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Coastal erosion vs riverine sediment discharge in the Arctic Shelf seas

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Abstract This article presents a comparison of sediment input by rivers and by coastal erosion into both the Laptev Sea and the Canadian Beaufort Sea (CBS). New data on coastal erosion in the Laptev Sea, which are based on field measurements and remote sensing information, and existing data on coastal erosion in the CBS as well as riverine sediment discharge into both the Laptev Sea and the CBS are included. Strong regional differences in the percentages of coastal erosion and riverine sediment supply are observed. The CBS is dominated by the riverine sediment discharge (64.45×10^6 t a^{-1}) mainly of the Mackenzie River, which is the largest single source of sediments in the Arctic. Riverine sediment discharge into the Laptev Sea amounts to 24.10×10^6 t a^{-1}, more than 70% of which are related to the Lena River. In comparison with the CBS, the Laptev Sea coast on average delivers approximately twice as much sediment mass per kilometer, a result of higher erosion rates due to higher cliffs and seasonal ice melting. In the Laptev Sea sediment input by coastal erosion (58.4×10^6 t a^{-1}) is therefore more important than in the CBS and the ratio between riverine and coastal sediment input amounts to 0.4. Coastal erosion supplying 5.6×10^6 t a^{-1} is less significant for the sediment budget of the CBS where riverine sediment discharge exceeds coastal sediment input by a factor of ca. 10.

Keywords Laptev Sea · Beaufort Sea · Coastal erosion · Fluvial sediment discharge · Sediment budget

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Introduction

Shore dynamics directly reflecting the complicated land–ocean interactions play an important role in the balance of sediments, organic carbon, and nutrients in the Arctic Basin. Formerly the rivers were considered as the main suppliers of sediments into the World Ocean. With respect to the Arctic coast of Russia this opinion was already questioned by Suzdalsky (1974), who came to the conclusion that river sediment transport and coastal erosion input of sediments into White, Barents, and Kara seas were of the same order of magnitude. A decade later Shuysky (1983) concluded that coastal erosion supplied as much sediment into the World Ocean as the rivers to their mouths. The results of more recent investigations, however, showed pronounced regional differences in the ratio between riverine and coastal erosion sediment input. Thus, Are (1999) suggested that the amount of sediment supplied to the Laptev Sea by rivers and shores was at least of the same order, but that the coastal erosion input was probably much larger than the input of the rivers. Reimnitz et al. (1988) made calculations for 344 km of Alaska coast in the Colville River area. They found that coastal erosion here supplied seven times more sediments to the Alaskan Beaufort Sea than rivers. In the Canadian Beaufort Sea (CBS), on the other hand, the Mackenzie River input is the dominant source of sediments (MacDonald et al. 1998).

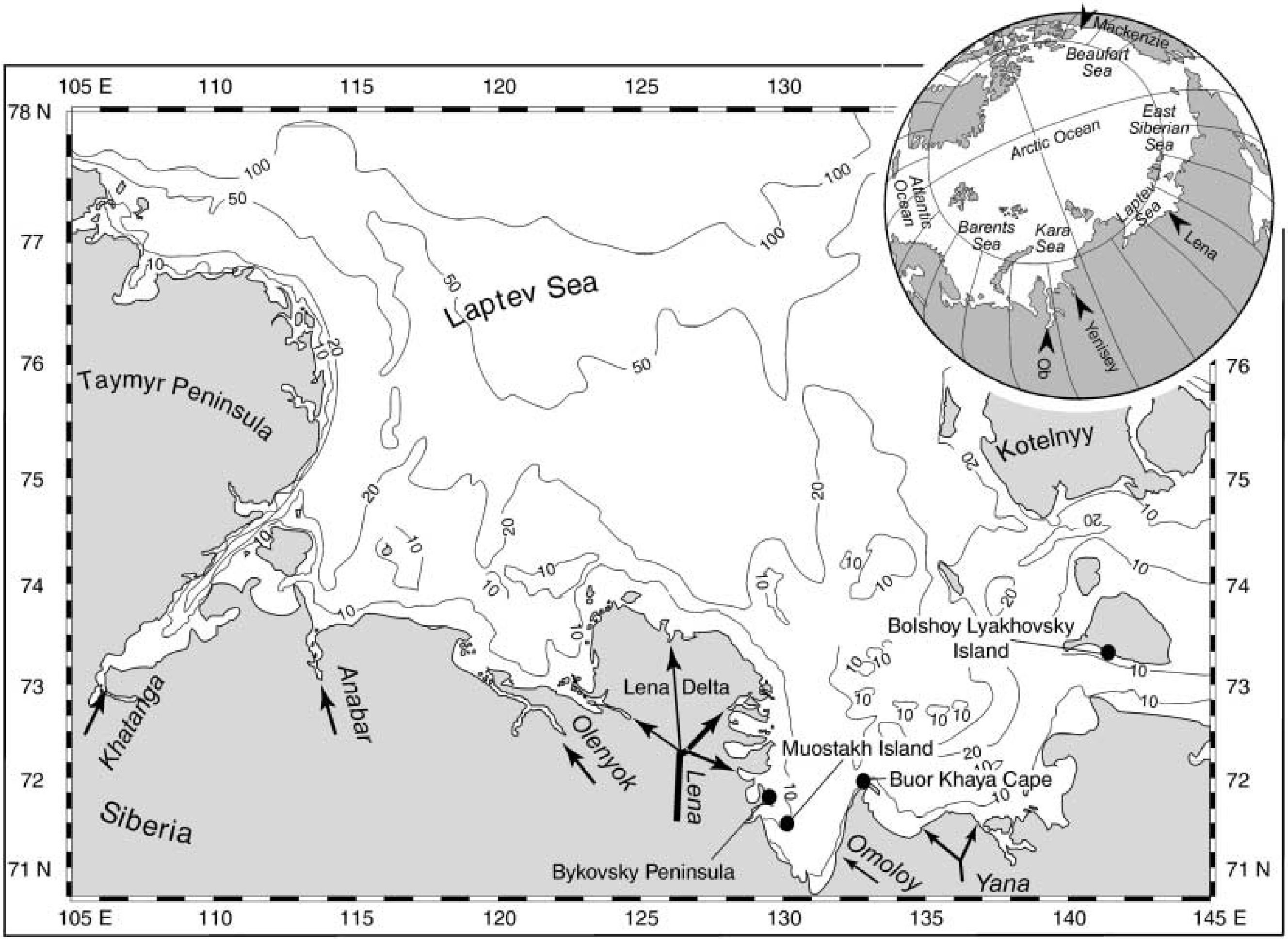
In this article we present new data on coastal erosion sediment input into the Laptev Sea and summarize the available data on riverine and coastal sediment input into the CBS and the Laptev Sea. In order to demonstrate the significance of coastal erosion for the sediment budget, a comparison between riverine and coastal sediment input into different Arctic seas is given.

Laptev Sea

The Laptev Sea is strongly influenced by continental runoff (Fig. 1). The main portion of water and sediment 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 and Meade 1983). Due to the extreme continental climate of East Siberia (winter temperatures of –45 to –50° and summer temperatures of +30 to +35°), the water discharge of the Lena River exhibits strong seasonal variations. The surface waters are frozen each year from October to May. The river-ice breakup in spring proceeds from South to North starting in the beginning of May in the southern part of the Lena Basin and reaching the delta around 15–20 June in average years. The daily water discharge exceeds 100,000 m^3 s^{-1} during spring flood in June and decreases to less than 2000 m^3 s^{-1} during April (Rachold et al. 1996).

The Laptev Sea is the region with the highest net-ice production rates in the Arctic Ocean and an important source region of the Transpolar Ice Drift system (Rigor and Colony 1997). Sea-ice formation is closely linked to freshwater discharge, mainly of the Lena River (Dmitrenko et al. 1998, 1999). A large-scale dynamic–thermodynamic sea-ice model has shown that the total net export of sea ice during winter (October to May) ranges between 3 and 7×10^5 km^2 (Kassens et al. 1998). Ice export from the Laptev Sea is of great importance for sedimentary

Fig. 1 Geographic location of the Laptev Sea. Key sites are indicated by *dots*



processes on the shelf, in the central Arctic Ocean, and in the Nordic seas, because substantial amounts of sediment are entrained into sea ice produced in the Laptev Sea (Eicken et al. 1997).

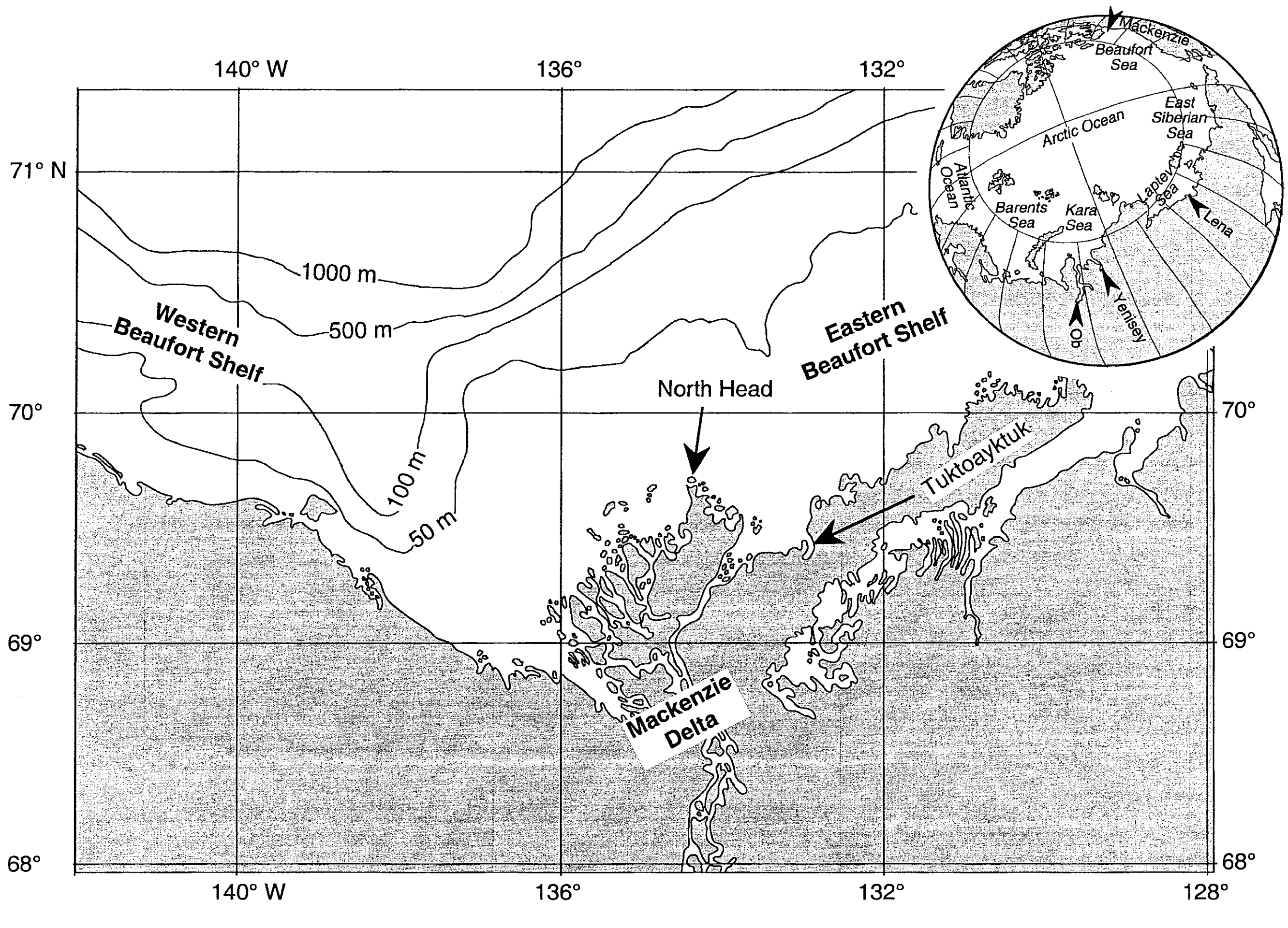
Coastal processes in the Laptev Sea area are controlled by its location in the high latitudes of Asia where waters of the Arctic Seas interact with permafrost landscapes of northeast Siberia and the Arctic Islands. The length of the continental and island shorelines of the Laptev Sea is over 5200 and 2200 km, respectively (e.g., Vorobiev 1959). Approximately one-third of the shoreline (2400 km) consists of an ice complex, i.e., ice-rich deposits which contain massive ice bodies.

Ground ice is not distributed uniformly and ice content of the ground is therefore highly variable. In the coastal area of Yakutia the frozen ground which composes the ice complex exhibits the highest ice content (up to 80% by volume). The ice complex in the cryolithozone is a specific horizon rich in ice wedges (Soloviev 1959). The lower limit of this horizon lies at the bottom of the ice wedges, whereas the upper limit is located at their top. Very large ice wedges tapering with depth occur in the Arctic coastal zone (up to 8 m in width), where they form a polygonal network at the surface. This coastal ice complex occurs at a hypsometric range between 50 m above sea level to 15 m below sea level. Detrital sediments in the ice complex occur in the form of discrete masses between ice wedges. The matrix of these bodies is composed of silt, organic-rich silt, organic-rich silty sand, and, less frequently, sand. Detrital sediments at different geomorphic levels and within a wide hypsometric range may have similar granulometric composition (Grigoriev 1993).

Canadian Beaufort Sea

The CBS is dominated by the influence of the Mackenzie River (Fig. 2), one of the largest rivers draining into the Arctic Basin and probably the most important single source of fluvial sediments (MacDonald et al. 1998). Of primary importance is the observation that the CBS appears to be quite different from both the Alaskan Beaufort Sea (ABS) and the Laptev Sea in terms of broad sediment budget and relative intensity of sediment transport mechanisms. Reimniz et al. (1994) describe several major differences between the Laptev Sea and the ABS ice regimes. Hill et al. (1991) address differences in aspects of coastal and shelf

Fig. 2 Geographic location of the Canadian Beaufort Sea



processes between the ABS and the CSB. In many respects the CBS occupies an intermediate position with respect to ice regime and physical oceanographic processes, whereas the supply of sediment to the moderate-sized shelf is unique in the Arctic Basin.

The Mackenzie shelf is approximately 100 km wide and encompasses an area of approximately 60,000 km^2 (Thomas et al. 1986). The shelf is seasonally ice covered; freeze-up usually starts in mid-October; approximately 2 m of first-year ice forms during winter when relatively immobile, landfast ice covers the inner shelf (<20 m water depth). Beyond the landfast ice zone, ice tends to move westward with the Beaufort Gyre. Divergence and convergence forced by the wind produces an intermittent flaw lead beyond the approximately 20-m isobath and extensive rubble zones (stamukhi) at the outer edge of the landfast ice (Stirling and Cleator 1981; Macdonald and Carmack 1991). Spring breakup commences in early June, first clearing the inshore region of the delta (Dean et al. 1994). Usually, by late September, the permanent pack-ice margin is located well offshore, the shelf is clear of ice, and, in an extreme year, there might be as much as 200–300 km of fetch; however, the ice-cover exhibits considerable year-to-year variability with attendant consequences on the oceanography of the shelf (e.g., Macdonald et al. 1987).

The Mackenzie River, the fourth largest in the Arctic, provides a seasonally varying input of both freshwater and suspended sediment (Thomas et al. 1986). Spring ice-breakup in the river occurs in May (prior to breakup of the sea ice as is also typical for the Lena River) and flooding of the surface of the landfast ice in front of the delta occurs annually. The Mackenzie Basin, from which the river derives its sediment load, has an area of 1.8×10^6 km^2.

The shoreline of the Mackenzie shelf is composed of unconsolidated but frozen sediments, and predominantly fine sands with lesser amounts of clay and diamict. Most of the coastline consists of low, retreating cliffs (1–50 m high). Barrier islands, spits, and other types of accretional landforms characterize approximately 40% of the coastline (Harper et al. 1985). In broad geographic terms, the western part of the CBS coast, west of Herschel Island, is similar to the ABS coast. It is composed of low (<5 m) coastal bluffs with variable ice content interspersed with large coastal alluvial fan deltas fronted by barrier islands. In the vicinity of Herschel Island and to the east, the coastal cliffs reach up to approximately 50 m and are characterized by gully erosion with frequent ice-rich thermokarst depressions. The Mackenzie Delta front is typified by very low (<1.5 m) organic-rich silty bluffs, which are mostly undergoing retreat at rates of several meters per year. Northern Richards Island and the islands of the outer Mackenzie delta are characterized by 10- to 20-m-high bluffs of fine sand with massive ice and ice wedges. The Kugmallit Bay and the Tuktoyaktuk Peninsula coastal zones are generally low and the backshore contains a high concentration of thermokarst lakes. The coastal bluffs are 3- to 10-m-high and are locally ice rich with occasional pingos formed in drained lake basins. Shallow drilling along the coast at the Tuktoyaktuk townsite has revealed a massive ice body, which extends several meters below present sea level (Shah 1982; Wolfe et al. 1998).

Data sources and methods

Riverine sediment discharge

Regular hydrological measurements in the Laptev Sea drainage area commenced in the period from 1925 to 1935. Presently, 340 hydrometeorological stations, which are randomly scattered over the drainage area, are in operation. At several of these stations, water discharge and in part also suspended load are measured daily. The data are available through publications of the St. Petersburg (formerly Leningrad) Hydrometeorological Service. Several articles on the water and sediment discharge, which are based on these data, are available. In our discussion we use data of Alabyan et al. (1995), Doronina (1962), Gordeev et al. (1996), and Ivanov and Piskun (1995).

Some recent papers (e.g., MacDonald et al. 1998; Carson et al. 1998) have focused on the input of water, sediment, and carbon into the CBS. A summary of estimates of Mackenzie River water and sediment discharge to the Beaufort Sea has recently been published by MacDonald et al. (1998), and a more up-to-date calculation of sediment and water supplies to the Mackenize River delta is presented by Carson et al. (1998). Our discussion is based on these two publications.

Coastal erosion sediment input

Our data on the sediment input by coastal erosion into the Laptev Sea are based on (a) long-term monitoring of coastal dynamics on key sites, (b) one-time or one-season field measurements of shorelines on key sites, (c) comparison of shorelines and cliff tops on different-time topographic maps, satellite images, and aerial photographs, and (d) comparison of the present-day field measurements with remote sensing information.

At numerous key sites along the Laptev Sea coast, i.e., the Lena Delta, Bykovsky Peninsula, Muostakh Island, Buor Khaya Cape, and Bolshoy Lyakhovsky Island, observations of coastal retreat rates were conducted almost annually (Fig. 1). During the field season 1999 all these sites have been re-visited (Rachold and Grigoriev, 2000).

The key sites are equipped with special fixed points and marks, which are renewed periodically. The oldest marks and fixed points, which are formed by a series of pegs placed near the shoreline or cliff tops, were installed in 1982. For a precise positioning of the present-day shoreline and/or cliff edges over an extended coastal section, we conducted theodolite surveys. The cliff altitude, ground texture, and ice content of the coastal deposits were studied as well. Then theodolite profiles were compared with the shoreline position according to old maps and aerial photographs. Stable natural points, which can be identified on maps and aerial photographs, were used for orientation. In this way we were able to calculate the land loss or accretion and the volume of eroded or accumulated coastal deposits.

For comparison with remote sensing data we used time series of topographic maps (scale 1:200,000, 1:100,000, and 1:25,000) and aerial photographs (scale 1:30,000–1:70,000) covering all of our key sites. The age of the maps and aerial photographs varied between 1951 and 1991. The comparison of shorelines and cliff tops on topographic maps, satellite images, and aerial photographs enabled us to define changes in shore morphology and geometry. Based on the present-day measurements of coastal morphological parameters, the modern position of the shoreline and trends of shoreline retreat rates were identified in fair detail.

In addition, we used data on the coastal erosion sediment input from a section between the Olenyok and Anabar Rivers published by Are (1999). These data include the sediments supplied by shoreface erosion, which is not the case for our data that only cover subaerial coastal erosion.

Data on coastal erosion in the CBS have been published by Dallimore et al. (1996), Harper (1990), Harper et al. (1985), Hill et al. (1986), and Hill et al. (1991). J.R. Harper and P.S. Penland (unpublished data) used long-term (decadal) cliff retreat rates together with cliff heights to estimate subaerial coastal erosion. No attempt was made to incorporate ice volume. More recent estimates suggest that the erosion rate used for certain parts of the coastline may be low, but this certainly would not change the sediment volumes by more than a factor of 2 (MacDonald et al. 1998).

In our discussion we use data on sediment input to the CBS presented by Dallimore et al. (1996) and Hill et al. (1991). It should be noted that in neither data set is an estimation of the contribution from shoreface erosion to the sediment budget of the CSB included.

Results and discussion

Sediment discharge of rivers draining to the Laptev Sea

Estimates of the sediment discharge of the Siberian rivers draining to the Laptev Sea are summarized in Table 1. All data sets refer to the sediment discharge in the upper reaches of the rivers several kilometers upstream from the deltas/estuaries. Furthermore, the data only consider the suspended load. To our knowledge, data on bedload of the Siberian rivers are not available.

Only one publication (Gordeev et al. 1996) lists all of the rivers draining to the Laptev Sea. Other articles have not included some of the smaller rivers. The estimates of total sediment discharge vary between 18.9×10^6 t a^{-1} and 26.8×10^6 t a^{-1}. Because each author used data of different years and stations, there is some discrepancy between the individual data sets listed in Table 1.

Several studies conducted in different river systems during the past decade present evidence for a significant loss of sediment load on subaerial parts of deltas before reaching the sea. In the case of the Lena River this is documented by a decrease in water turbidity along a main distributary, being due to "intensive sedimentation along the channel" (Korotaev 1991). Korotaev (1991) believes that only approximately 30% of the Lena River suspended load measured at the lowest gauging station at Kyusyr, 150 km upstream from the delta apex, reaches the sea, whereas the rest of it is deposited in the delta. Alabyan et al. (1995) state that $2.1–3.5\times10^6$ t a^{-1} of the total 21×10^6 t a^{-1} of the load measured at Kyusyr enter the sea; however, the databases for these figures are not well documented.

The key for a comparison of the sediment supply to Arctic shelves from rivers vs that from coastal retreat, therefore, is to establish whether deposition is occurring on subaerial parts of deltas and in the channels. To evaluate the foregoing question, we take a critical look at the delta front, the delta surface, and channel floors of the active parts of the Lena River Delta for regions where the suspended load or the

Table 1 Riverine sediment discharge to the Laptev Sea in 10^6 t a^{-1}

	Gordeev et al. (1996)	Alabyan et al. (1995)	Doronina (1962)	Ivanov and Piskun (1995)
Khatanga	1.70	1.40	-	-
Anabar	0.10	0.40	0.24	-
Olenyok	1.10	1.00	0.54	1.48
Lena	17.6	21.0	11.8	18.4
Omoloy	0.13	-	-	-
Yana	3.50	3.00	6.36	4.19
Sum	24.1	26.8	18.9	24.1

fine fraction of the total load may be trapped. As discussed by Are and Reimnitz (in press), the delta front is advancing only along relatively short segments. Considerable regions appear to be either stable or are even retreating; therefore, progradation does not act as a sediment sink and we thus looked at the broad delta plain for evidence of surficial deposition of the river's fine sediments.

A 15- to 30-km-wide zone of islands 400–1000 years old and 3 m above sea level characterizes the flat, interdistributary parts of the active delta (Korotayev 1991). These islands are composed of sand and the Lena River Delta has no natural levees (Fig. 3). The pattern of smaller distributaries between islands of the delta is very similar to that seen on topographic maps prepared from air photos approximately 45 years previously. The island surfaces are therefore over 50 years, perhaps several hundred years old and show little change. These sandy islands are, however, marked by complex traces of formerly migrating channels. As these traces are well preserved, the area shown is not draped by mud. The strongest evidence against deposition on the lower delta plain are the six cabins shown on the topographic map (triangles in Fig. 3). Natives do not inhabit areas of annual mud deposition; thus, we are left only with channel floors as possible sinks for the missing fine fraction of the sediment load.

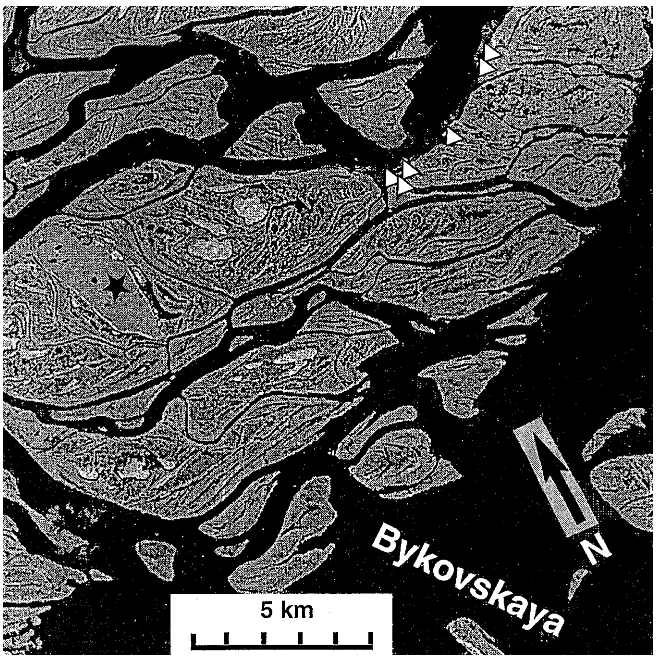


Fig. 3 Segment of a July 1996 SPOT satellite image of the Lena Delta showing numerous islands which, according to a topographic map, range from 2 to 6 m above sea level. The shapes and positions of islands are generally unchanged since topographic maps were made approximately 45 years previously. *Star* marks a 30-m-high ice complex, and *triangles* show locations of six cabins. The delta has no natural levees and is not being covered by fine sediments

According to Ivanov (1967) the Bykovskaya Channel floors are composed mainly of sand, locally of gravel, and flow velocities are generally too high for the deposition of mud. Our own sampling of channel floors revealed sand as the main sediment type.

Lastly, the statements that only 10–30% of the suspended sediment load reaches the sea are not supported by our own measurements; thus, we did not find a decrease in suspended sediment concentrations along the lower course of the river below the gauging station. We therefore conclude that most of the Lena River suspended sediments are supplied to the sea. We do not know whether our conclusion also applies to other Arctic deltas, but we think that specific measurements are necessary to answer the question (see below for Mackenzie River Delta). Observations on one Alaskan River discharging into the Arctic Ocean at Prudhoe Bay allow the conclusion that the fines are not retained on land but instead reach the sea. The Sagavanirktok River is the second largest of Arctic Alaska and has been mined for its gravel resources. The bed is covered by gravel to the delta front, easily visible from the air at time of freeze-up when discharge is low. Reimnitz and Maurer (1979) present evidence that neither sand nor gravel reaches the sea during spring floods and no gravel is found on the <2-m-deep ramp fringing the delta. The fact that sand and gravel are exposed on the delta is indirect evidence that all the fines are flushed out to sea during spring floods.

In conclusion, it can be stated that the sediment discharge data listed in Table 1 represent the amount of sediment that is actually supplied to the Laptev Sea by rivers. For comparison with the sediment input by coastal erosion we used the data given by Gordeev et al. (1996), which include all rivers and which are within the range of the other data sets.

Sediment discharge of rivers draining to the Canadian Beaufort Sea

The Mackenzie River discharges approximately 3.3×10^{11} m^3 a^{-1} of freshwater (Brunskill 1986), most of which is supplied between May and September. There is a large interannual variability in the freshwater discharge (±25%) and in the amount of sediment carried. Part of the disparity in the estimates of water discharge is due to different years and different stations being used. Sediment load is considerably more difficult to calculate; as the best present estimate we accept a figure of 128×10^6 t a^{-1}. It is based on daily sediment loads and discharges where available and on stage-discharge curves and sediment ratings (Carson et al. 1998). This value agrees well with the estimates by Hill et al. (1991) [125×10^6 t a^{-1}, based on C.P. Lewis' (unpublished data) calculations] and Brunskill (1986; 118×10^6 t a^{-1}). Of the 128×10^6 t, approximately 4×10^6

t is sandy bedload and the remainder is suspended load (Carson et al. 1998).

We have only partial data sets upon which to evaluate the input from other rivers along the Beaufort coast. All evidence suggests that input from these sources is small relative to the Mackenzie River and is hence of local importance only (e.g., Hill et al. 1991; Forbes 1981). Rating the drainage areas against the yield of the Babbage River, J.R. Harper and P.S. Penland (unpublished data) estimated that the Yukon River delivered 1.45×10^6 t a^{-1}.

In contrast to the Lena River delta, the Mackenzie delta is a repository of a considerable amount of the annual riverine sediment discharge. MacDonald et al. (1998) summarized information on the sedimentation in the Mackenzie Delta. This is important, because it must be subtracted from the sediment input into the delta from the river in order to calculate sediment delivery to the Beaufort Sea. Historical methods based on the volume of sediment in the delta and its age suggest an average deposition rate in the delta during the past 10,000–12,000 years of $136–163\times10^6$ t a^{-1} (Hill et al. 1991; C.P. Lewis, unpublished data). Studies on modern sedimentation rates indicate a range from $76–82\times10^6$ t a^{-1}, or approximately half that calculated from delta volumes (Pearce 1993). An independent check on this estimate, available from radiocarbon dates obtained on boreholes drilled in the delta (Johnson and Brown 1965; S.R. Dallimore, pers. commun.), indicates that delta plain sedimentation rates range from 0.3 to 0.8 cm a^{-1} which yields a corresponding sedimentation rate of between 25 and 69×10^6 t a^{-1} (using dry bulk density of 1.2 g cm^{-3}). The disparity between estimates of modern sediment deposition and those based on total Holocene sediment volume could be due to changes in sedimentation rate with time (e.g., the Mackenzie delivered more sediment in the early Holocene), episodic sedimentation that is relatively important but not accounted for in the Water Survey data, or simply due to errors in the various estimates. MacDonald et al. (1998) suggested using an estimate based on several recent studies of modern sedimentation (65×10^6 t a^{-1}). Thus, the currently best estimate for the net quantity of sediment reaching the Beaufort Sea from rivers along the Canadian coast is: $128+1.45–65=64.45\times10^6$ t a^{-1}.

Coastal erosion sediment input into the Laptev Sea

Coastal erosion rates along the Laptev Sea have been studied by Are (1980, 1985, 1999), Galabala (1987), Grigoriev (1966), Grigoriev (1993, 1996), Kluyev (1970), Korotaev (1991), Razumov (in press), and others. Nevertheless, the role of erosion is still not sufficiently investigated in this region. Thus far it is not possible to precisely determine the average long-term and average annual retreat rates of the shoreline along the entire Laptev Sea coast.

Ice-rich deposits are a characteristic feature of the Laptev Sea coastline. The ice complex is intensely eroded and washed away by waters of the Laptev Sea. During storms wave-cut notches are formed along the bases of coastal cliffs composed of the ice complex. These notches result in block disintegration of the coasts. Frozen blocks are washed away by seawater. As a result, meltwater from ground ice is supplied to the sea together with detrital material predominantly composed of silt.

The mean absolute height of these coastal cliffs is 10 m. The rates of their retreat vary within a wide range from a few centimeters a^{-1} to 20 m a^{-1}. The dominant mean rates of retreat due to thermal abrasion are 2–6 m a^{-1} (Are 1980). Because approximately 40% of the coasts are at the stage of temporary stabilization (Grigoriev 1996), the mean rate of coast disintegration is approximately 2.5 m a^{-1}. Based on this value and the length of the coasts within the ice complex (2400 km), the mean annual volume of frozen ground eroded is estimated at 60×10^6 m^3. Ice content amounts to 40% on average for ice wedges and 10% for segregated ice, respectively. The remaining 50% are formed by silt, organic-rich silt, and organic-rich silty sand. Thus, the mean annual volume of detrital material supplied to the sea is 30×10^6 m^3. Based on a density of 1.27 g cm^{-3} for the ice complex and 1.48 g cm^{-3} for the deposits excluding the ice, the total amount of material reworked by thermal abrasion and thermal denudation can be quantified as: 76.2×10^6 t a^{-1} for the total ice complex, and 44.4×10^6 t a^{-1} for the detrital material.

The Laptev Sea coasts, which consists of Quaternary deposits with lower ice content than the ice complex (10–30% by volume), extend for approximately 1600 km. In contrast to the coasts with the ice complex, the cliffs of this coastal type are lower (5 m on average) and are destroyed by thermal abrasion and thermal denudation at average rates of approximately 1 m a^{-1}. The mean annual volume of the material supplied to the sea due to destruction of such coasts is approximately 8×10^6 m^3. The total amount of the reworked detrital material is approximately 9.5×10^6 t a^{-1}.

Contribution of other types of coasts to the total loads supplied to the Laptev Sea is less significant. A rough estimate amounts to $3–6\times10^6$ t a^{-1}. We use a value of 4×10^6 t a^{-1} for the purpose of our discussion.

The data on both total sediment input by coastal erosion and sediment mass per kilometer shoreline are presented in Table 2. In addition, results for the Olenyok-Anabar region published by Are (1999) are included for comparison. Although Are's (1999) data, in contrast to our data, also include the contribution of shoreface erosion, his estimate is similar to our value for ice-rich coasts of the Laptev Sea. Summing up the values for the three different types of coasts discussed previously, we conclude that the amount of sediments supplied to the Laptev Sea by coastal ero-

Table 2 Sediment input into the Laptev Sea through coastal erosion of the continental shoreline excluding islands

Types of shore	Length of coast (km)	Total subaerial erosion (10^6 t a^{-1})	Subaerial erosion (10^6 t a^{-1} km^{-1})
Ice complex (ice content 40–70%)	2400	44.4	0.019
Quaternary–Holocene deposits (ice content 10–30%)	1600	9.5	0.006
Other types of shore	1200	4.5	0.004
Olenyok-Anabar coast[a]	85	2.1	0.020
Laptev Sea, total	5200	58.4	0.011

[a] From Are (1999)

sion today amounts to 58.4×10^6 t a^{-1} and average sediment input per kilometer of shoreline is approximately 0.011×10^6 t a^{-1} km^{-1}.

The history of coastal dynamics of the Laptev Sea is closely related to global climatic changes, i.e., transgressions and regressions of sea level during the Quaternary. Sea level is thought to have been 100 m lower than at present during the Sartan glaciation (10–23 ka BP; Fairbanks 1989). The lowest extreme of insolation occurred 22 ka BP, whereas maximum glaciation was established 17–18 ka BP. Undoubtedly, ice-rich coasts in Yakutia responded to the changes in temperature and hydrologic conditions. High rates of thermal abrasion and sea transgression caused the ice complex deposits to be retained below sea level in the littoral zone. This is documented by sediment cores drilled 10 km seaward from the recent coastline and by seismic data (Rachold and Grigoriev, 2000). During the last transgression (6–17 ka BP) the rates of eustatic sea level rise were, on average, 9 m per ka (Kaplin 1973). According to Are (1980), the southward retreat of the shoreline was 35–90 m a^{-1} in the late Pleistocene to early Holocene. In addition, thermal abrasion was most probably more intense during the Holocene climatic optimum, which lasted for 3 ka at the final stage of the transgression. After the stabilization of sea level, approximately 5 ka ago, a 10- to 50-km-wide strip of coastal land was removed by thermal abrasion (Are 1980).

Coastal erosion sediment input into the Canadian Beaufort Sea

Erosion rates for the Mackenzie coast are high, reaching values of up to approximately 20 m a^{-1} for very low deltaic coasts (Harper et al. 1985; Harper 1990; Hill et al. 1986), but more typically 1–2 m a^{-1}. Volumes of material supplied to the shoreface and the shelf by erosion are a function of linear erosion rate, coastal bluff height, sediment type, and ice content. Portions of the material eroded from coastal bluffs are transported seawards to be deposited in deeper water, whereas the coarser fraction may be stored in nearshore bars or transported alongshore to barrier beaches and spits (Dallimore et al. 1996). In addition, a portion of both the fine and coarse sediment eroded from unlithified coastal bluffs is stored in thermokarst embayments (e.g., Ruz et al. 1992). The contribution from shoreface erosion to the sediment budget of the CBS has not yet been quantified. This is due in part to the relative complexity imparted to the region by the influence of the Mackenzie River on modern sedimentation, thermal regime, and the antecedent offshore physiography. In contrast to the ABS coast as described by Reimnitz et al. (1988), thermokarst depressions along parts of the CBS coast (east of the Mackenzie Trough) are often deep enough to escape erosion during transgression and are therefore more or less permanent repositories for eroded material and Mackenzie River sediments (e.g., Héquette and Hill 1989).

J.R. Harper and P.S. Penland (unpublished data) estimate that approximately 2.9×10^6 m^3 a^{-1} of sediment, including ice, is produced by subaerial coastal erosion. A more recent estimate of 5.6×10^6 t a^{-1} considering ice content was published by Hill et al. (1991); however, as described previously, a portion of this material would be transferred alongshore and landward to be stored in thermokarst embayments.

Table 3 presents the estimates for coastal erosion sediment input into the CBS; data for ABS (Reimnitz et al. 1988) are shown for comparison. A detailed study of North Head (Fig. 2), a rapidly eroding headland on the CBS coast, showed that locally significantly larger amounts of material are derived from subaerial erosion (Dallimore et al. 1996). This study area is characterized by relatively high (10–20 m) ice-rich coastal bluffs. The ABS coast delivers more sediment than the CBS coast, a result which is surprising given that the open water season is longer and fetch distance is greater in the latter location than the form-

Table 3 Sediment input into the Canadian Beaufort Sea through coastal erosion (Hill et al. 1991; Dallimore et al. 1996). Alaskan Beaufort Sea (Reimnitz et al. 1988) is shown for comparison

Location	Length of coast (km)	Total subaerial erosion (10^6 t a^{-1})	Subaerial erosion (10^6 t a^{-1} km^{-1})
ABS[a]	344	2.30	0.007
CBS[b]	1150	5.60	0.005
North Head, CBS[c]	3	0.04	0.012

[a] Reimnitz et al. (1988), [b] Hill et al. (1991), [c] Dallimore et al. (1996)

Table 4 Comparison of riverine and coastal sediment input into the Laptev and Beaufort seas (From Gordeev et al. 1996; MacDonald et al. 1998; Hill et al. 1991)

	Laptev Sea	Canadian Beaufort Sea
Riverine sediment discharge (10^6 t a^{-1})	24.10[a]	64.45[b]
Total coastal erosion sediment input (10^6 t a^{-1})	58.4	5.6[c]
Coastal erosion sediment input (10^6 t a^{-1} km^{-1})	0.011	0.05[c]
Riverine/coastal	0.4	11.5

[a] Gordeev et al. (1996), [b] MacDonald et al. (1998), [c] Hill et al. (1991)

er. Differences may be a result of different methods used to measure subaerial erosion (comparison of charts and maps over a 30-year time span in Alaska; comparison of air photos over a 20-year span in Canada). Alternatively, differences may relate to the relative importance of ice entrainment and transport in the ABS. Measurements of the coastal retreat along some sections of the coast using a common technique would be useful for future comparisons.

Much of the Beaufort Shelf was subaerially exposed during past sea level lowstands associated with glaciations, and permafrost has been preserved beneath the seabed in the area east of the Mackenzie trough. Permafrost thicknesses of up to 750 m have been documented (Taylor et al. 1996). Ice-bonded sediments have not been documented in the Mackenzie Trough or on the western shelf (M.J. O'Connor and Associates, unpublished data). Ice-bonded permafrost is preserved, in part, because mean annual bottom temperatures below a water depth of approximately 10 m remain below 0°C. Above 10 m water depth, the presence of warm Mackenzie River water is the basis for positive mean annual temperatures; thus, as transgression occurs, the transition from subaerial to subaqueous conditions involves a rapid increase in mean annual temperature from approximately –10 to +2°C and then a gradual decline to –1°C as the water depth increases. The time spent in positive temperatures varies with coastal morphology and the rate of sea-level rise. Thawing occurs to variable depths, giving rise to a highly variable ice-bonded surface. Seabed subsidence will accompany thawing with thaw strains of approximately 1 m per 10 m of thawed settlement in the vicinity of North Head (Dallimore et al. 1996) at rates of approximately 5–7 mm a^{-1}. Greater thaw strains are expected where massive ice is present below the seabed (e.g., at Tuktoyaktuk: see Shah 1982; Wolfe et al. 1998).

Warm-water temperatures and subsequent thaw subsidence in a narrow coastal band following transgression leads to the question of its role in forcing coastal erosion by the creation of local accommodation space (Hill and Solomon, in press). In addition, this has significant implications for the calculation of the shoreface contribution to sediment delivery to the shelf. Removal of volume in the nearshore by thawing of excess ice does not involve erosion of material from a nearshore equilibrium profile. In fact, it would limit the development of an equilibrium profile during the course of thaw settlement. Initial settlement probably occurs rapidly, then decreases as the rate of seabed thawing decreases with the square root of time. The depth to well-bonded permafrost at North Head is more than 30 m below the seabed within 600 m from the shore, although this depth may be related to the presence of a previously thawed thermokarst lake (Taylor et al. 1996). The depth to ice-bonded permafrost is 50 m in 32 m of water at the Amauligak wellsite and only 10 m in 11 m of water at Isserk. Based on geothermal modeling and comparison with sea-level curves, Amauligak is thought to have been transgressed approximately 6 ka BP giving an approximate rate of coastal retreat of 45 km per 6 ka or 7.5 m a^{-1} (Taylor et al. 1996). Although this is higher than the present average rate of retreat, it is consistent with a decreasing rate of sea-level rise.

Conclusion

Our estimates of riverine sediment discharge and sediment input by coastal erosion into both the CBS and the Laptev Sea are listed in Table 4. The fluvial sediment input into the CBS is more than twice that of the input into the Laptev Sea and two orders of magnitude more than that entering the ABS between Drew Point and Prudhoe Bay (0.74×10^6 t a^{-1}; Reimnitz et al. 1988). Although coastal erosion may be important locally (North Head, see above), in the CBS it is clearly much less than the Mackenzie River delivery. The ratio between riverine sediment discharge and coastal erosion sediment input is approximately 10.

In comparison with the CBS, the Laptev Sea coast on average delivers approximately twice as much sediment mass per kilometer, a result of higher erosion rates due to higher cliffs and seasonal ice melting. North Head, a rapidly eroding headland on the CBS coast, which is characterized by relatively high (10–20 m) ice-rich coastal bluffs, provides a similar magnitude of material from subaerial erosion as does the Laptev Sea coast.

If we compare the sediment discharge of the major rivers draining into the Laptev Sea with the amount of load from the coasts, we conclude that coastal erosion is much more important in the Laptev Sea than in the CBS. The ratio between riverine and coastal input is approximately 0.4.

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