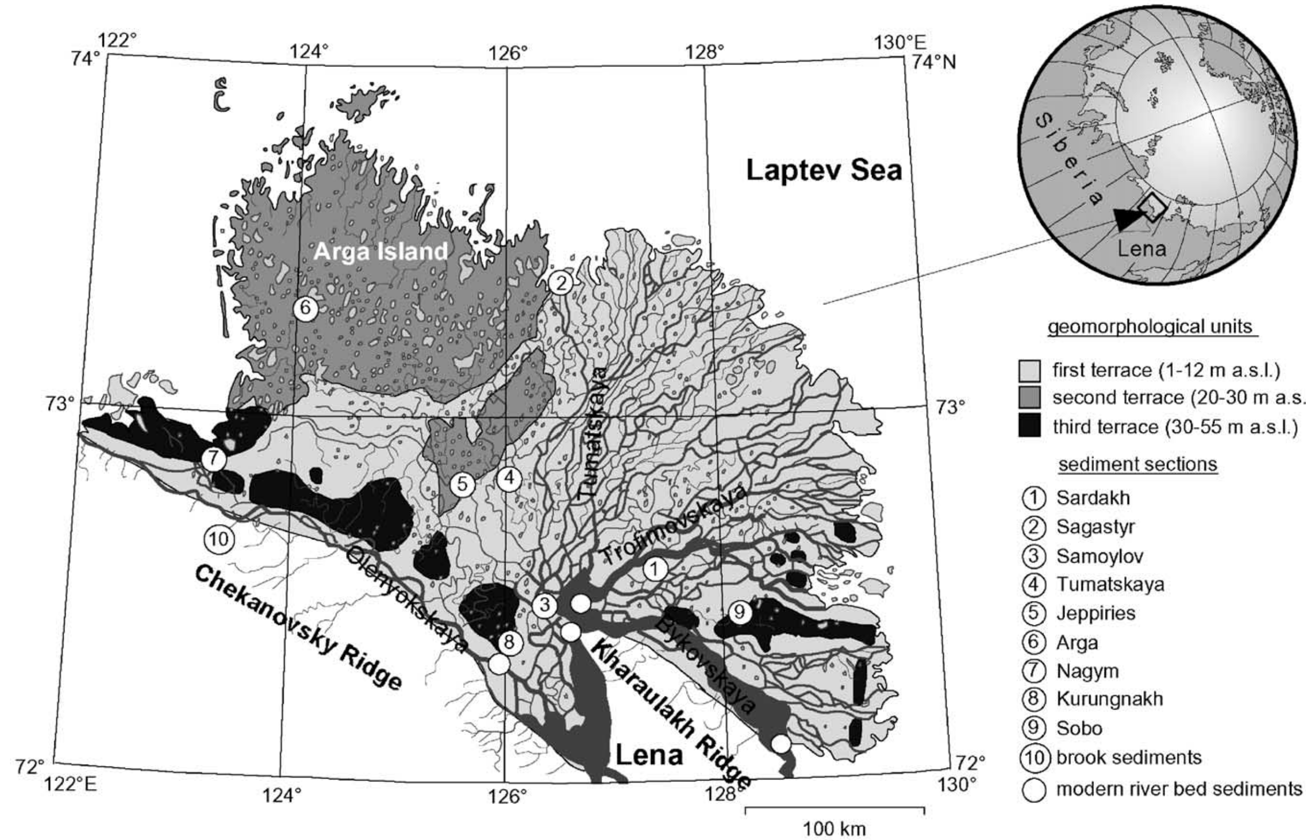

Fig. 1. Geomorphological overview of the Lena Delta (after Grigoriev, 1993) and distribution of sampling sites.

(30–55 m a.s.l.). They outline individual islands along the Olenyokskaya and Bykovskaya branches at the southern rim of the delta setting. The third terrace can be subdivided into two areas due to a considerable difference in altitude (more than 20 m) between the western and the eastern sector (Grigoriev, 1993; Pavlova and Dorozkhina, 1999, 2000). The age relationships between the major fluvial terraces are not yet clear. Especially, the age and origin of the second sandy terrace and the third terrace including the IC are still being discussed (Are and Reimnitz, 2000). The term "Ice Complex" is applied to permafrost sequences, which usually consist of fine-grained loess-like sediments within organic-rich to peaty formations. They have a high content of segregated ice and polygonal ice wedges several meters in height and width. These deposits were formed during the Late Pleistocene regression (marine isotope stages 5–3) on the dry Laptev Sea shelf and in the North Siberian lowlands (Soloviev, 1989; Sher, 1995, Alekseev, 1997; Romanovskii et al., 2000). Ice Complex deposits in the region are regarded as remnants of a Late Pleistocene accumulation plain (Sher, 1999). In the Lena Delta, they reach thicknesses of 20–30 m (Grigoriev, 1993). Knowledge about the age of the IC, the underlying sands and the sands of the second terrace is necessary for understanding the modern structure of the delta. Originally, the second terrace was considered to be younger than the IC remnants and to be overlapping them (Ivanov, 1970, 1972 cited in Are and Reimnitz, 2000). Later, it was proposed that the sands composing the second terrace are underlying the IC (Galabala, 1987 cited in Are and Reimnitz, 2000).

Not only the age but also the origin of the sandy sediments of the second and third terrace is in debate. Both glacial and periglacial genesis have been suggested. It was proposed that glaciers along with subglacial and proglacial meltwater were the agents that created the sandy sediments (Grosswald, 1998; Grosswald and Hughes, 1999). Fluvio-nival processes under periglacial conditions distant from a northern ice shield but associated with local glaciers from the south are suggested by others (Galabala, 1997). Various authors discuss an alluvial or even a marine origin of the sandy sediments, as summarized in Are and Reimnitz (2000). The origin of the IC is controversial as well. Fluvial (Slagoda, 1993), niveo-fluvial (Kunitsky, 1989), aeolian (Tomirdiaro, 1996), ice-dammed alluvial (Grosswald et al., 1999) or polygenetic processes as discussed in Schirrmeister et al. (1999) have been proposed.

The main objective of the present study is to reconstruct the paleogeographic and paleoenvironmental development of the Lena Delta area during the late

Pleistocene and Holocene. Sediment sampling has been conducted at selected sediment profiles of the three terraces (Fig. 1). They are regarded as representative localities for the Lena Delta setting according to previous studies carried out in the area (Grigoriev, 1993). New dates establish age relations between the delta terraces. The dates are used together with recently published luminescence and radiocarbon age determinations from Lena Delta sediments. In order to identify the source region of the sandy sediments composing the second and the third terrace including the IC, heavy mineral studies are applied. The heavy mineral distributions serve as a helpful tool for provenance studies and paleoenvironmental reconstructions (Morton and Hallsworth, 1994; Dill, 1998; Peregovich et al., 1999). Although heavy mineral studies are available for recent Lena River sediments (Serova and Gorbunova, 1997; Behrends et al., 1999; Hoops, 2000), a comparison of terrace deposits is missing. Grain size distributions and total organic carbon (TOC) contents are used to characterize the sedimentary environments of the terrace sediments and the major sediment facies, respectively.

2. Material and methods

Fieldwork was carried out during the expeditions LENA 1998 (Schwamborn et al., 1999) and LENA 2000 (Schirrmeister, in press). Sampling was done by permafrost drilling to recover frozen sediment cores (max. depth 9.25 m) and through natural exposures. River bedload sediments are used for comparative grain size analysis. Sampling was carried out during an expedition to the Lena River in 1995 (Rachold et al., 1997). Sediment sections and sampling sites are equally distributed on the terraces and the major fluvial branches. They are regarded as the representative sediment sites according to previous works conducted in the area (Grigoriev, 1993), therefore, reflecting the general sedimentary and geomorphological situation in the delta.

Grain size distributions for terrace sediments were determined by laser particle sizing (LS200, Coulter Corp.). Prior to the measurements, the individual samples were oxidized (3%-H_2O_2) to remove organic matter, and dispersed (10%-NH_4OH) to diminish the surface tension. Total organic carbon was analyzed using a Metalyt-CS-1000-S (Eltra Corp.) in corresponding pulverized samples after removal of carbonate with HCl (10%) at a temperature of 80°C. Heavy mineral analysis was applied to the 63–125 μm subfraction. Sample preparation was performed according to standard procedures (Boenigk, 1983; Mange and Maurer, 1991). The heavy minerals were separated using sodium metatungstate solution ($Na_6(H_2W_{12}O_{40}) \cdot H_2O$) with a density of 2.89 g/cm^3. On average, <200 transparent grains were counted on slides. Results are expressed in grain %. Samples from sections of each terrace and the IC (Kurungnakh section) were examined for their heavy mineral spectra. Samples were chosen from bottom, middle and top sediment layers of the representative profiles. Heavy mineral data of recent Lena River sediments of the same grain size fraction obtained by Hoops (2000) were used for comparison.

AMS radiocarbon dating of sediments is based on selected organic-rich layers and plant remains. Measurements were performed at the Leibniz Laboratory for Age Determinations, University of Kiel. Only the ^{14}C AMS ages of the extracted residues free of humic acids are used for age interpretation. Results are expressed using a timescale based on ^{14}C ages (ka BP). For a more complete assessment of age determinations for Lena Delta sediments, published results of radiocarbon (Kuptsov and Lisitsin, 1996; Pavlova et al., 1999) and luminescence dates (Krbetschek et al., in press) are incorporated in the review of aged sediments.

3. Results

3.1. Distribution of ^{14}C- and IR-OSL-dated sediments and their lithological description

An overview of the radiocarbon and luminescence dates for Lena Delta sediments reveals that different ages can be found at similar hypsometric marks and time ranges of the individual terraces may overlap each other (Table 1). The third terrace as observed along the Olenyokskaya branch is exposed as an high shore cliff up to ~35 m. The lower part of the section is dominated by ice-poor (<25 wt%) sandy layers showing wavy bedding that are intercalated with root horizons (0–14 m a.s.l.). The amount of root horizons decreases towards the top. This sediment facies is comparable to the recent alluvium of the first terrace as observed in nearby located sandy islands along the river. At the easternmost outcrops of the third terrace (see Fig. 1), the same lithofacies of sandy sediments has been detected by drilling (Grigoriev, 1993). Dates of the lower sandy sediments span a range from 88 to 37 ka BP (Nagym and Kurungnakh sections in Table 1). Measured AMS ages are at the limits of the age range covered by the ^{14}C method, making the age determinations from both methods suitable only to narrow the sedimentation period to the time of marine isotope stages 5 to early stage 3. On top, the sandy sequence is covered by the IC consisting of ice-rich (up to 80 wt%) peaty deposits in alternation with organic-rich silty sand (14–35 m a.s.l.). Ice wedges of 5–10 m in height and width occur throughout the IC. Formation of IC deposits took place between 43 (Nagym and Kurungnakh sections in Table 1) and 14 ka BP as indicated by a radiocarbon date from

Table 1
List of ^{14}C and IR-OSL dates for Lena Delta sediments

Section	Altitude (m a.s.l.)	Lab. no.	Measured age (^{14}C yr BP) *(IR-OSL ka BP)*	Reference
First terrace				
Samoylov (core)	7.5	KIA-8169	435±30	This study
Samoylov (core)	6.6	KIA-8170	230±25	This study
Samoylov (core)	6.2	KIA-8171	500±25	This study
Samoylov (core)w	1.3	KIA-8172	2605±30	This study
Samoylov (core)	1.2	KIA-8173	2530±30	This study
Samoylov (core)	0.4	KIA-8174	2635±35	This study
Samoylov (core)	0.1	KIA-8175	2730±40	This study
Samoylov (outcrop)	6.2	IORAN-4167	3700±260	Kuptsov and Lisitsin (1996)
Samoylov (outcrop)	4.2	IORAN-4164	4220±240	Kuptsov and Lisitsin (1996)
Samoylov (outcrop)	3.6	IORAN-4101	2140±110	Kuptsov and Lisitsin (1996)
Sardakh (core)	8.5	KIA-6759	2755±25	This study
Sardakh (core)	8.1	KIA-6760	1360±20	This study
Sardakh (core)	6.6	KIA-6761	2525±30	This study
Sardakh (core)	3.9	KIA-6762	3460±30	This study
Sardakh (core)	1.7	KIA-6763	3025±35	This study
Sardakh (core)	0.6	KIA-6764	3420±35	This study
Sardakh (core)	−0.2	KIA-6765	2830±35	This study
Sagastyr (outcrop)	0.4	KIA-12519	360±25	This study
Sagastyr (outcrop)	0.6	KIA-12520	645±25	This study
Sagastyr (outcrop)	0.9	KIA-12521	650±25	This study
Sagastyr (outcrop)	1.1	LU-4201	1400±90	Pavlova et al. (1999)
M. Tumatskaya (outcrop)	2.5	LU-4191	8570±160	Pavlova et al. (1999)
Second terrace				
Arga (outcrop)	27.9	ARG-5	*13.1±1.1*	Krbetschek et al. (in press)
Arga (outcrop)	27.3	ARG-4	*12.0±1.1*	Krbetschek et al. (in press)
Arga (outcrop)	26.6	ARG-3	*13.3±1.5*	Krbetschek et al. (in press)
Arga (outcrop)	25.3	ARG-1	*13.4±1.1*	Krbetschek et al. (in press)
Jeppiries (outcrop)	7.5	LU-4198	6430±120	Pavlova et al. (1999)
Third terrace (Ice Complex)				
Sobo (outcrop) IC-top	14.0	GIN-4115	14,340±150	Grigoriev (1993)
Nagym (outcrop) IC-bottom	11.0	KIA-9899	42,930+3100/−2230	Krbetschek et al. (in press)
Kurungnakh (outcrop) IC-bottom	14.0	KIA-6755	42,910+840/−760	Krbetschek et al. (in press)
Third terrace (lower sand)				
Nagym (outcrop)	10.3	OLE-6	*55.0±9.0*	Krbetschek et al. (in press)
Nagym (outcrop)	5.8	OLE-3	*49.0±22.0*	Krbetschek et al. (in press)
Nagym (outcrop)	5.1	KIA-6753	<56,790	Krbetschek et al. (in press)
Nagym (outcrop)	4.0	OLE-2	*52.0±10.0*	Krbetschek et al. (in press)
Nagym (outcrop)	3.4	OLE-1	*57.0±9.0*	Krbetschek et al. (in press)
Nagym (outcrop)	3.1	KIA-6754	<54,520	Krbetschek et al. (in press)
Kurungnakh (outcrop)	12.5	KIA-6756	37,230+510/−480	Krbetschek et al. (in press)
Kurungnakh (outcrop)	8.9	OLE-10	*65.0±8.0*	Krbetschek et al. (in press)
Kurungnakh (outcrop)	7.7	KIA-6757	39,400+510/−480	Krbetschek et al. (in press)
Kurungnakh (outcrop)	5.7	OLE-8	*71.0±40.0*	Krbetschek et al. (in press)
Kurungnakh (outcrop)	4.3	OLE-7	*88.0±14.0*	Krbetschek et al. (in press)
Kurungnakh (outcrop)	4.0	KIA-6758	49,440+1760/−1440	Krbetschek et al. (in press)

the upper part of the Sobo section (Fig. 2 and Table 1). The IC deposits overlie the lower sandy sequences with a sharp facies boundary.

Outcrops of the second terrace (Arga section) show structureless, organic-poor and fine-sandy sequences. Commonly, they have a low ice content (<25 wt%) but contain a net of narrow-standing (dm scale) ice veins. Formation of the ice veins took place probably at the transition time of Late Pleistocene to Early Holocene as deduced from oxygen isotope measurements (Meyer, unpublished data). The results resemble measurements from Bykovsky Peninsula, southeast of the Lena Delta, which have been dated to this time (Meyer et al., in press). According to IR-OSL and ^{14}C age determinations, the sandy sediments have a Late Pleistocene (14.5–10.9 ka BP) to Early Holocene age (6.4 ka BP,

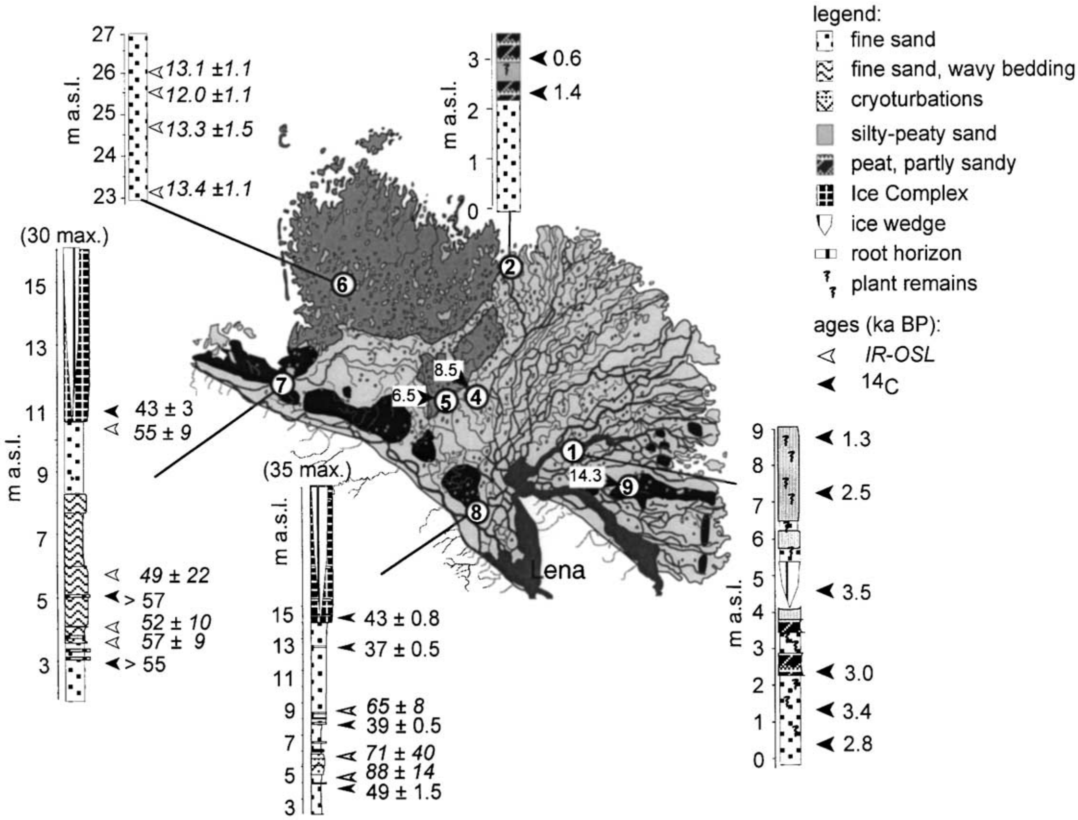

Fig. 2. Representative sediment sections with radiocarbon and luminescence ages. References for age determinations are given in Table 1.

Jeppiries section) (Table 1). Although the age data from the Arga section are not completely in correct chronological order from the bottom to the top of the profile, the overlapping of the error ranges does not indicate age inversion (Krbetschek et al., in press). It seems likely that the overlapping error ranges of the luminescence dates are associated with a high accumulation rate implied by a fluvial environment under upper flow regime.

In the easternmost Delta area (Sardakh section), where modern sedimentation is taking place (first terrace deposits), alluvial facies of the sediments changes from peaty sands at the bottom to silty-sandy peats towards the surface (Fig. 2). The sediments have high ice contents (> 50 wt%), and subaerial or buried ice wedges of 2–3 m in height and width are common. The ages of the first terrace change from Early Holocene (8.5 ka BP) in the west (M. Tumatskaya section) to late Holocene (<2.8 ka BP) in the east (Samoylov and Sardakh sections) to latest Holocene (<1.4 ka BP) in the north (Sagastyr section). The pattern of radiocarbon dates from Samoylov and Sardakh, as a group, shows poor correlation between age and depth. Various age inversions in core sample and outcrop dates in these sections indicate that the sediments from the inner delta plain are highly reworked. Numerous small islands on the delta plain undergo erosion at the river exposed shore banks and show accumulation at the opposite tips in downstream position. Most probably, organic material that was initially incorporated and stored upstream for a period has been remobilized and finally deposited on the delta plain. This finding, like previous studies (Stanley and Chen, 2000), argues that the use of the youngest dates is preferable. Based on the existing information, it is not possible to identify the exact facies boundary of channel fill and the beginning of organic-rich deltaic sedimentation. To accurately date the beginning of modern delta accumulation, longer cored profiles with reliable age determinations from the modern depocenter are needed. Only a larger number of dates in the Holocene part could confirm the tendency that the deposits are progressively younger from west to east.

According to recent studies on the Late Pleistocene and Holocene history of the Laptev Sea, post-glacial sea level rise reached only the modern coastline at 6–5 ka BP (Bauch et al., 1999; Romanovskii et al., 1999; Müller-Lupp et al., 2000; Hubberten and Romanovskii, in press). These studies show that post-glacial sea level rise followed the glacio-eustatic sea level record reconstructed by Fairbanks (1989). For the Early to Middle Weichselian, the sea level curve of Chappell et al. (1996) can be applied (Romanovskii et al., 1999; Hubberten and Romanovskii, in press). The continental shelf is very flat with a break occurring at 50–60 m water depth, and varies in width from 300 to over 500 km (Holmes and Creager, 1974). This implies that during the deposition of the sandy sediments of the third terrace and the IC at 60 and 30 ka BP, sea level was about 60 m lower than at present (Hubberten and Romanovskii, in press). The sea level at 12.7 ka BP, during the deposition of the uppermost sediments of the second terrace, is calculated to have been lower by approximately 70 m than at present (Müller-Lupp et al., 2000). Thus, the paleo-coastline of the Laptev Sea was more than 150 km north of the modern shoreline throughout the Late Pleistocene and Early Holocene. Then, after the termination of the Last Glacial, the sea first invaded the mouths of the Pleistocene river valleys on the shelf as indicated in sediment cores from the Laptev shelf (Bauch et al., 1999; Peregovich et al., 1999). In consequence, all deposits in the Lena Delta showing ages older than 6–5 ka BP have to be related to intra-continental sedimentation.

3.2. Heavy mineral analysis

The sandy sediments from all the three terraces are similar in their heavy mineral associations (Table 2). They are dominated by amphibole (30%) with varying amounts of garnet, epidote, ortho- and clino-pyroxene (each $10 \pm 2\%$). Typically, terrace sands have considerable amounts (8–17%) of opaque minerals and alterites (rock fragments and weathered particles). Apatite is present (3%) and zircon, biotite and titanite are observed in accessory amounts (<2%). Recent Lena River sands, in comparison, are generally characterized by the same heavy mineral assemblage, mainly by the dominance of amphibole (27%) and opaque minerals (23%), followed by alterites (11%) and typically similar amounts of orthopyroxene, garnet (each 10%) and clinopyroxene (8%). Epidote is less abundant than in the terrace sands (2%). Apatite, zircon, biotite, titanite and metamorphic minerals such as sillimanite and kyanite are equally common, but rare (<2%).

The heavy mineral composition of the IC deposits (Kurungnakh section) is clearly different from the Lena River signal (Table 3). It shows the highest amounts of garnet (25%) and an enrichment in epidote (15%). Amphibole is common as opaque grains (14–15%), but IC sediments are poor in pyroxenes (<2%). Zoisite, a mineral which does not appear elsewhere in the delta sediments, can be observed (8%). Apatite (8%) is more abundant than in the Lena River derived sediments. Corundum and tourmaline are found in accessory amounts, as well as zircon. Comparative studies of brook sediments from the Chekanovsky Ridge south and southwest of the Lena Delta (Fig. 1) show that garnet dominates (45%). As in the IC, equal amounts of amphibole, apatite, zoisite and epidote occur (6–8%), although in varying amounts (Table 3).

Table 2
Results of heavy mineral analysis for terrace sediments (in grain %). Means have been calculated since the heavy mineral compositions from the individual samples resemble each other within each terrace[a]

Sample	amp	cpx	opx	ep	zr	gar	ap	sill	ky	rut	tit	bio	alt	Opaque	Number of grains
First terrace															
Top (Sardakh section)	26.4	11.2	10.4	10.4	1.6	8.0	4.8	0	0	0	0.8	0	8.8	17.6	250
Middle (Sardakh section)	23.3	9.0	9.0	11.3	2.3	9.8	4.5	0	0.8	0	1.5	0	11.3	17.3	266
Bottom (Samoylov section)	29.8	13.2	11.6	9.1	0.8	7.4	4.1	0	0	0	0	0	5.8	18.2	242
Mean %	26.5	11.1	10.3	10.2	1.5	8.6	4.3	0	0.4	0	0.8	0	8.5	17.7	
Second terrace															
Top (Arga section)	29.7	11.7	18.0	8.1	0.0	14.4	2.7	0	0	0	1.8	0	1.8	11.7	222
Middle (Arga section)	29.4	6.3	8.7	10.3	1.6	10.3	5.6	0	0	0	0	0	16.7	11.1	252
Bottom (Arga section)	28.4	8.1	13.5	13.5	0.7	8.8	2.7	0	0	0	0.7	0	11.5	12.2	296
Mean %	29.2	8.7	13.4	10.6	0.8	11.2	3.7	0	0	0	0.8	0	10.0	11.7	
Third terrace															
Top (Kurungnakh section)	31.5	5.6	7.9	9.0	3.4	10.1	4.5	0	1.1	0	1.1	0.0	11.2	14.6	267
Middle (Kurungnakh section)	27.1	8.2	8.2	8.2	1.2	10.6	5.9	0	0	0	3.5	1.2	10.6	15.3	255
Bottom (Kurungnakh section)	26.0	10.6	11.5	10.6	1.9	12.5	0.0	0	0	0	1.0	0	6.7	19.2	260
Mean %	28.2	8.1	9.2	9.3	2.2	11.1	3.5	0	0.4	0	1.9	0.4	9.5	16.4	
Recent Lena River sediments															
Lena River Delta[b]	25.9	5.8	10.9	2.2	2.9	10.2	1.1	0.4	0.4	0.7	0.4	0	13.5	25.5	274
Lena River Delta[b]	29.7	9.6	10.4	2.0	0.4	10.4	1.2	0	0	0	2.4	2.8	9.6	21.3	249
Mean %	27.8	7.7	10.7	2.1	1.7	10.3	1.1	0.2	0.2	0.4	1.4	1.4	11.6	23.4	

[a] amp = amphibole, cpx = clinopyroxene, opx = orthopyroxene, ep = epidote, zr = zircon, gar = garnet, ap = apatite, sill = sillimanite, ky = kyanite, rut = rutile, tit = titanite, bio = biotite, alt = alterite, opaque.
[b] Data after Hoops (2000).

Table 3
Results of heavy mineral analysis for IC sediments and Chekanovsky Ridge brook sediments (in grain %). Means have been calculated since the heavy mineral compositions from the individual samples resemble each other within the IC and the brook sediments, respectively[a]

Sample	amp	cpx	opx	tourm	ep	zr	gar	ap	zoi	stau	tit	kor	alt	Opaque	Number of grains
Ice Complex															
Top (Kurungnakh section)	15.9	0.9	1.9	1.9	15.9	1.9	25.2	3.7	12.1	0	0.9	0	6.5	13.1	321
Middle (Kurungnakh section)	12.0	1.1	2.2	1.1	15.2	1.1	25.0	12.0	4.3	0	2.2	1.1	4.3	18.5	276
Bottom (Kurungnakh section)	15.3	1.0	2.0	1.0	16.3	1.0	25.5	7.1	6.1	0	2.0	1.1	5.1	16.3	294
Mean %	14.4	1.0	2.0	1.3	15.8	1.3	25.2	7.6	7.5	0	1.7	0.7	5.3	16.0	
Chekanovsky Ridge (N 72°40′, E 123°30′)															
Brook sediments	7.6	0	0	0	7.6	2.2	45.7	9.8	5.4	2.2	0	0	5.4	14.1	276
Brook sediments	9.6	0	0	0	8.5	1.1	42.6	10.6	4.3	4.3	0	0	6.4	12.8	282
Brook sediments	8.5	0	0	0	8.5	3.2	45.7	8.5	6.4	3.2	0	0	4.3	11.7	282
Mean %	8.6	0	0	0	8.2	2.1	44.7	9.6	5.4	3.2	0	0	5.4	12.9	

[a] amp = amphibole, cpx = clinopyroxene, opx = orthopyroxene, tourm = tourmaline, ep = epidote, zr = zircon, gar = garnet, ap = apatite, zoi = zoisit, stau = staurolite, tit = titanite, kor = korund, alt = alterite, opaque.

In summary, the following essentials can be deduced from the heavy mineral studies: sandy sediments of the three fluvial terraces except those from the IC deposits show a heavy mineral composition similar to that of recent Lena River sediments (Fig. 3). The Lena River signal is characterized by an integral heavy mineral composition due to the large catchment comprising terrigenous clastic and metamorphic rocks (Hoops, 2000). The source area of the sandy sediments in the terraces of the Lena Delta during the entire time of fluvial to deltaic accumulation was the Lena catchment. According to comparative studies, the source area of the IC's clastic material is most likely found in the Chekanovsky Ridge. Brook sediments from Chekanovsky outlets (Fig. 1) show a heavy mineral composition very similar to the composition of the IC sediments. Correlation of the IC and the detrital material from the Chekanovsky Ridge is supported by the same palette of dominant minerals contributing to the heavy mineral spectra (Fig. 3). Hydrodynamic sorting may have caused the smaller relative amount of garnet in the IC sediments. Thus, the mountain ridges to the south could not have been thoroughly glaciated between ~43 and 14 ka BP when they acted as a source area. A similar conclusion for IC deposits from Bykovsky Peninsula, southeast of the Lena Delta, which are derived from the Kharaulakh mountains, has been published recently (Siegert et al., in press).

3.3. Grain size characteristics and TOC content

Grain size parameters are valuable in discriminating depositional subenvironments (Engelhardt et al., 1973; Füchtbauer, 1988). Arithmetic mean (first statistical moment) and sorting (second statistical moment) reflect the flow strength and the degree of uniformity in the deposits produced by current action during the grain transport and deposition (Tucker, 1996). Sediment grain size data for Lena Delta sediments (Fig. 4A and B) indicate that there are two different sediment populations building the three terraces and one interposed between them. Moderately sorted fine sands forming the base of the third terrace match the sandy sediments of the second terrace (Fig. 4B). In contrast, sediments from the IC are finer and poorly sorted. Moreover, unlike any other sedimentary facies in the delta, the sediments from the IC show polymodal grain size distributions (Fig. 5). Thus, multiple transport processes for the formation of the IC sediments have to be considered. First terrace deposits are positioned between IC sediments and the former two terraces (Fig. 4B). Their grain size distribution and sorting change from river bedload deposits at the bottom of the deltaic sequences to suspension load bedding towards the top, as in the Sardakh and Sagastyr sections (Schwamborn et al., 2000b). Generally, smaller mean grain sizes correspond to poorer sorting, e.g. for deltaic sediments of the first terrace and the organic-rich IC sediments. However, presumably wave-winnowed, well-sorted fine sands have been found as intercalations within silty-sandy to peaty first terrace deposits. Fig. 4B indicates that, with regard to mean grain size, the third and second terrace sands plot close to recent fluvial bedload sands of the major delta branches. They show overlapping ranges in standard deviations. In addition, the second statistical moment (sorting) supports the conclusion that they may have been derived from the same parent population, as they show overlapping error bars. Therefore, the pre-Holocene sandy sediments of the second and the third terrace are attributed to fluvial bedload sedimentation. A low TOC content (<0.4 wt%) is common to these bedload sands (Fig. 4C and D). In contrast, high TOC contents (<18 wt%) are associated

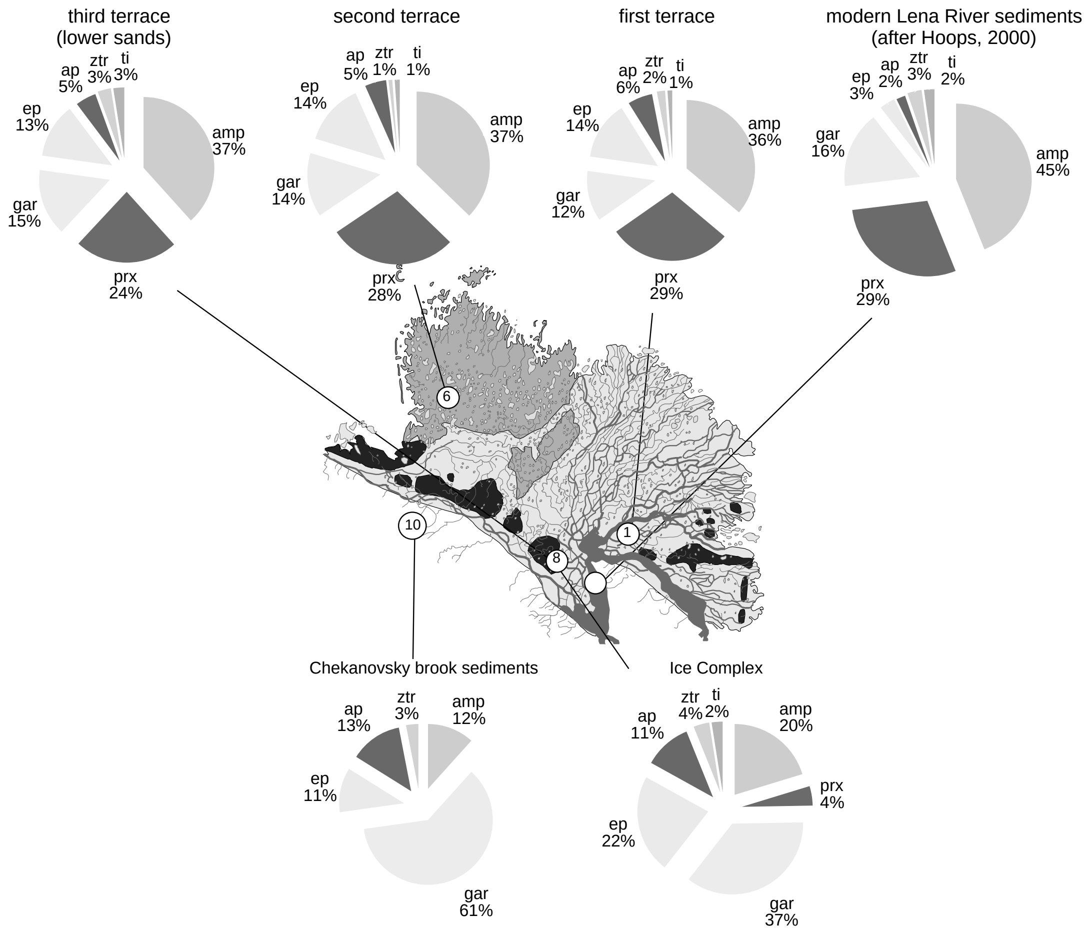

Fig. 3. Heavy mineral associations of the sandy sediments from the first, second and third terrace and their assumed sediment source, the Lena River. Likewise, the heavy mineral association of the Ice Complex deposits and their assumed sediment source, the mountain ridges to the south (i.e. the Chekanovsky Mountains). The same abbreviations for mineral names are valid as used in Tables 2 and 3 plus ztr = zircon + tourmaline + rutile.

with fine-grained sediments that are preferentially deposited in the deltaic plain (first terrace) and the IC.

4. Discussion

The review of the age determinations and mineralogical properties allows a general reconstruction of the sediment succession in the Lena Delta (Fig. 6).

4.1. Third terrace lower sands (Nagym and Kurungnakh sections)

The third terrace represents a fluvial stage of the Lena River for the period of ~88–43 ka BP. Grain size characteristics of the sandy deposits from the third terrace are associated with a bedload environment. Sediment structures like wavy bedding and cryoturbations with interlayers of root horizons point to fluvial sedimentation under shallow water conditions comparable to recent floodplain environments.

4.2. IC (Nagym and Kurungnakh sections)

IC deposits on top of the fluvial sequences of the third terrace are regarded as periglacial polygenetic formations of Late Pleistocene time between 43 and 14 ka BP. They are derived from the Chekanovsky Ridge and presumably transported to the northern foreland through local outflows. Multiple processes including gravitational sliding, surface runoff, solifluction and wind have reworked, transported and redeposited primarily accumulated material. Changing hydraulic conditions or reworking may have modified the heavy mineral composition in single sediment layers. Water flow, both in the uplands and the lowlands, was active during seasonal thawing of irregularly distributed snow cover in snow and firn fields, which were probably widespread in the area (Kunitsky, 1989; Galabala, 1997; Kunitsky et al., in press). Although fluvial activity through Late Pleistocene time is seen in seismic data of the exposed Laptev shelf (Kleiber and Niessen, 1999), IC deposition in the

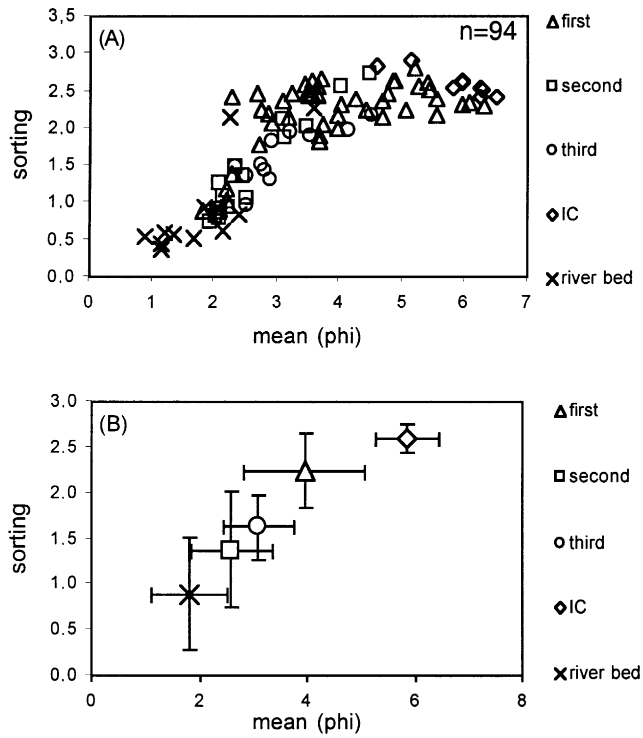

Fig. 4. Mean values, sorting and TOC content of sediment samples. Sample groups listed are first, second and third terrace and IC sediments, comparisons are from grab samples of Lena River bedload. (A) Scatter plot of mean versus sorting for the samples utilized. (B) Mean and sorting show the separation and grouping of sample sets. Error bars indicate standard deviation. (C) Scatter plot of relationship between mean and TOC content. (D) Mean and TOC with error bars that show the separation and grouping of sample sets.

area of the Olenyokskaya branch is only possible during a time of Lena River inactivity in this delta sector. Otherwise, the locally derived and fine-grained sediments would have been removed with the Lena River downflow.

The strong facies change from the underlying fluvial sands to the IC is interpreted as resulting from tectonic activity. There are strong indications for tectonic movements in the Lena Delta area. This includes the development of extensional halfgraben structures on the Laptev shelf to the north due to riftogenesis (Drachev et al., 1998; Hinz et al., 1999; Franke et al., 2000) and compression tectonics in the continental mountain ridges to the south (Romanovskii, 1978; Mikulenko and Timirshin, 1996; Grinenko, 1998). Fault systems belonging to the "Lena–Taymyr dislocation" run subparallel to the coastal line from the Taymyr Penninsula in the west to the Lena Delta area in the east (Mikulenko and Timirshin, 1996). Here, the course of the fault system is marked by the Olenyokskaya branch and is regarded as a central structure within the Lena Delta (Fig. 7). It is associated with the uplifting of the continental side. Considerable tectonic movements in the Verkhoyansk and Kharaulakh mountains to the south occurred until 50 ka BP (Romanovskii, 1978). Local uplift ranged from several hundreds to more than 1000 m.

4.3. Second terrace (Arga section)

Sedimentological and mineralogical parameters indicate that sediments of the second terrace are similar to recent Lena River bedload. The lack of silt, clay or organic matter in the Arga sands is interpreted as a result of a highly energetic periglacial channel network. The overlapping IR-OSL age determinations of the Arga sands suggest high accumulation rates. This points to a braided river system implying an upper flow regime, since for the same slope braided rivers tend to have higher discharges than meandering rivers (Allen, 1970; Panin et al., 1999). Braided rivers are generally found close to the hinterland, where the slope of the drainage basin is high and low sinuosity rivers flow on flat foreland plains (Quirk, 1996). In the case of Lena River, the slope providing the fluvial energy may be replaced by the "Lena Pipe", the narrow fluvial pathway between the Chekanovsky and the Kharaulakh Mountains (Fig. 6). It enhances fluvial energy before the Lena River reaches the lowland plain. To understand the sediment facies of the second terrace, the Arga sands may be compared with the European periglacial river systems. They are also characterized by a pronounced enrichment in fluvial activity at 17–12 ka BP (Sidorchuk and Borisova, 2000) with a periglacial peak discharge that is believed to have been up to 8 times larger than

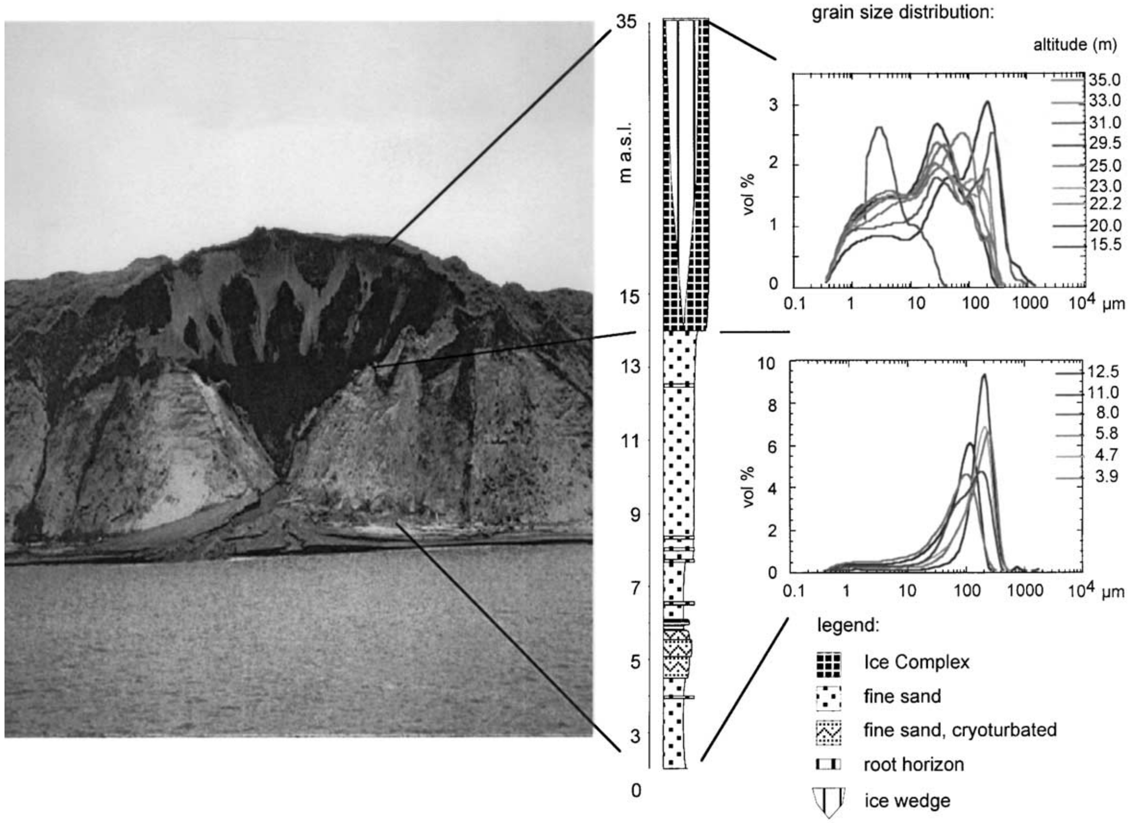

Fig. 5. Grain size distributions for IC deposits and low-sands from Kurungnakh section.

that in modern times (Sidorchuk et al., 2000). The river deposits have similar characteristics like the flat-lying Arga sands. They are built of massive fine-grained deposits, they lack low-lying interchannel areas and as a result, levees, crevasse deltas and lacustrine deposits of the same age are not present (Mol et al., 2000). More deposits like those described above have been dated to Late Pleistocene age in eastern Germany (Mol, 1997) and eastern Netherlands (Huisink, 2000).

Fine-sandy sediments from these Late Pleistocene periglacial environments building flat-lying, alluvial fan-like and structureless deposits have been attributed to niveo-fluvial activity, or so-called "abluation" (Liedtke, 1981). This means that the sandy deposits are related especially to fluvial peak discharges after snowmelt in spring where high sediment load of the river is caused by increased slope wash in the drainage basin. The outwash delivers particularly fine-grained sediments to the river. The sediment load of the river is further enhanced by bank erosion of the increased periglacial river activity and may be accompanied by pronounced aeolian activity that is promoted by sparse vegetation cover in the periglacial environment (Huissteden et al., 2000). Such a period of pronounced fluvial action and the geomorphological effects of river activity point to environmental changes in the catchment. They are believed to last only a short time and to express times of climatic change (Vandenberghe, 1995).

Correspondingly, in a core (PS2458) from the Laptev Sea continental margin (78°N, 135°E, 985 m water depth) off the mouth of the presumed Late Pleistocene Lena River, deglacial changes in the freshwater outflow can be reconstructed from the oxygen isotope record of planktic foraminifers. A short term event (<0.5 ka) of maximum outflow at ~ 13 ka BP correlates in time to an oxygen isotope minimum both in the central Arctic Ocean (Lomonosov Ridge) and in the western Fram Strait (Spielhagen et al., 1998). A major melting event in the Siberian highlands of the Lena River catchment was proposed, which contributed to high fluvial activity at that time. Widespread thick sand deposits are described in the northern Yakutian lowlands and in the river lowlands of the Lena River catchment, amongst them the Arga sands (Galabala, 1997). A periglacial origin was interpreted including fluvial and aeolian activity. Equivalent deposits on the Laptev shelf may be found in submarine channels, separated by shoals, which cross the shelf and connect the river mouths with troughs or the shelf break further north (Lastochkin, 1982; Pavlidis et al., 1997; Kleiber and Niessen, 1999). Geophysical investigations on Arga Island carried out with a radio-echo sound system suggest that the sandy environment

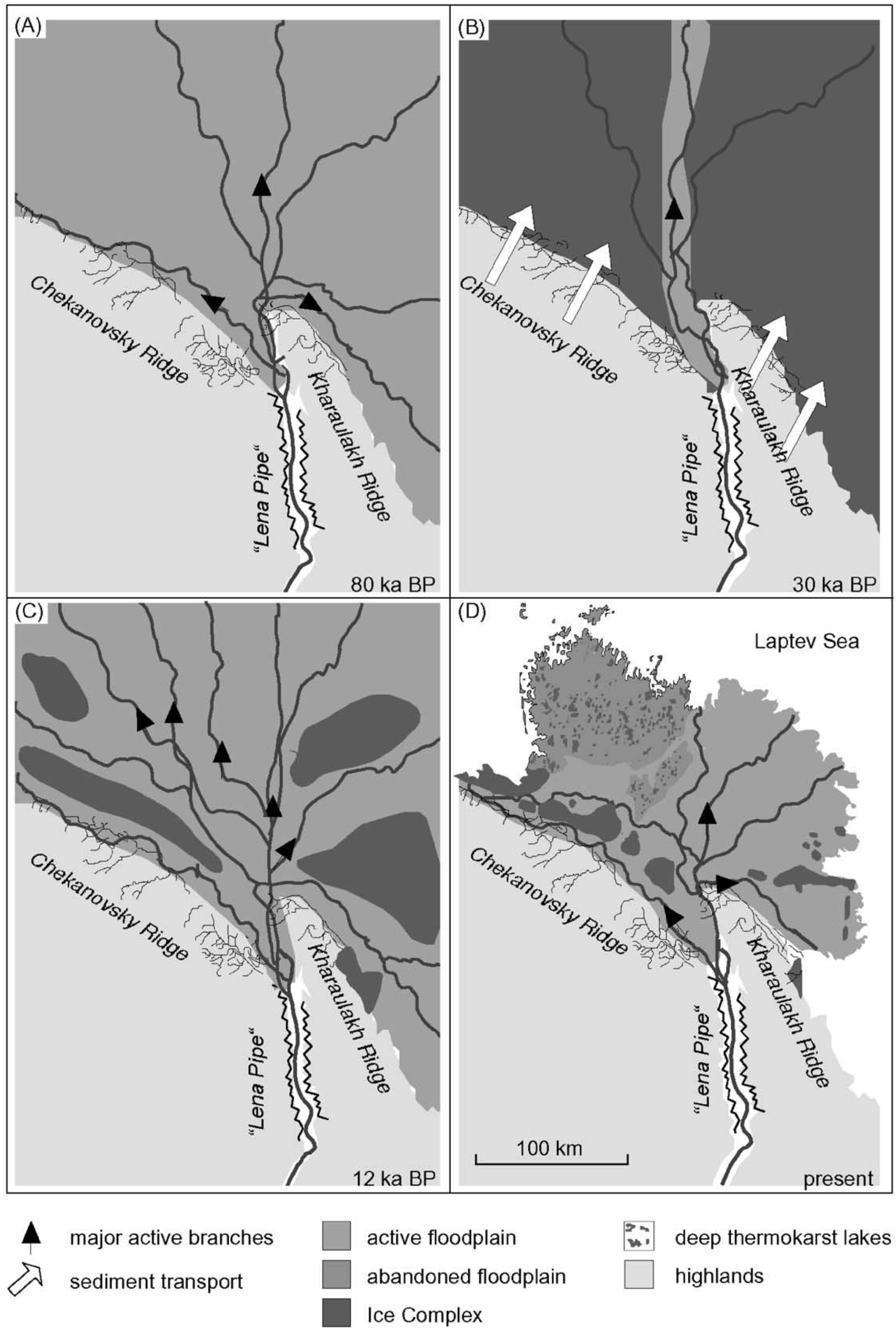

Fig. 6. Paleogeographic sketch maps illustrating the Late Quaternary development of the Lena Delta. See the text for further discussion. (A) Lowstand system consisting of exposed Laptev shelf and river discharge in Olenyok and Bykov branches and to the north. (B) Phase of IC deposition from down the highlands. River activity only to the north. (C) Accumulation of the Arga sands. (D) Major aggradation of the modern, subaerial delta as rising sea level backflooded a large portion of the lowstand delta surface. Subsidence in the eastern sector promotes progressive fluvial erosion of former floodplain deposits.

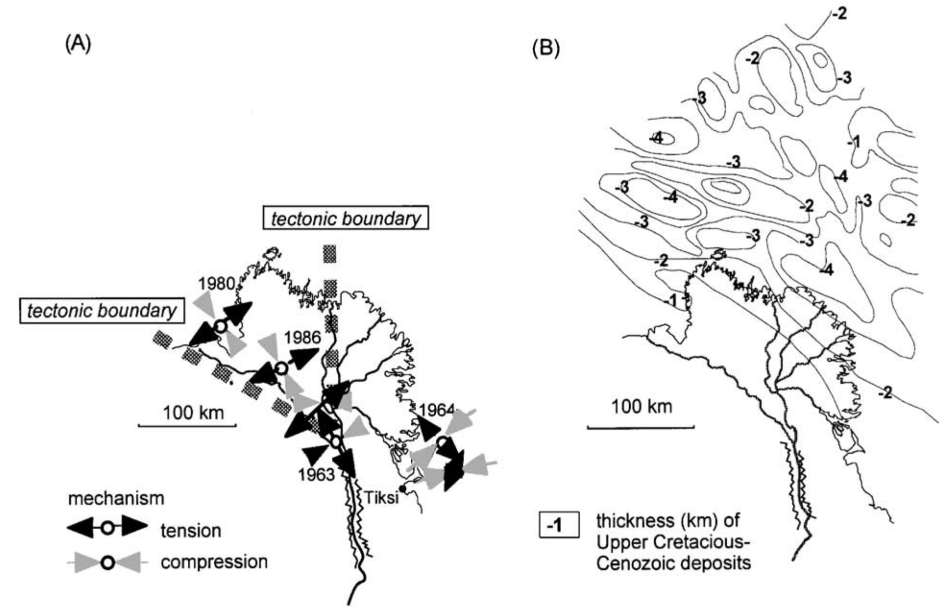

Fig. 7. (a) Distribution of recent earthquake occurrence (magnitude 5–6) in the Lena Delta area (after Avetisov, 1999). The Lena Delta is demarcated by tectonic boundaries between the western and the eastern sector (according to Pavlova and Dorozkhina, 2000) and along the Olenypkskaya branch in the south (according to Mikulenko and Timirshin, 1996). (b) Thicknesses of upper Cretacious-Cenozoic deposits in the Lena Delta area (after Grigoriev et al., 1996).

found here continues at least down to about 60 m (Schwamborn et al., 2000a). Fluvial (periglacial slope wash) sediments on Bykovsky Peninsula, southeast of the Lena Delta region, have recently been dated to 12 ka BP in conformity with the Arga sands (Schirrmeister and Grosse, unpublished data). Thus, periglacial outwash sedimentation during early summer peak discharge of the Lena River may be postulated for the sandy deposits on Arga Island.

At the onset of the Holocene, this fluvial plain was abandoned, and between 8–7 ka BP the initiation of thermokarst created hollows and lakes on the surface (Schwamborn et al., in press). Glacial features identified by Grosswald et al. (1999) have neither been found exposed on Arga Island nor in the lake sediments of Lake Nikolay (Schwamborn et al., in press), which is centrally positioned in the area of presumed glaciation.

As river discharge does not currently reach the topographic level of 20 m a.s.l., corresponding to the average elevation of the second terrace, either tectonic uplift of the western sector or downdrop of the eastern sector is evident. A sublongitudinal fracture zone running through the Lena Delta separates the western from the eastern sector already observed by Lungershausen (1967). The base of the IC deposits shows a considerable difference in altitude (more than 20 m) between the western and the eastern sections (Grigoriev, 1993; Pavlova and Dorozkhina, 2000). From 10 to 28 m a.s.l. in the western sector the base dips to −8 to −10 m a.s.l. in the eastern sector. In addition, whereas a full complex of terraces is developed in the western sector, the eastern sector is dominated by floodplain alluvium and relics of the third terrace. This has been taken as an confirmation for a tectonic boundary between these two Lena Delta sectors running from north to south along the Tumatskaya branch (Pavlova and Dorozkhina, 2000) (Fig. 7). Possible equivalent sandy sediments of the second terrace in the eastern sector are considered to have been removed by fluvial erosion. Neotectonic activity is documented until recent times (Avetisov, 1999). Both compression and tension patterns are reported in the area with earthquake magnitudes between 5 and 6 (Fig. 7). Furthermore, the tectonic situation shows an aulacogenic character in the most eastern Lena Delta area with a Quaternary sediment infill 4 times as thick as in the western areas as revealed by gravimetric and seismic measurements (Grigoriev et al., 1996). Regional subsidence reaches from 1 km in the western delta sector to 4–5 km seaward of the delta in the east (Fig. 7). The asymmetry of the downwarp located east off the delta and its very irregular western border are characteristic of rifts that have formed at the junction of substantially different lithospheric plates (Avetisov, 2000).

4.4. First terrace (Samoylov, Sardakh and Sagastyr sections)

In the Holocene actual delta sector, the fluvial facies of the sediments changes from organic-rich sands at the bottom to silty-sandy peats towards the surface. This gradual facies change is regarded as typical for the transition of delta growth on top of backfilled fluvial channels. However, the exact facies boundary has not been detected. Inversions of age determinations document high energetic sedimentation conditions on the delta plain. The accumulation occurred shortly after river highstand in early summer. Generally, the ages change from Early Holocene in the west to late Holocene in the east, possibly indicating river migration of this direction. In the Early Holocene, climatic warming and restoration of vegetation led to a decrease of peak discharge of the Lena River, presumably a decrease of bedload and a relatively increased load of fine-grained material and organic-rich suspension. Only clay-sized material is still being washed out to sea. This resulted in a change of river pattern from aggrading braided channels to floodplain sedimentation or slightly meandering channels according to Korotaev (1986).

5. Conclusions

The Lena Delta area is a geomorphic composite of erosional remnants from different Late Pleistocene- to Holocene-aged fluvial stages and deltaic sedimentation. The latter is found primarily in the eastern sector. The western sector is dominated by exposed peaty-sandy and sandy uplands formed during the Last Glacial sea level lowstand. Lower fluvial sands of the third terrace represent Paleo-Lena River deposits of Late Pleistocene age (marine isotope stages 5 to early 3). The overlying IC deposits result from local outwash from the nearby mountain ridges to the south. Periglacially characterized river deposits of the second terrace represent a Late Weichselian stadial. These deposits are interpreted as a river response to a short term climatic change in the catchment.

The general outline of the modern delta began to form after the mid-Holocene. It is remarkable that the initiation of the delta at its modern position is delayed compared to the mean timing of the initial Holocene delta development compiled by Stanley and Warne (1994). They calculated a mean of ~7.0 ka BP for northern latitude deltas whereas the deltaic sedimentation of the Lena Delta only started after 6–5 ka BP as seen from the transgression history of the Laptev Sea (Bauch et al., 1999). This may be due to the great lateral extension of the Laptev shelf (up to 500 km) and its low bottom slope inclination (Are, 1996).

The delta is a part of the seismically active zone with considerable block uplift. The tectonic activity is responsible for preserving mainly the western parts of the second and third terraces against fluvial erosion. Tectonic movement is also regarded crucial for the strong facies boundary between the fluvial sands of the third terrace and the overlying IC.

The sediment analyses do not support the hypothesis for a Late Pleistocene glaciation in the Lena Delta area simultaneous with the north European Weichselian glaciation. In combination with core analysis and seismic surveys from the Laptev shelf, sediment analyses suggest a continuous sedimentation of Lena River sands in the area throughout Late Pleistocene and Holocene time. The period not covered by fluvial sedimentation (between 43 and 14 ka BP) may be explained by progressive river erosion of these sediments.

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References

Alabyan, A.M., Chalov, R.S., Korotaev, V.N., Sidorchuk, A.U., Zaytsev, A.A., 1995. In: Kassens, H., Piepenburg, D., Thiede, J., Timokhov, L., Hubberten, H.-W., Priamikov, S. (Eds.), Natural and Technologic Water and Sediment Supply to the Laptev Sea, Reports on the Polar Research, 75, 265–271.

Alekseev, M.N., 1997. Paleogeography and geochronology in the Russian Eastern Arctic during the second half of the Quaternary. Quaternary International 41/42, 11–15.

Allen, J.R.L., 1970. Physical Processes of Sedimentation. Elsevier, New York, 248pp.

Are, F., 1996. Dynamics of the littoral zone of Arctic Seas (state of the art and goals). Polarforschung 64, 123–131.

Are, F., 1999. The role of the coastline for sedimentation in the Laptev Sea. In: Kassens, H., Bauch, H., Dmitrenko, I., Eicken, H., Hubberten, H.-W., Melles, M., Thiede, J., Timokhov, L. (Eds.), Land–ocean Systems in the Siberian Arctic: Dynamics and History. Springer, Berlin, pp. 287–299.

Are, F.E., Reimnitz, E., 2000. An overview of the Lena River Delta setting: geology, tectonics, geomorphology, and hydrology. Journal of Coastal Research 16, 1083–1093.

Avetisov, G.P., 1999. Geodynamics of the zone of continental continuation of Mid-Arctic earthquakes belt (Laptev Sea). Physics of the Earth and Planetary Interiors 114, 59–70.

Avetisov, G.P. (2000). Once again on the earthquakes of the Laptev Sea, geological–geophysical features of the Lithosphere of the Arctic region, Vol. 3, St. Petersburg, Ministry of Natural Resources of Russian Federation, All-Russia Research Institute for Geology and Mineral Resources of the World Ocean, pp. 104–114 (in Russian).

Bauch, H., Kassens, H., Erlenkeuser, H., Grootes, P.M., Dehn, J., Peregovich, B., Thiede, J., 1999. Depositional environment of the Laptev Sea (Arctic Siberia) during the Holocene. Boreas 28, 194–204.

Behrends, M., Hoops, E., Peregovich, B., 1999. Distribution patterns of heavy minerals in Siberian Rivers, the Laptev Sea and the eastern Arctic Ocean. In: Kassens, H., Bauch, H., Dmitrenko, I., Eicken, H., Hubberten, H.-W., Melles, M., Thiede, J., Timokhov,

L. (Eds.), Land–ocean Systems in the Siberian Arctic: Dynamics and History. Springer, Berlin, pp. 265–286.

Boenigk, W., 1983. Schwermineralanalyse. Ferdinand Enke Publishers, Stuttgart, 158pp.

Chappell, J., Omura, A., Esat, T., McCulloch, M., Pandolfi, J., Ota, Y., Pillans, B., 1996. Reconciliation of late Quaternary sea levels derived from coral terraces at Huaon Peninsula with deep sea oxygen isotope records. Earth and Planetary Science Letters 141, 227–236.

Dill, H.G., 1998. A review of heavy minerals in clastic sediments with case studies from the alluvial-fan through the nearshore-marine environments. Earth-Science Reviews 45, 103–132.

Drachev, S.S., Savostin, L.A., Groshev, V.G., Bruni, I.E., 1998. Structure and geology of the continental shelf of the Laptev Sea, Eastern Russian Arctic. Tectonophysics 298, 357–393.

Engelhardt, W.V., Füchtbauer, H., Müller, G., 1973. Die Bildung von Sedimenten und Sedimentgesteinen. Schweizerbart'sche Verlagsbuch-handlung, Stuttgart, pp. 56–154.

Fairbanks, R.G., 1989. A 17,000 year glacio-eustatic sea-level record: influence of glacial melting on the Younger Dryas event and deep-ocean circulation. Nature 342, 637–642.

Franke, D., Krüger, F., Klinge, K., 2000. Tectonics of the Laptev Sea–Moma 'rift' region: investigation with seismologic broadband data. Journal of Seismology 4, 99–116.

Füchtbauer, H., 1988. Sedimente und Sedimentgesteine. Schweizerbart'sche Verlagsbuch-handlung, Stuttgart. pp. 129–139.

Fukuda, M., 1994. Occurrence of Ice Complex (Edoma) in Lena River Delta region and big Lhyakhovsky Island, high Arctic Eastern Siberia. Proceedings of the Second Symposium on the Joint Siberian Permafrost Studies between Japan and Russia in 1993, Hokkaido, pp. 1–9.

Galabala, R.O., 1987. New data on the Lena Delta structure. Quaternary of North-East USSR, Magadan, 152–172 (in Russian).

Galabala, R.O., 1997. Perelekti and the initiation of glaciation in Siberia. Quaternary International 41/42, 152–171.

Gordeev, V.V., Shevchenko, V.P., 1995. Chemical composition of suspended sediments in the Lena River and its mixing zone. Russian–German Cooperation, Laptev Sea System. Reports on Polar Research 176, 154–169.

Grigoriev, M.N., 1993. Criomorphogenesis in the Lena Delta. Permafrost Institute Press, Yakutsk, 176pp (in Russian).

Grigoriev, M.N., Imaev, V.S., Imaeva, L.P., Kozmin, B.M., Kunitsky, V.V., Larionov, A.G., Mikulenko, K.I., Skryabin, R.M., Timirshin, K.V., 1996. Geology, seismicity, and cryogenic processes in the Arctic areas of western Yakutia. Yakutian Scientific Center SD RAS, Yakutsk, 84pp (in Russian).

Grinenko, O.V., 1998. Vserossiyskoe soveshchanie "Glavnye itogi v izuchenii chetvertichnogo perioda i osnovnye napravleniya issledovaniya v XXI veke". Tezisy dokladov., Sankt Petersburg, pp. 155–156 (in Russian).

Grosswald, M.G., 1998. Late-Weichselian Ice Sheets in Arctic and Pacific Siberia. Quaternary International 45/46, 3–18.

Grosswald, M.G., Hughes, T.J., 1999. The case for an ice shelf in the Pleistocene Arctic ocean. Polar Geography 23, 23–54.

Grosswald, M.G., Hughes, T.J., Lasca, N.P., 1999. Oriented lake-and-ridge assemblages of the Arctic coastal plains: glacial landforms modified by thermokarst and solifluction. Polar Record 35, 215–230.

Hinz, K., Block, M., Cramer, B., Franke, D., Kos'ko, M., Meyer, H., Neben, S., Reichert C., Roeser, H.-A., 1999. Die Laptev-See—russ. Arktis: neue geowissenschaftliche Erkenntnisse über den geologischen Bau und die Entwicklung des riesigen Schelfes der Laptev-See. Geo-Berlin 1998, Gemeinsame Jahrestagung von DGG, DMG, GGW und Pal. Ges., Berlin, p. 133.

Holmes, M.L., Creager, J.S., 1974. Holocene history of the Laptev continental shelf. In: Herman, Y. (Ed.), Marine Geology and Oceanography. Springer, Berlin, pp. 211–229.

Hoops, E., 2000. Heavy mineral distribution of east Siberian River sediments. Ph.D. thesis, University of Potsdam.

Hubberten, H.-W., Romanovski N.N. (in press). Terrestrial and offshore permafrost evolution of the Laptev Sea region during the Last Pleistocene–Holocene glacial-eustatic cycle. In: Paepe, R. (Ed.), Permafrost Response on Economic Development, Environmental Security and Natural Resources Potential, Proceedings of the NATO-ARW, Novosibirsk, 1998, Kluwer, Dordrecht.

Huisink, M., 2000. Changing river styles in response to Weichselian climate changes in the Vecht valley, eastern Netherlands. Sedimentary Geology 133, 115–134.

Huissteden, vanJ.K., Vandenberghe, J., Hammen, v.d.T., Laan, W., 2000. Fluvial and aeolian interaction under permafrost conditions: Weichselian Late Pleniglacia, Twente, eastern Netherlands. Catena 40, 307–321.

Ivanov, O.A., 1970. The main stages of evolution of North-East USSR subarctic plains during the Cenozoic. Severnyi Ledovityi okean i ego poberezye v kaynozoye. Gidrometeozidat, Leningrad, pp. 474–479 (in Russian).

Ivanov, O.A., 1972. The Stratigraphy and Correlation of Neogene and Quaternary Sediments on Subarctic Plains of East Yakutia. Problemy izucheniya chetvertichnogo perioda. Nauka, Moscow, pp. 202–211 (in Russian).

Kleiber, H.P., Niessen, F., 1999. Late Pleistocene Paleoriver channels on the Laptev Sea shelf—implications from sub-bottom profiling. In: Kassens, H., Bauch, H., Dmitrenko, I., Eicken, H., Hubberten, H.-W., Melles, M., Thiede, J., Timokhov, L. (Eds.), Land–ocean Systems in the Siberian Arctic: Dynamics and History. Springer, Berlin, pp. 657–665.

Korotaev, V.N., 1986. Geomorphology of river deltas on the Arctic coast of Siberia. Polar Geography and Geology 10, 139–147.

Krbetschek, M.R., Gonser, G., Schwamborn, G. (in press). Luminescence dating results on sediment sequences of the Lena Delta. Polarforschung.

Kunitsky, V.V., 1989. Cryolithology in the Lena River Mouth. Permafrost Institute Press, Yakutsk, Russia, 162pp (in Russian).

Kunitsky, V.V., Schirrmeister, L., Grosse, G., Kienast, F. (in press). Snow patches in nival landscapes and their role for the Ice Complex formation in the Laptev Sea lowlands. Polarforschung.

Kuptsov, V.M., Lisitsin, A.P., 1996. Radiocarbon of Quaternary along shore and bottom deposits of the Lena and the Laptev Sea sediments. Marine Chemistry 53, 301–311.

Lastochkin, A.N., 1982. Methodi Marskaga Geomorfologitcheskaga Kartografirowaniya. Leningrad, Nedra, Leningradskoye Otdelenye (in Russian).

Liedtke, H., 1981. Die Nordischen Vereisungen in Mitteleuropa. Forschungen zur deutschen Landeskunde 204. Zentralausschuß für deutsche Landeskunde, Trier, 307pp.

Lungershausen, G.F., 1967. Neotectonics of the Siberian Platform and Surrounding Mountains. Tektonicheskie dvizheniya i noveishie struktury zemnoi kory. Nedra, Moscow, pp. 410–417 (in Russian).

Mange, M.A., Maurer, H.F.W., 1991. Schwerminerale in Farbe. Ferdinand Enke Publishers, Stuttgart, 148pp.

Meyer, H., Dereviagin, A., Siegert, C., Hubberten, H.-W. (in press). Paleoclimate studies on Bykovski Peninsula, North Siberia—hydrogen and oxygen isotopes in ground ice. Polarforschung.

Mikulenko, K.I., Timirshin, K.V., 1996. Geological construction of the Lena Delta. In: Grigoriev, M.N., Imaev, V.S., Imaeva, L.P., Kozmin, B.M., Kunitsky, V.V., Larionov, A.G., Mikulenko, K.I., Skryabin, R.M., Timirshin, K.V. (Eds.), Geology, Seismicity, and Cryogenic Processes in the Arctic Areas of Western Yakutia.

Yakutian Scientific Center SD RAS, Yakutsk, pp. 29–39 (in Russian).
Mol, J., 1997. Fluvial response to Weichselian climate changes in the Niederlausitz (Germany). Journal of Quaternary Science 21, 43–60.
Mol, J., Vandenberghe, J., Kasse, C., 2000. River response to variations of periglacial climate in mid-latitude Europe. Geomorphology 33, 131–148.
Morton, A.C., Hallsworth, C., 1994. Identifying provenance-specific features of detrital heavy mineral assemblages in sandstones. Sedimentary Geology 90, 241–256.
Müller-Lupp, T., Bauch, H.A., Erlenkeuser, H., Hefter, J., Kassens, H., Thiede, J., 2000. Changes in the deposition of terrestrial organic matter on the Laptev Sea shelf during the Holocene; evidence from stable carbon isotopes. International Journal of Earth Sciences 89, 563–568.
Panin, A.V., Sidorchuk, A.Y., Chernov, A.V., 1999. Historical background to floodplain morphology: examples from the East European Plain. In: Marriott, S.B., Alexander, J. (Eds.), Floodplains: Interdisciplinary Approaches, Special Publication 163. Geological Society, London, pp. 217–229.
Pavlidis, Y.A., Dunayev, N.N., Shcherbakov, F.A., 1997. The Late Pleistocene paleogeography of Arctic Eurasian shelves. Quaternary International 41–42, 3–9.
Pavlova, E., Dorozkhina, M., 1999. Geological–geomorphological studies in the northern Lena River Delta. In: Rachold, V., Grigoriev, M.N. (Eds.), Expeditions in Siberia in 1999, Reports on Polar Research, 315, 112–128.
Pavlova, E., Dorozkhina, M., 2000. Geological–geomorphological studies in the western and central sectors of the Lena River Delta. In: Rachold, V., Grigoriev, M.N. (Eds.), Expeditions in Siberia in 2000, Reports on Polar Research, 354, 75–90.
Pavlova, E., Dorozkhina, M., Rachold, V., 1999. Geomorphological structure of the western sector of the Lena River Delta. Terra Nostra, 99/11: Fifth Workshop on Russian–German Cooperation: Laptev Sea System, Program and Abstracts, St. Petersburg, p. 57.
Peregovich, B., Hoops, E., Rachold, V., 1999. Sediment transport to the Laptev Sea (Siberian Arctic) during the Holocene—evidence from the heavy mineral composition of fluvial and marine sediments. Boreas 28, 205–214.
Quirk, D.G., 1996. Base profile: a unifying concept in alluvial sequence stratigraphy. In: Howell, J.A., Aitken, J.F. (Eds.), High Resolution Sequence Stratigraphy: Innovations and Applications, Special Publication 104. Geological Society, London, pp. 37–49.
Rachold, V., Alabyan, A., Hubberten, H.-W., Korotaev, V.N., Zaitsev, A.A., 1996. Sediment transport to the Laptev Sea—hydrology and geochemistry of the Lena River. Polar Research 15, 183–196.
Rachold, V., Hoops, E., Alabyan, A., Korotaev, V.N., Zaitsev, A.A., 1997. Expedition to the Lena and Yana rivers June–September 1995. Reports on Polar Research 248, 193–210.
Rachold, V., Grigoriev, M.N., Antonow, M., 1999. Modern sedimentation and environmental history of the Lena Delta. In: Rachold, V., Grigoriev, M.N. (Eds.), Russian–German Cooperation System Laptev Sea 2000: the Lena Delta 1998 Expedition, Reports on Polar Research, 315, 81–82.
Romanovskii, N.N., 1978. Effect of neotectonic movements on formation of permafrost regions. In: Sanger, F.J., Hyde, P.J. (Eds.), Second international conference on permafrost; USSR contribution. National Academy of Science, Washington, DC, US, pp. 184–188.
Romanovskii, N.N., Kholodov, A.L., Gavrilov, A.V., Tumskoy, V.E., Hubberten, H.-W., Kassens, H., 1999. Ice-bonded permafrost thickness in the eastern part of the Laptev Sea shelf. Kryosphera Zemli 3, 22–32.
Romanovskii, N.N., Hubberten, H.-W., Gavrilov, A.V., Tumskoy, V.E., Tipenko, G.S., Grigoriev, M.N., Siegert, C., 2000. Thermokarst and land–ocean interactions, Laptev Sea region, Russia. Permafrost and Periglacial Processes 11, 137–152.
Schirrmeister, L. (in press). Late Quaternary and recent environmental situation around the Olenyok Channel (western Lena Delta) and on Bykovsky Peninsula, In: Rachold, V., Grigoriev, M.N. (Eds.), Expeditions in Siberia in 2000, Reports on Polar Research, 315, 85–98.
Schirrmeister, L., Siegert, C., Kunitsky, V., Sher, A., 1999. Paleoclimate signals of ice-rich permafrost. In: Rachold, V., Grigoriev, M.N. (Eds.), Expeditions in Siberia in 1998, Reports on Polar Research 315, 145–152.
Schwamborn, G., Schneider, W., Grigoriev, M.N., Rachold, V., Antonow, M., 1999. Sedimentation and environmental history of the Lena Delta. In: Rachold, V., Grigoriev, M.N. (Eds.), Expeditions in Siberia in 1998, Reports on Polar Research 315, 94–111.
Schwamborn, G., Rachold, V., Schneider, W., Grigoriev, M., Nixdorf, U., 2000a. Ground penetrating radar and shallow seismic—stratigraphic and permafrost investigations of Lake Nikolay, Lena Delta, Arctic Siberia. Proceedings of the Eighth International Conference on Ground Penetrating Radar, SPIE Vol. 4084, Brisbane, Australia, pp. 783–789.
Schwamborn, G., Schneider, W., Grigoriev, M.N., Rachold, V., 2000b. Sedimentation and environmental history of the Lena Delta. Proceedings of the International Conference on Past Global Changes (PAGES), Geological Society of Czech Republic, Prague, GeoLines, 11, 35–38.
Schwamborn, G., Tumskoy, V., Andreev, A.A., Rachold, V., Grigoriev, M.N., Pavlova, E.Y., Dorozkhina, M.V., Hubberten, H.-W. (in press). Evolution of Lake Nikolay, Arga Island, Western Lena River Delta, during Late Weichselian and Holocene time. Polarforschung.
Serova, V.V., Gorbunova, Z.N., 1997. Mineral composition of soil, aerosols, suspended matter and bottom sediments of the Lena estuary and the Laptev Sea. Oceanology, Marine Geology 37, 131–135.
Sher, A., 1995. Is there any real evidence for a huge shelf ice sheet in east Siberia? Quaternary International 28, 39–40.
Sher, A., 1999. Ice Complex of the Laptev Sea shelf area: paleoecology, age and other problems and current solutions. Quaternary Environment of the Eurasian North (QUEEN), Proceedings of the Third Workshop—Abstracts, Øystese, Norway, 16–18 April, p. 55.
Sidorchuk, A.Y., Borisova, O.K., 2000. Method of paleogeographical analogues in paleohydrological reconstructions. Quaternary International 72, 95–106.
Sidorchuk, A.Y., Panin, A.V., Borisova, O.K., Elias, S.A., Syvistki, J.P., 2000. Channel morphology and river flow in the northern Russian Plain in the Late Glacial and Holocene. International Journal of Earth Sciences 89, 541–549.
Siegert, C., Schirrmeister, L., Babiy, O.A. (in press). The composition of Late Pleistocene permafrost deposits—new sedimentological, mineralogical and geochemical data from the Ice Complex of the Bykovsky Peninsula, Northern Siberia. Polarforschung.
Slagoda, E.A., 1993. Genesis and microstructure of cryolithogenic deposits of the Bykovsky Peninsula and the Muostakh Island. Ph.D. thesis, Permafrost Institute Yakutsk, RAS Siberian Section, 218pp (in Russian).
Soloviev, P.A., 1989. Agricultural Atlas of Yakutskaya ASSR. GUGK Press, Moscow, p. 27.
Spielhagen, R., Erlenkeuser, H., Heinemeier, J., 1998. Deglacial freshwater outflow from Lena River (Siberia). Quaternary Environment of the Eurasian North (QUEEN), proceedings of the Second Workshop—Abstracts, St. Petersburg, 5–6 February, p. 48.

Stanley, D.J., Chen, Z., 2000. Radiocarbon dates in China's Holocene Yangtze Delta: record of sediment storage and reworking, not timing of deposition. Journal of Coastal Research 16, 1126–1132.

Stanley, D.J., Warne, A.G., 1994. Worldwide initiation of Holocene marine deltas by deceleration of sea-level rise. Science 265, 228–231.

Tomirdiaro, S.V., 1996. Palaeogeography of Beringia and Arctida. In: West, F.H. (Ed.), American Beginnings. University of Chicago, Chicago, pp. 58–69.

Tucker, M., 1996. Methoden der Sedimentologie. Ferdinand Enke, Stuttgart, pp. 67–79.

Vandenberghe, J., 1995. Timescales, climate and river development. Quaternary Science Reviews 14, 631–638.