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Comparative Shoreface Evolution along the Laptev Sea Coast

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Summary: Field investigations of the Laptev Sea shoreface morphology were carried out (1) off erosional shores composed of unconsolidated sediments, (2) off the modern delta shores of the Lena River, and (3) off rocky shores.

It was found that profiles off erosional shores had a concave shape. This shape is not well described by commonly applied power functions, a feature, which is in disagreement with the generally accepted concept of the equilibrium shape of shoreface profiles. The position of the lower shoreface boundary is determined by the elevation of the coastal lowland inundated during the last transgression (at -5 to -10 m) and may easily be recognized by a sharp, an order of magnitude decrease in the mean inclination of the sea floor. The mean shoreface inclination depends on sediment grain-size and ranges from 0.0022 to 0.033. The concave shape of the shoreface did not change substantially during the last 20-30 years, which indicates that shoreline retreat did not slow down and hence suggests continued intensive coastal erosion in the 21st century.

The underwater part of the Lena River delta extends up to 35 km offshore. Its upper part is formed by a shallow and up to 18-km wide bench, which reaches depths of 2-3 m along the outer edge. The evolution of the delta was irregular. Whereas some parts of the delta are advancing rapidly (58 m/year), other parts are eroding. Comparison of measured profiles with older bathymetric data gave an opportunity to evaluate the changes of the underwater delta over past decades. Bathymetric surveys of the seabed around the delta can thus contribute towards a quantification of the sediment budget of the river-sea system.

In addition, some sections of the Laptev Sea coast are composed of bedrock that has a comparatively low resistance to wave erosion. These sections may supply a considerable amount of sediment, especially if the cliffs are high. This source must therefore also be taken into account when assessing the contribution of shore erosion to the Laptev Sea sediment budget.

Zusammenfassung: Geländeuntersuchungen zur Morphologie des seewärtigen Küstenprofils im Bereich der Laptewsee wurden (1) an Erosionsküsten bestehend aus unverfestigtem Sediment, (2) vor dem aktiven Teil des Lena-Deltas und (3) an aus Festgestein aufgebauten Küsten durchgeführt.

Es zeigte sich, dass die Profile im Bereich von Erosionsküsten eine konkave Form aufweisen. Die Form lässt sich mit Hilfe von Potenz-Funktionen, die normalerweise zur mathematischen Beschreibung der Morphologie des seewärtigen Küstenprofils genutzt werden, nur schlecht rekonstruieren. Diese Beobachtung steht im Widerspruch zum Konzept des Equilibriums des seewärtigen Küstenprofils. Die Position der unteren Grenze des seewärtigen Kpüstenprofils wird durch die Höhe des küstennahen Flachlands bestimmt, das während der letzten Transgression (bei -5 bis -10 m) überschwemmt wurde, und lässt sich am Anstieg des Neigungswinkels um eine Größenordnung leicht identifizieren. Die mittlere Neigung des seewärtigen Küstenprofils hängt ab von der Korngröße der Sedimente und liegt zwischen 0.0022 und 0.033. Die konkave Form des seewärtigen Küstenprofils hat sich während der letzten 20-30 Jahre nur unwesentlich geändert, was darauf hindeutet, dass die Rückzugsrate der Küste sich nicht verringerte und dass im 21. Jahrhundert weiterhin hohe Küstenerosionsraten zu erwarten sind.

Der submarine Teil des Lena-Deltas erstreckt sich bis in 35 km Entfernung von der Küstenlinie. Der obere Teil wird von einer flachen, bis zu 18 km breiten Rampe gebildet, deren Wassertiefe am äußeren Ende 2-3 m erreicht. Die Entwicklung des Deltas verlief regional sehr unterschiedlich. Während einige Teile des Deltas heute sehr stark voranschreiten (58 m/Jahr), werden andere Bereiche erodiert. Durch den Vergleich gemessener Profile mit alten bathymetrischen Karten können Änderungen in der Morphologie des submarinen Lena-Detlas während der letzten Jahrzehnte identifiziert werden. Bathymetrische Vermessungen vor dem Lena-Delta können daher genutzt werden, um das Sedimentbudget in diesem Bereich zu quantifizieren.

Weiterhin bestehen einige Abschnitte der Laptewsee-Küste aus verfestigten Gesteinen, die eine vergleichsweise geringe Widerstandskraft gegen Wellenerosion aufweisen. Diese Abschnitte können daher einen signifikanten Beitrag zum Sedimenteintrag leisten, insbesondere bei hohen Kliffs. Zur Quantifizierung des Sedimenteintrags in die Laptewsee durch Küstenerosion müssen diese Küstenabschnitte daher berücksichtigt werden.

INTRODUCTION

The shoreface may be broadly defined as the shore-parallel strip of the seabed affected by waves; this includes the area from the surf zone down to the depth of the effective storm wave base (ZENKOVICH 1962, REINECK & SINGH 1990). The effective wave base may be calculated on the basis of grain size and basic wave parameters (CLIFTON 1976, FLEMMING 1999). Its relative position is often geomorphologically defined by the slope of an underwater accretion terrace (Fig. 1). In shallow seas, however, accretion terraces may not exist because the critical wave base exceeds the water depth. In such situations it can be difficult to identify the lower limit of the shoreface. According to REINECK & SINGH (1990), it may be associated with the depth at which the comparatively steep slope of the shoreface changes into the more gentle slope of the transition zone. However, along some coastal profiles a

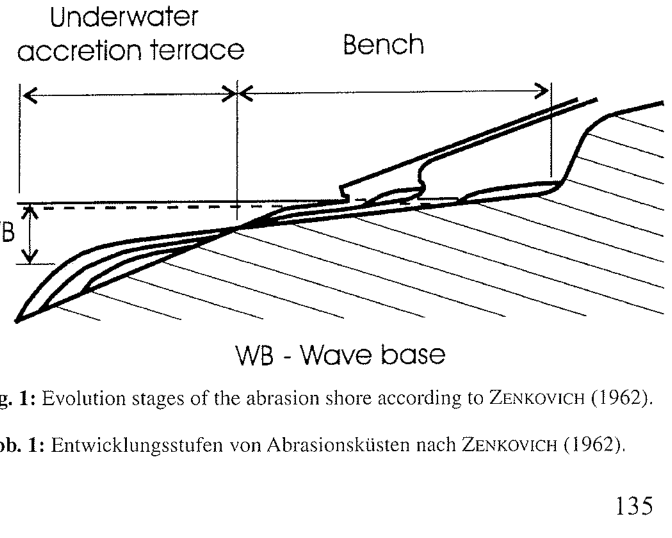

Fig. 1: Evolution stages of the abrasion shore according to ZENKOVICH (1962).

Abb. 1: Entwicklungsstufen von Abrasionsküsten nach ZENKOVICH (1962).

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change of inclination is not recognizable. Sometimes the boundary between the shoreface and the transition zone is indicated by a change in sediment composition from sandy on the shoreface to silty in the transition zone.

There are several reasons for the study of shoreface morphology. One of them is connected with the assessment of sediment input to the sea by coastal erosion which is an important component of the marine sediment budget (ARE 1999). Eroded sediments are supplied to the sea both from the shoreface and the cliff, the sediment supplied by the shoreface sometimes substantially exceeding that coming from the cliff. Thus, to quantify sediment input from coastal erosion it is important to identify the position of the lower (outer) shoreface boundary.

Another reason to study the shoreface is connected with the problem of coastal erosion modeling. The essential mechanism of coastal erosion is the downcutting of the shoreface, cliff retreat merely being a consequence of this process (ZENKOVICH 1962). Therefore, in modern mathematical models, shoreface dynamics is used as the basis for calculating coastline change (THIELER et al. 2000). Indeed, shoreface geometry is one of the main input parameters to these models. The basic notion of an equilibrium shoreface profile as suggested by BRUUN (1954) is inherent in all models considering erosion of coast composed of unconsolidated sediments. According to the "Bruun rule" the shape of the equilibrium profile is concave and, in a first approximation, may be described by the relationship

$$h = A \cdot x^{m} \qquad (1)$$

where h is the water depth (m), x is the distance from the shore (m), A is a non-dimensional sediment-scaling parameter which increases with increasing grain size, and m is a coefficient describing the shoreface shape (DEAN 1997). Equation (1) shows that the shape of the shoreface profile depends on the sediment grain size.

All existing models of coastline change are primarily based on data from high-energy, mid-latitudinal coasts and do not take the impact of permafrost into account. The influence of permafrost and other complicated geocryological processes on shoreface dynamics and geometry are still entirely unexplored.

Very little is known about the shoreface of Arctic coasts in general, the Laptev Sea being a case in point. The whole southern part of this sea is very shallow and waves rework the sea floor up to several hundred kilometres from the shore. However, it is obviously unreasonable to consider seabed at such distances from the coast as coastal erosion. In this situation the application of a shoreface model becomes meaningless. Therefore, in order to calculate the contribution of coastal erosion to the sediment budget it is necessary to identify the offshore boundary between erosion of pre-transgressive sediments (derived from downcutting) and reworking of modern marine materials.

To improve our knowledge about the nature of the shoreface along shallow Arctic coasts, all existing data on shoreface morphology, coastal geology, geocryology, and oceanography were compiled in a first step. Because such data were found to be very scarce, they were augmented by extensive field investigations along representative sections of the coast (key sections) within the framework of the Russian-German „Laptev Sea 2000" project. Thus, a total of 17 coastal key sections between the Taymyr Peninsula in the west and the Dm. Laptev Strait in the east were surveyed during the 1999 and 2000 field seasons (RACHOLD & GRIGORIEV 2000, RACHOLD & GRIGORIEV 2002, Fig. 2).

METHODS

The main part of the field work involved cross-shore bathymetrical profiling carried out by hull-mounted echosounders on board of R/V „Dunay" (1999) and „Sofron Danilov" (2000). The accuracy of the depth measurements was about 0.1 m. All profiles were recorded on strip-chart recorder with a vertical scale of 1 cm = 2 m (1999) and 1 cm = 1 m (2000). Navigation and distance measurements were conducted through the use of magnetic compass and GPS with a resolution of approximately 30 m.

In the coastal shallows inaccessible for the research vessels (<2.5 m depth for „Dunay", and <3.5 m for „Sofron Danilov") depth profiling was carried out from a motorboat using a portable echosounder with a 0.1 m resolution. A precision laser theodolite (Elta-36) was used for measurements of distances <1.5 km as shown in Figure 3. Because this technique is unsuitable for the measurements of larger distances, for example around the Lena Delta front where the 2 m isobath is situated as far as 18 km from the shore, a magnetic compass and GPS were used in such cases.

In addition, several high quality bathymetric profiles produced by shallow seismic surveys (ARE et al. 2000) were also evaluated for this study. In total, about 115 km of profiles were measured during two field seasons.

Besides field measurements, extensive information was derived from navigation charts (scales 1:25,000 to 1:500,000), which were based on bathymetric data obtained at different times since 1953. The charts were mainly used to reveal the changes in shoreface position and morphology during the last few decades. They were also used to fill in the gaps between the survey profiles.

To meaningfully compare measured profiles with the bathymetric data taken from navigational charts, it is necessary to take sea-level fluctuations into account which in the Laptev Sea coastal zone may exceed 2 m. For this purpose, data of the water level gauge operated at the polar stations Tiksi and Dunay were used (Fig. 2). These record the sea-level deviation from the mean Baltic level every three hours. The navigation charts are compiled relative to the Baltic level.

RESULTS

The shoreface profiles were obtained off (1) erosional shores composed of unconsolidated Quaternary deposits, (2) accreting shores of the Lena River delta, and (3) erosional rocky shores.

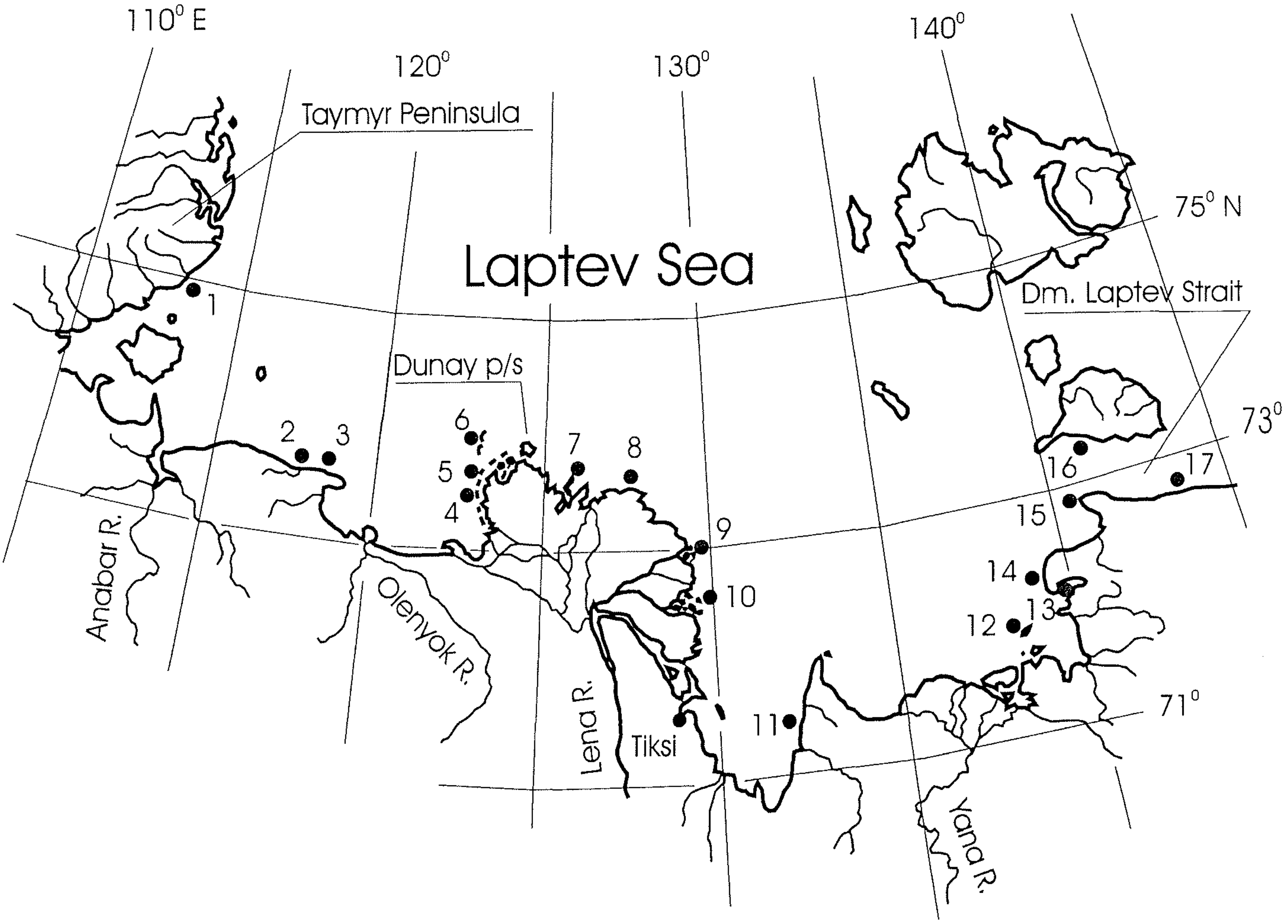

Fig. 2: Key sections of shore face profile study.

Abb. 2: Schlüssellokalitäten der Küstenuntersuchungen.

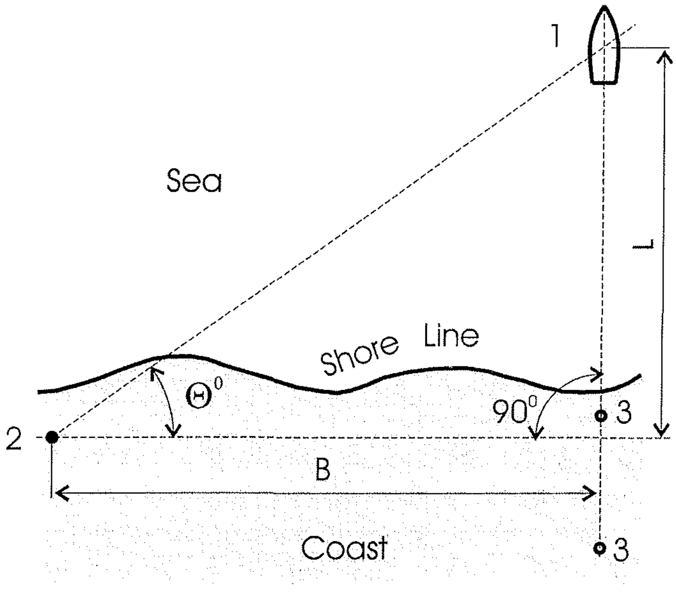

Fig. 3: The scheme of geodetic measurements. L = B tg Θ°; 1: boat, 2: theodolite, 3: landmarks.

Abb. 3: Schematische Darstellung der geodätischen Vermessungen. L = B tg Θ°; 1: Boot, 2: Theodolit, 3: Landmarken.

Erosional shores

The shorelines, composed of ice complex, are famous for their spectacular appearance and high rate of retreat (Fig. 4). Bathymetric surveys were conducted up to distances of 0.5-18 km from the coast and up to water depths of 4-11 m along five key sections (# 2, 3, 11, 12, and 14 in Fig. 2). Seven of the profiles (above listed sections included) were manually extended up to 17-34 km from the shore and up to 9-17 m water depths using navigational charts. Geometric parameters of these profiles are listed in Table 1. All of the profiles slope very gently (mean sea floor inclination 0.002) but nevertheless exhibit a clearly developed concave shape. The lower shoreface boundary is recognized where the sea floor inclination decreases by one order of magnitude, being located at distances of 2-18 km from the shore (Tab. 1; Fig. 5).

As can be seen from Table 1, the shoreface inclination off the coasts composed of ice complex differs significantly from one key section to another. These differences most probably reflect the dependence of inclination on sediment grain size and ice content. The same dependence controls thermoterrace surface inclination. Therefore thermoterrace morphology indirectly indicates coastal sediment grain-size and ice content. For example, in Figure 6 (key section 17) a thermoterrace about

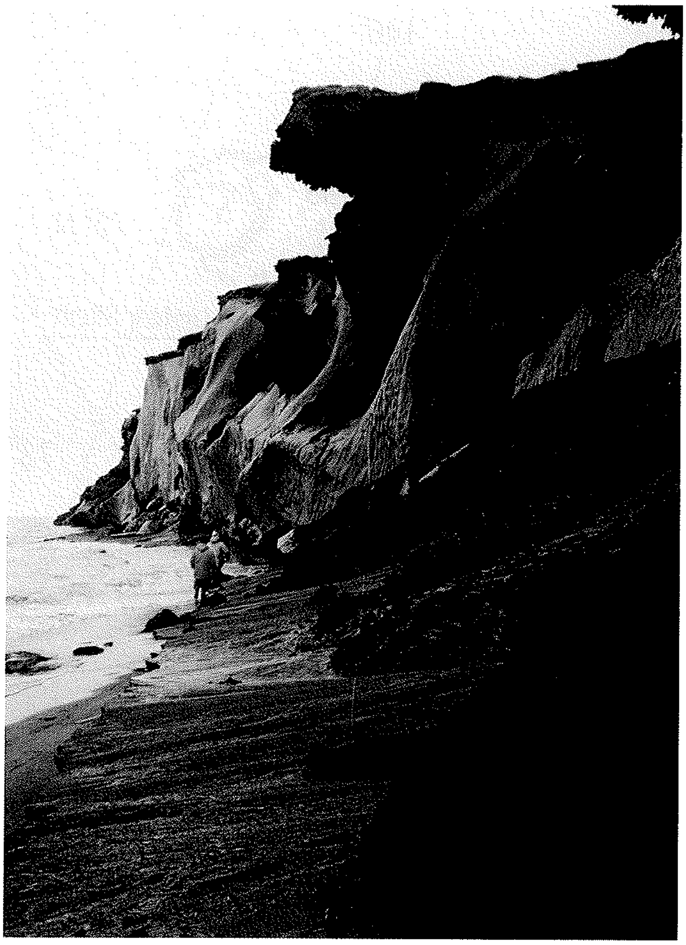

Fig. 4: Erosion shore of Muostakh Island composed of ice complex. The cliff height 20 m. The mean shore retreat rate 11 m/year in 1951-1999.

Abb. 4: Erosionsküste der vom Eiskomplex gebildeten Insel Muostakh. Die Kliffhöhe beträgt 20 m, die mittlere Rückzugsrate der Küste im Zeitraum 1951-1999 liegt bei 11 m/Jahr.

100 m wide and having an extremely small inclination is seen in the background. The fresh products of thermodenudation, accreting between the nearest ice complex exposure and the shoreline, have an equally small inclination. It is clearly evident that the volume of the ice wedges exceeds the volume of the enclosed sediment by far. The thawing of the ice complex produces mudflows, which create thermoterraces with particularly small inclinations. A much steeper and narrower thermoterrace due to a lower ice content in the ice complex and to coarser sediment is illustrated in Figure 7 (key section 11). Correspondingly, the mean shoreface inclination of key section 17 (0.0011) is much smaller than that of key section 11 (0.0045). Shoreface profiles in sand (key sections 4,5,6,7) and in gravel (Cape Svyatoy Nos, section 15) are much steeper than profiles off the coasts composed of ice complex (Tab. 1).

It is remarkable that in the eastern part of the Laptev Sea four of the five shoreface profiles (Fig. 5 bottom) have clearly developed lower boundaries at a depth of about 10 m, but in the western part (Fig. 5 top) five of the six profiles have this boundary in a depth range of 4 to 6 m.

On all near shore-profiles from 1 to 4 longshore bars as high as 1.2 m are revealed. Farther offshore and up to the 10-m isobath, by contrast, the ship-based echosounder profiles show a very smooth relief. No trace of ice gouging is evident anywhere.

The comparison of measured profiles with profiles taken along the same tracks from the navigational charts based on bathymetric surveys between 1962-1980 does not allow a reliable evaluation of erosion rates of the shoreface because of insufficient accuracy of the geodetic closure. But this comparison testifies that the upper part of the shoreface retains its shape during coastline retreat. Two appropriate examples are illustrated in Figure 8. Figure 8A represents key section 2 (Cape Mamontov Klyk) in the western part of the Laptev Sea. The dotted line reproduces a profile taken from a navigational chart. The solid line between 0.5 and 2 km is based on detailed portable echosounder measurements, whereas the offshore part represents a ship-based echosounder profile. A similar comparison is reproduced in Figure 8B for key section 12 in the eastern part of the Laptev Sea (Makar Is.).

Considerable sea floor changes are revealed only along key section 3 near Cape Terpyay-Tumsa in the western part of the Laptev Sea where the 30-40 m high coastal cliff is composed of an ice complex (Fig. 9A). According to our measurements this section of the shore has retreated by about 100 m during the last 20 years. The shape of the shoreface profile did not change substantially over this time interval, but beyond the shoreface between the 5 and 10 m isobath (2-13 km off-shore), the sea floor has been lowered by 0.6-0.9 m, and by as much as 2.7 m at a distance of 10 km.

Eight kilometers to the east the low coast of the Terpyay-Tumsa Peninsula begins. According to the State Geological Map (1:200,000 scale) this peninsula is composed of late Holocene marine sediment. No measurements on the coastal erosion rate were carried out along this section, but visual evidence for coastal retreat is absent. The shape of the seabed profile (Fig. 9B) has changed considerably when compared to those of Figure 9A. A low rise situated 7 km off-shore, and still poorly developed along the profile of Fig. 9A, has evolved laterally into a 5.4 m high shore-parallel ridge, the water depth above its crest having decreased from as much as 4.6 m to only 2 m. In addition the nearshore section of the shoreface profile has become convex. Up to 6 km from the shore the seabed has accreted vertically by 0.6-0.8 m during the 18 years between 1962 and 1980.

Accreting shores of the Lena River delta.

The shoreface of the delta was surveyed along key sections 8, 9, and 10 (Fig. 2).

Key section 8

In the vicinity of this key section many small interdistributary channels enter the sea. The mouths of the large channels are situated rather far from the section 8 (Fig. 10). Because of rough weather it was unfortunately not possible to go ashore during our survey for a closer investigation of the coast which is presumably composed of sands and peat (GRIGORIEV 1993). The elevation of Amerika-Kuba Island is 3 m above mean sea

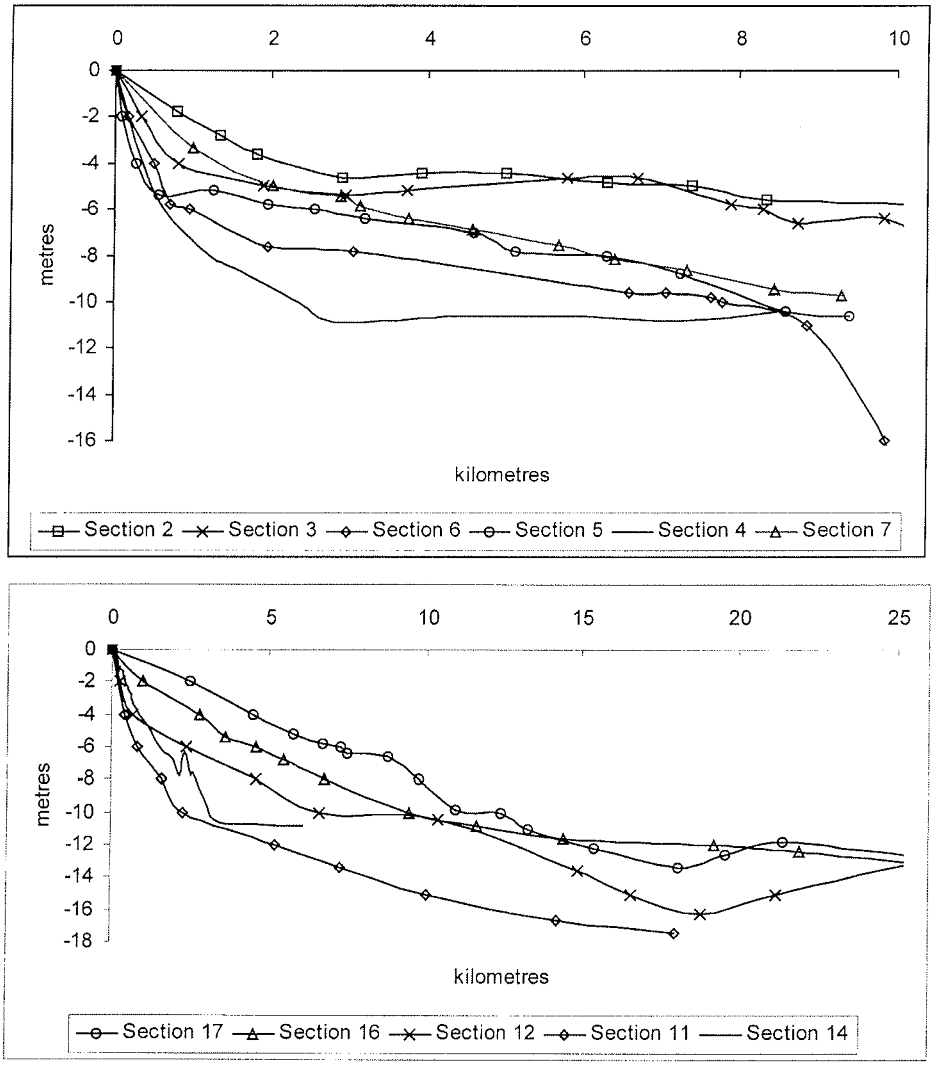

Fig. 5: Shore face profiles of Laptev Sea erosion coasts west (top) and east (bottom) form the Lena Delta.

Abb. 5: Seewärtige Küstenrofile von Erosionsküsten der Laptewsee westlich (oben) und östlich (unten) des Lena-Deltas.

Fig. 6: The shore on the key section 17, Oyogosky Yar, south coast of the Dm. Laptev Strait. Thermoterrace with extremely small surface inclination.

Abb. 6: Küste bei Schlüssellokalität 17, Oyogosky Yar, südliche Küste der Dm. Laptev-Straße. Thermoterrasse mit extrem flachem Neigungswinkel.

Fig. 7: The shore of key section 11, west coast of Buor-Khaya Peninsula. Thermoterrace with comparatively large surface inclination.

Abb. 7: Küste bei Schlüssellokalität 11, westliche Küste der Halbinsel Buor-Khaya. Thermoterrasse mit vergleichsweise starkem Neigungswinkel.

Key section		Sea floor inclination			Depth of lower shoreface boundary (m)	Shoreface width (km)
No.	Name	Shoreface upper part	Mean value	Beyond the shoreface		
Ice complex East						
11	Buor-Khaya Pen.	0.016	0.0045	0.00068	10.0	2.3
12	Makar Is.	0.0054	0.0015	0.00011	10.0	6.7
14	Shirokostan Pen.	0.0043	0.0030	0.000077	10.6	3.5
17	Kondratyeva R. mouth	0.0009	0.00074	0.00005	13.4	
16	Zimovyo R. mouth	0.002	0.0011	0.00016	10.8	9.5
Mean values		*0.0057*	*0.0022*	*0.00022*	*10.9*	*8.0*
Ice complex West						
2	Cape Mamontov Klyk	0.002	0.0015	0.00033	4.6	2.9
3	Cape Terpyay-Tumsa	0.0061	0.0034	0.0002	5.25	1.5
Mean values		*0.0045*	*0.0024*	*0.00026*	*5.05*	*2.2*
Sands						
5	Arga Is. North	0.022	0.0098	0.00045	5.4	0.6
4	Arga Is. South	0.012	0.0039	0.00011	10.8	2.8
7	Kuba Is.	0.0034	0.0025	0.0007	5.0	2.0
6	Aerosyomka Is.	0.01	0.0096	0.0014	5.85	0.6
Mean values		*0.012*	*0.0064*	*0.00067*	*6.76*	*1.5*
Gravel						
15	Cape Svyatoy Nos	0.05	0.033	0.0038	6.0	0.2
Bedrock						
1	Cape Tsvetkova	0.036	0.006	0.00052	6.4/15.2/25	0.6/2.6/4.2

Tab. 1: Geometric parameters of the investigated profiles

Tab. 1: Geometrische Verhältnisse der untersuchten Profile.

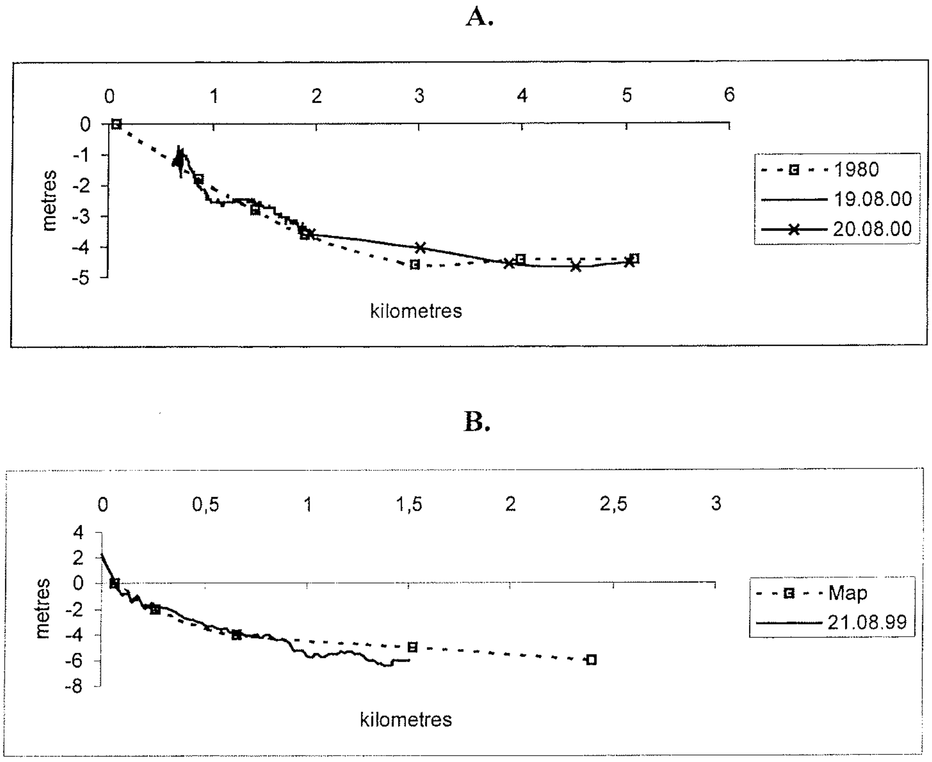

Fig. 8: Upper part of the shore face profile: (A.): key section 2, Cape Mamontov Klyk; (B.): key section 12, Makar Island.

Abb. 8: Oberer Teil der seewärtigen Küstenprofile: (A.): Schlüssellokalität 2, Kap Mamontov Klyk; (B.): Schlüssellokalität 12, Insel Makar.

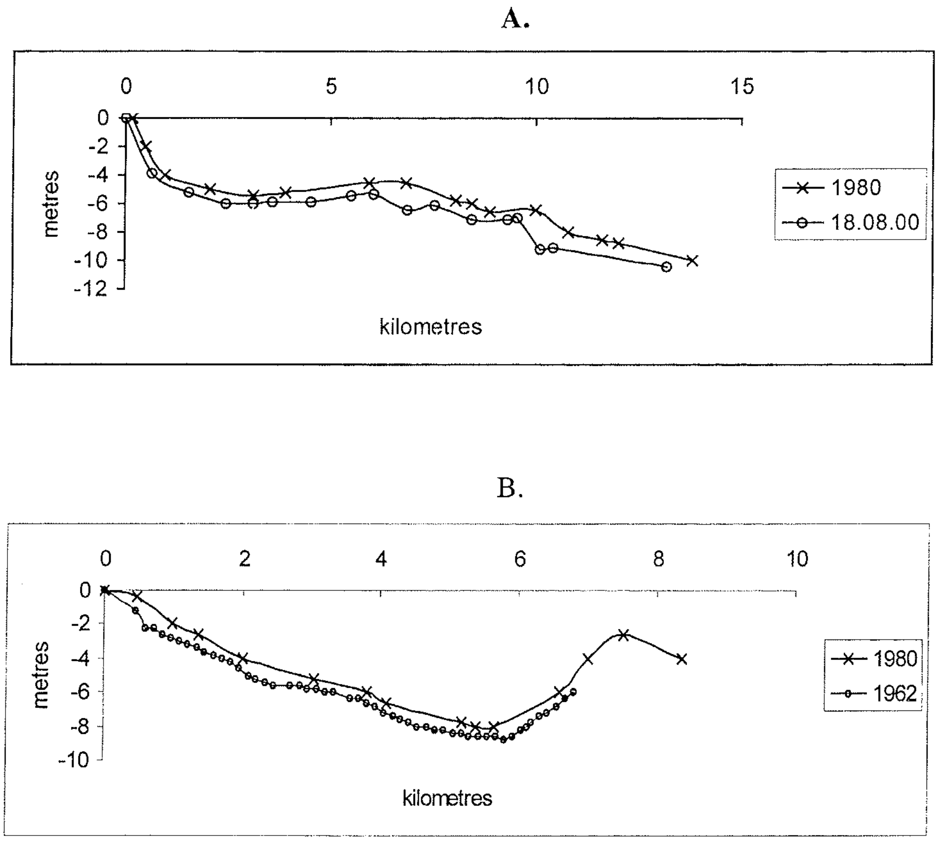

Fig. 9: Erosion of (A.) and accretion on (B.) the sea floor near the Cape Terpyay-Tumsa, key section 3.

Abb. 9: Erosion (A.) und Akkumulation am Meeresboden nahe Kap Terpyay-Tumsa, Schlüssellokalität 3.

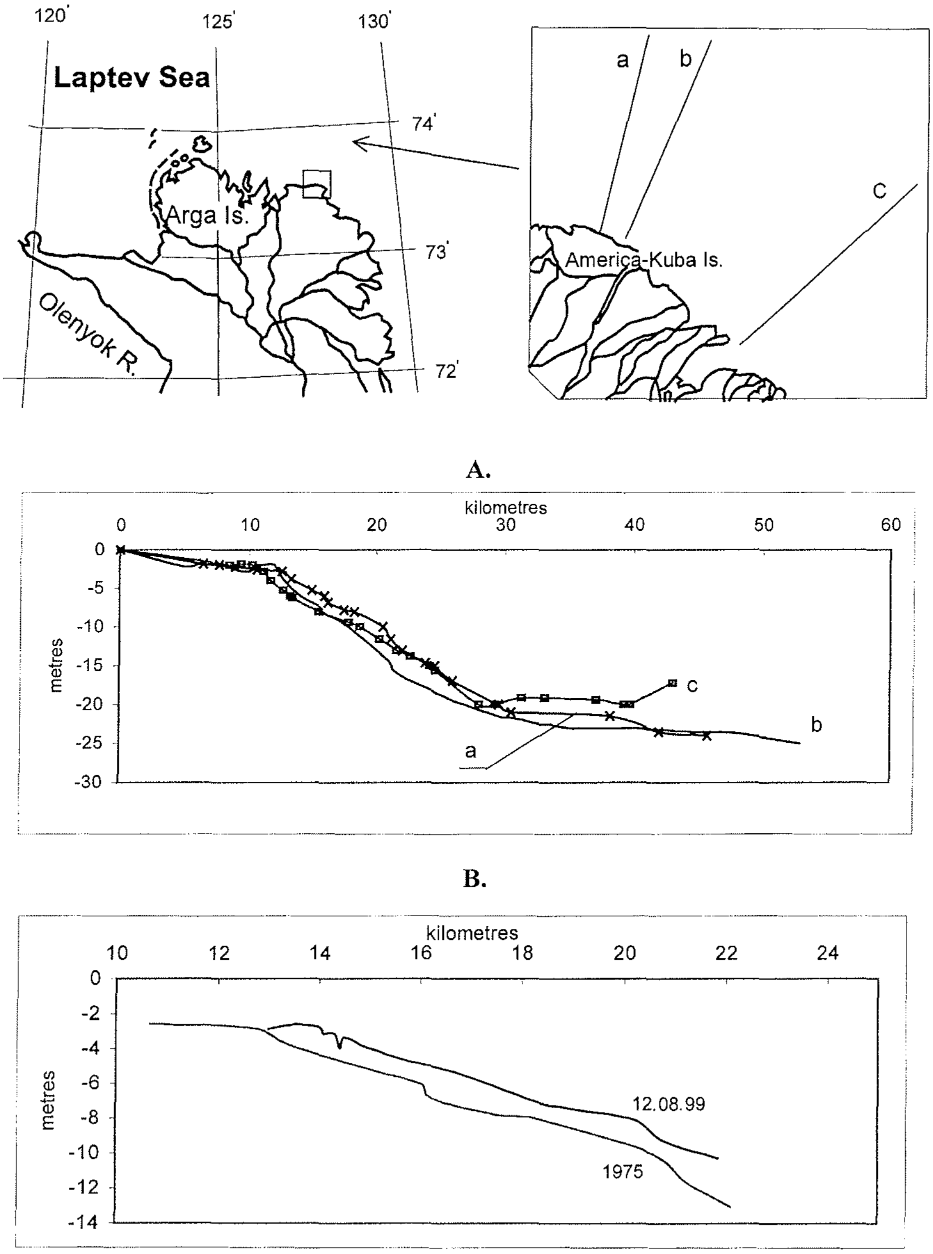

Fig. 10: Shore face profiles on key section 8. Profiles a, b, and c are taken from a navigation map of 1:100,000 scale, based on measurements carried out in 1953-1975.

Abb. 10: Seewärtige Küstenprofile bei Schlüssellokalität 8. Die Profile a, b und c sind Navigationskarten (Maßstab 1:100.000) entnommen, die auf Messungen der Jahre 1953-1975 beruhen.

level according to a topographic map. Three shore face profiles are reproduced in Figure 10A. They have been extracted from a navigational chart (1:100,000 scale) based on measurements carried out before 1976. All these profiles have a similar shape. A flat and extremely shallow, 10-13 km wide bench characterizes the nearshore sections. The average inclinations of the individual benches ranges from 0.00017-0.00019, the maximum water depths at the outer edge reaching between 2-2.8 m. Further off-shore the sea floor inclination increases sharply by an order of magnitude, reaching values of 0.001 and staying constant up to a water depth of 20-21 m, where the active prodelta ends and the submerged shelf plain begins. The shoreface profile along line 1 was surveyed on 12 August 1999 by means of a ship-based echosounder. A comparison of the measured profile with the same profile extracted from a chart (Fig. 10B) reveals that during the 24 years between 1975 and 1999 the active prodelta advanced seawards by 1.4 km (58 m/year) without changing its inclination (0.001).

Key section 9

This section is located opposite the mouth of the Bolshaya Trofimovskaya Channel, which flows into a bay with numerous low islands (Fig. 2). According to Danilova (1965) the shoreline advanced considerably in this area. A shoreface profile extracted from a navigation map of 1:100,000 scale based on measurements between 1967-1975 is illustrated in Figure 11. The outer limit of a well-developed shallow bench occurs at a water depth a little less than 3 m. The inclination of the bench surface is 0.00035. The mean inclination of the outer slope, by contrast, is 0.001. For comparison, a profile measured along the same line by a research vessel on 22 August 2000 is shown in the same figure. Unlike key section 8, the

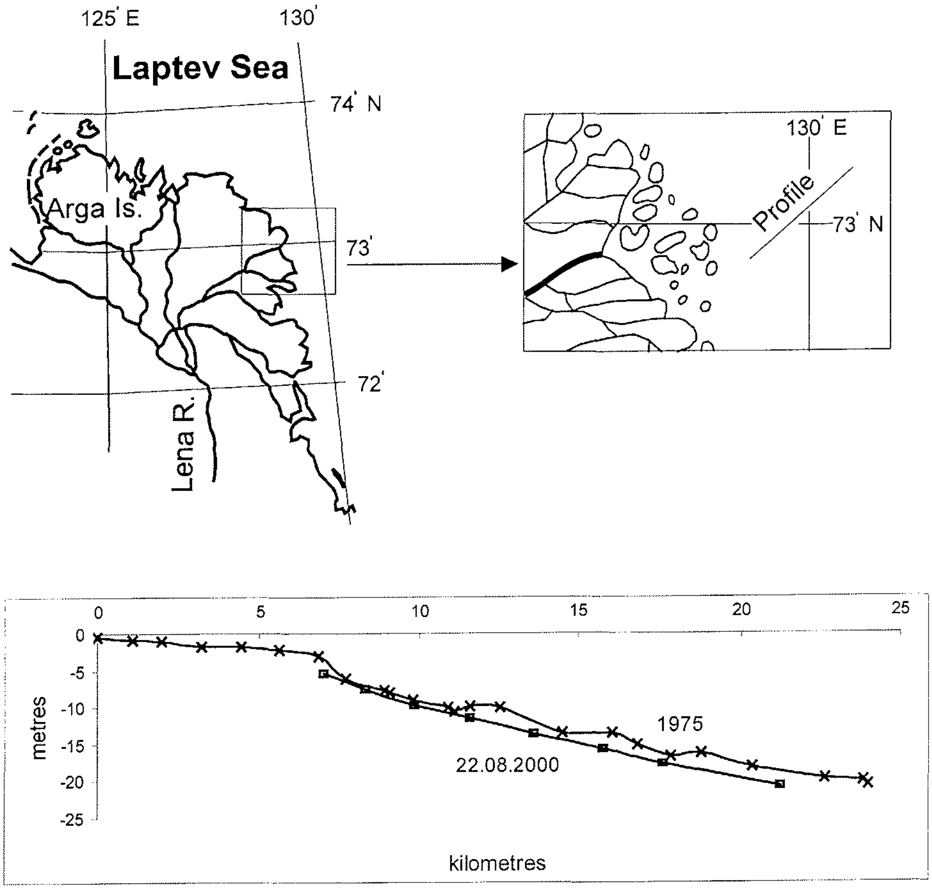

Fig. 11: Shore face profiles on key section 9. B. Trofimovskaya Channel mouth.

Abb. 11: Seewärtige Küstenprofile bei Schlüssellokalität 9, B. Mündung des Trofimovskaya-Kanals.

comparison of the two profiles in this case shows erosion of the prodelta, the most intensive erosion taking place at depths >10 m.

The difference in shape of the outer and steeper part of the shoreface in sections 8 (Fig. 10) and 9 (Fig. 11) deserves attention. In section 8 the surface of this part is rather flat, and the seaward boundary is clearly marked by a sharp change of inclination. The profile in section 9, by contrast, has a very smooth and slightly concave shape, as is typical for retreating shorelines.

Key section 10

This section is located opposite the Sardakhsky Channel mouth (Figs. 2 and 12). The measured shoreface profile starts near a nameless island, the last one downstream of the channel (Fig. 12). The northwest coast of the island is bordered by a vertical cliff as high as 1 m. The island surface gradually declines and submerges in a southeastern direction. The highest part of the island is vegetated and it is entirely flooded at times of strong river discharge. As a result, sediment accretion is taking place on the whole island. The northwest coast of the island has retreated between 1969 and 1999 by 2 m/year on average. The low southeast shore, by contrast, has advanced rapidly into the sea. The shoreface profile was measured by portable (1) and ship-based (2) echosounders (Fig. 12A). The geodetic closure accuracy of profile (2), however, is insufficient for a comparison with the bathymetric chart data. On the whole, the shapes of the profiles are similar but considerably more complicated than those of sections 8 and 9. The mean inclination of the shallow bench is 0.00042 up to 9 km from the shore. Further offshore the sea floor is almost horizontal up to 14 km from the shore. The bench profile is slightly concave and the water depth at its outer limit is about 4 m, which is much deeper than in sections 8 and 9 (2-3 m). The outer slope inclination is 0.001.

Three depressions in the nearshore part of profile (1) are shown in greater detail in Figure 12B. Similar relief forms have also been observed on the echograms obtained by shallow seismic surveys, carried out in the Arangastakh-Kubata Bay (Fig. 12). Most likely these features are produced by strudel scour of the sea floor in the wake of high river discharge during spring floods. According to Fig. 12B, the widths of the depressions (from left to right) are 68, 67, and 109 m respectively, their depths being in the range of 2.2-2.3 m. The recording interval of the portable echosounder was 32-36 m, and the actual widths of the depressions therefore were on average less then 68-109 m, but larger than 32-36 m. The strudel scours up to 25 m wide and 6 m deep were previously reported from the Beaufort Sea, Alaska, where the rivers are much smaller then the Lena River (REIMNITZ & KEMPEMA 1983).

Another pronounced morphological feature on profile (1) is the sharp increase in water depth at a distance of 2.5 km from the shore (Fig. 12A). The scarp may have been created by a storm at a lower sea level stand. However, when comparing this increase with the shoaling trend 5-6 km from the shore, a

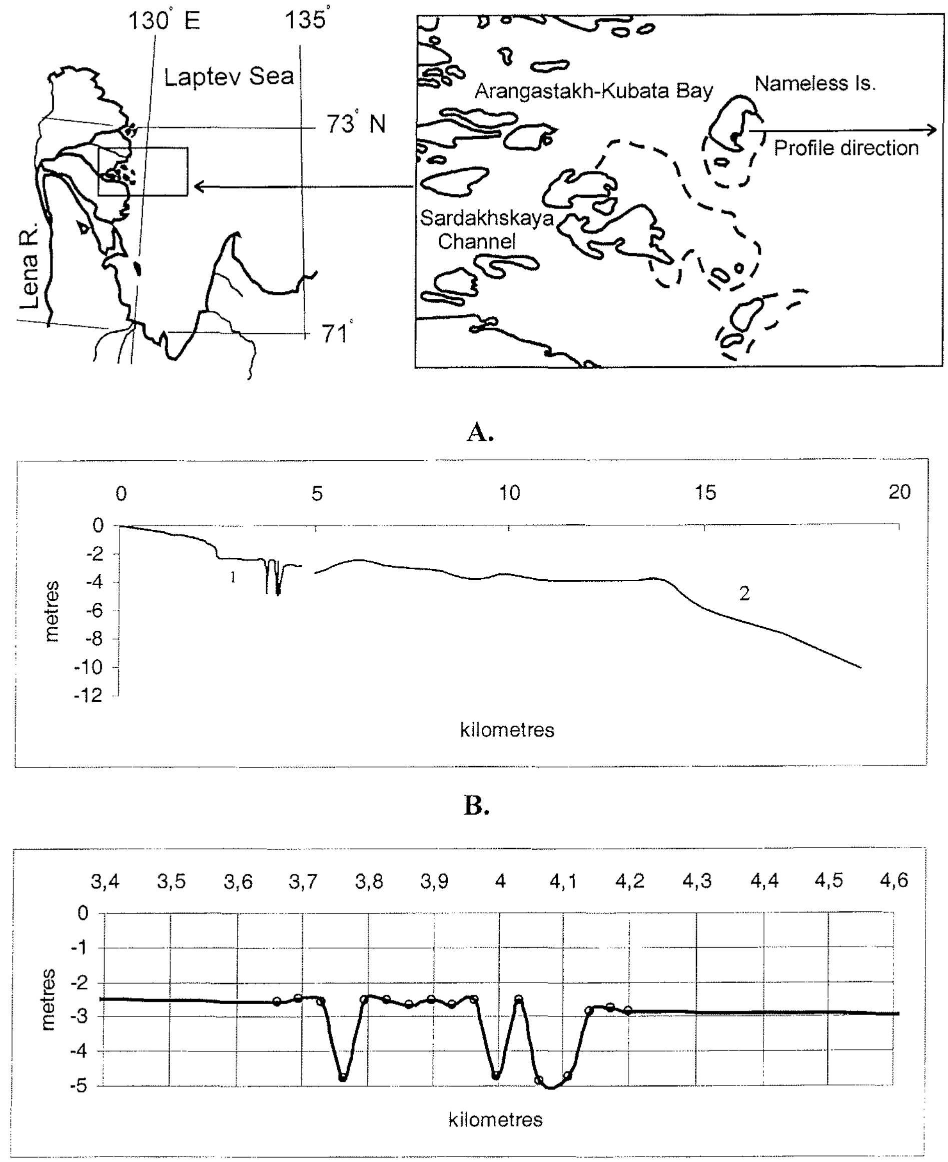

Fig. 12: Shore face profiles on key section 10, Sardakhskaya Channel mouth. (A.): measured by hand-held echosounder on 14 August 1999; (B.): measured by ship-based echosounder on 15 August 1999.

Abb. 12: Seewärtige Küstenprofile bei Schlüssellokalität 10, Mündung des Sardakhskaya-Kanals. (A.): mit tragbarem Echolot am 14.08. 1999; (B.): mit Schiffsecholot am 15.08.99 aufgezeichnet.

3-km wide and about 1-m deep valley may have been eroded by spring floodwaters flowing below the fast ice.

Erosional rocky shores

Several coastal sections situated in different parts of the Laptev Sea coast are composed of bedrock. No published information on their dynamics is available. We have investigated such shores in key sections 1, 13, 15 (Fig. 2) and in Tiksi Bay.

Key section 1

This section is situated on Cape Tsvetkova. Here the coast is bordered by a flat cliff about 30 m high and ≈60° steep with a vegetated slope behind it (Fig. 13). Paleozoic metamorphic sandstones with conglomerate interbeds and hard coal inclusions are exposed in the cliff. The only Quaternary sediments occur in a thin weathered surface layer. The outcrop continues northward for an unknown distance, and southward for 14 km up to the mouth of the Korotkaya River. South of the river the coast is composed of unconsolidated sediments.

Figure 13 shows that the rocks composing the cliff have undergone intensive tectonic transformation. Intensive mechanical destruction occurs on the surface of the cliff. Strong jointing and the steep dip of the bedding favor it.

Our brief observations do not allow a quantitative evaluation of the rate of retreat of this coast, but indirect evidence testifies that this coast supplies a considerable amount of sediments to the sea. Amongst such evidence is:

(1) The water depth near the shore is comparatively large. The inclination of the upper part of the shoreface profile is 0.04 (Tab. 1), the inclination of the beach profile being even larger (Fig. 14). This testifies of high-energy sea influence on the shore.

(2) Large accumulations of weathering products on the beach in front of the cliff are absent, indicating that the sea rapidly removes these products.

(3) At the base of the cliff the weathering products consist of

Fig. 13: General view of the Cape Tsvetkova coast, key section 1.

Abb. 13: Überblick der Küste bei Kap Tsvetkova, Schlüssellokalität 1.

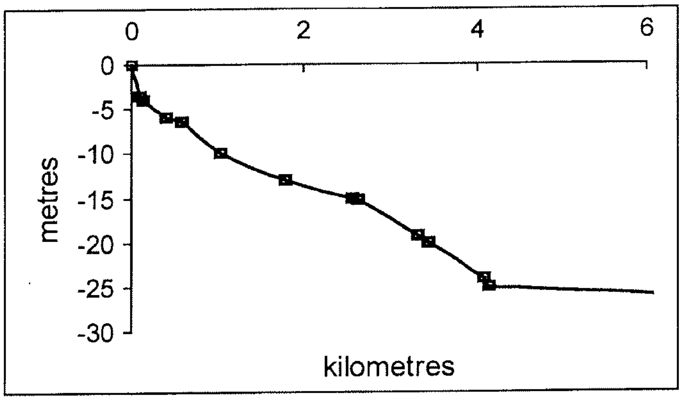

Fig. 14: Cape Tsvetkova shore face profile.

Abb. 14: Seewärtiges Küstenprofil bei Kap Tsvetkova.

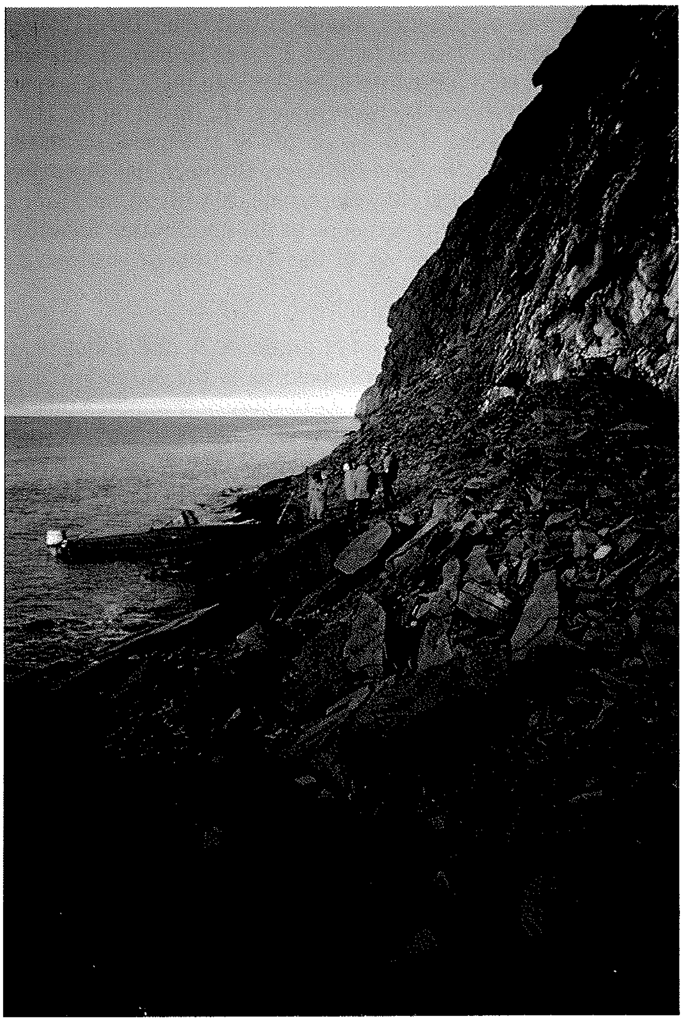

Fig. 15: Cape Tsvetkova abrasion shore.

Abb. 15: Abrasionsküste bei Kap Tsvetkova.

coarse-fragmental material (Fig. 15) but at the waters edge fine gravels prevail. This testifies that the resistance of local bedrock against fragmentation is low. Inspite of this no wave-cut noches are observed at the cliff base. Thus, weathering destroys the coast faster than wave erosion.

The sediment supplied to the sea from the shore evidently moves southward along the shore feeding Tsvetkova spit, which forms a famous walrus breeding ground, as well as a sequence of longshore bars situated beyond the rocky coast.

A shoreface profile off Tsvetkova Cape, taken from a 1:50,000 navigation chart is presented in Figure 15. This profile does not correspond to the classical model of an abrasion shoreface (Fig. 1) because of the absence of a wave-cut bench (underwater abrasion terrace) and an offshore accretion terrace. The shape of the profile is slightly concave up to the 15-m isobath, which is typical for erosional shores composed of unconsolidated material. Such shapes testify that the sea not only successfully removes sediment coming from the cliff, but also erodes the shoreface, maintaining a large inclination on its upper part (0.04).

Up to a depth of 15 m (Fig. 15) the upper part of the profile consists of two concave sections. The upper one, from the shore up to 6.4-m water depth, may be interpreted as having been eroded by a recent temperate storm. The lower section at a depth range from 6.4 to 15 m, was probably excavated by earlier exceptionally strong storms. The sharp break in the profile at 15-m depth is probably a structural feature marking the lower shoreface boundary (Fig. 15).

Key sections 13 and 15

In key sections 13 at Vankina Bay, 15 at Cape Svyatoy Nos, and in Tiksi Bay some parts of the coast are also composed of bedrock, but these are more resistant against wave erosion than the rocks at Cape Tsvetkova. Chokurdakh Mountain, located in the northeastern part of Vankina Bay, also undergoes wave erosion. Two shoreface profiles off this mountain were taken from Vankina Bay bathymetric chart of 1:25,000 scale (Fig. 16). Profile A starts at a 5-7 m high cliff composed of consolidated Jurassic tuffs and Permian sandstones with dikes of granodiorite porphyrites. Boulders and other debris cover the beach and shoreface up to the 1.2-1.7 m isobath. Sands and silts are distributed further offshore. Beyond the 2.5-m isobath the sea floor is covered by fine-grained silt. Based on the classical abrasion model (Fig. 1), profile A in Figure 16 corresponds to a young development stage. Between the shore and the 1-m isobath a faintly developed bench with an inclination of 0.02 is visible. The outer slope of the underwater accretion terrace extends offshore up to the 2 m isobath (inclination 0.03).

Profile B is situated 4 km east of profile A. A cliff about 16 m high is composed of the same rocks as in the A section. The shape of this profile (Fig. 16) more closely resembles that of the classical model. Its upper part up to the 1-m isobath may be considered as a bench (inclination 0.008). A convex shape extending further offshore to the 4-m isobath represents an underwater accretion terrace (inclination 0.003). The bottom sediment distribution confirms this interpretation. Boulders and pebbly debris cover the bench surface. Further offshore, approximately up to the 1.6-m isobath, the sea floor is covered by sandy silt with small additions of debris, grit and pebbles. No data on the bottom sediments beyond the 1.6-m isobath are available.

Large-sized boulders characterize the beach at Cape Svyatoy Nos. In Tiksi Bay, rather weathered carbonate rocks, which are not displaced by waves, are found on the beach east of the town. Such shores evidently do not supply substantial amounts of sediment to the sea.

DISCUSSION

Shoreface off erosional shores

The data in Table 1 show that the lower limit of the shoreface in the Laptev Sea can easily be identified morphometrically by an order of magnitude decrease in the sea floor inclination. This fact is important for the understanding of shoreface profile formation in all shallow seas where the potential depth of mechanical influence of waves on the seabed sediments is limited by the water depth. Wave fetch in the southern Laptev Sea reaches several hundred km, but the water depth does not exceed 20 m. During storms intensive sediment reworking therefore occurs over a huge area (ARE 1996). That, however, is not a coastal process but rather a normal shelf sediment dynamic process. It is evident that the offshore limit of the shoreface is not determined by hydrodynamic factors but by the seabed level. The southern part of the Laptev Sea comprises a vast lowland submerged during the last transgression, and the level of this lowland thus determines the offshore limit of the lower shoreface. In the eastern Laptev Sea the water depth of the lower shoreface limit is twice as deep as that in the western parts (ca. 10 and 5 m isobath, respectively, Tab. 1). This is explained by corresponding differences in seabed levels.

In some places of the western Laptev Sea near-shore water depths exceed 5 m. This produces a corresponding drop in the lower shoreface limit (Fig. 5A, section 4). In the eastern part one shoreface profile in section 17 looks anomalous (Fig. 5B). Its inclination is an order of magnitude lower than that of the other profiles (Tab. 1), and the shape is not concave but in its upper parts even slightly convex. Although we lack the data for a plausible explanation of this anomaly, it has to be considered that key section 17 is situated at the exit from the Dm. Laptev Strait to the East-Siberian Sea. Possibly a partial deposition of sediments transported out of the strait occurs in this region.

A typical feature of all profiles, except for section 17, is their concave shape. The inclination of the profiles generally increases with increasing grain size of the bottom sediment (Tab. 1). Both features are compatible with the theory of an equili-

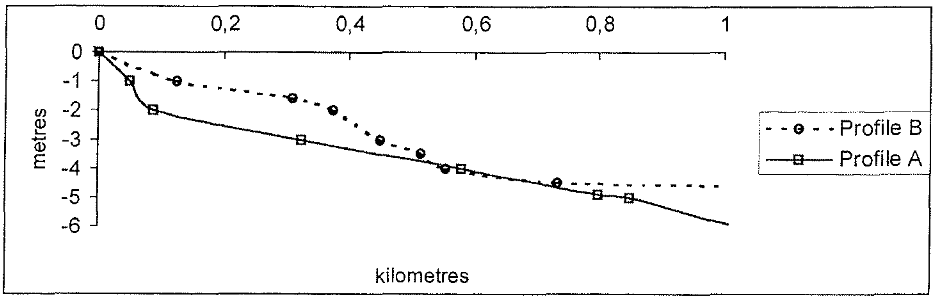

Fig. 16: Shore face profiles of abrasion coast in Vankina Guba Bay, key section 13.

Abb. 16: Seewärtige Küstenprofile von Abrasionsküsten in der Vankina Guba-Bucht, Schlüssellokalität 13.

brium shoreface profile (BRUUN 1954, ZENKOVICH 1962). All our measurements were carried out along shores, which are continuously retreating without any sign of deceleration in the future. What then is the essence of the equilibrium profile theory of BRUUN (1954) and ZENKOVICH (1962)?

BRUUN (1954) stated „An equilibrium beach profile is a statistical average profile which maintains its form apart from small fluctuations including seasonal fluctuations.“ ZENKOVICH (1967) and LARSON (1991) give essentially the same definitions for shores composed of unconsolidated sediments. The emphasis is thus on a dynamic equilibrium of the profile shape and not on the stability of the shoreline. Shoreface profiles off stable (dead) shores are called „ultimate equilibrium profile“ by ZENKOVICH (1962), but he does not discuss it in detail.

Numerous wave tank experiments on shoreface profile formation were carried out in different parts of the world. For example, SIVAKOV (1961) performed 35 experiments to study the ultimate equilibrium shoreface profile in sands. One of the results is presented in Figure 17. The water depth in the tank was 50 cm. The thickness of the fine-grained sand layer (76 % of particles <0.5 mm) was 60 cm and the initial inclination of the shoreface 0.5. The final equilibrium was reached after a run of 180,000 waves 10 cm high with a 1.12 s period. A sharp increase of the profile inclination at a depth of 33 cm marks the lower limit of the shoreface. Clearly, this experiment was carried out under conditions at which the water depth exceeded that of the shoreface boundary position and does therefore not correspond to the Laptev Sea conditions. Nevertheless, the results of the experiment deserve attention. In particular, it should be noted that the ultimate equilibrium postulated by ZENKOVICH (1962) is reached in the course of a decreasing inclination of the shoreface profile. Furthermore, it was demonstrated that an underwater accretion terrace not only develops off rocky coasts, but also off sandy shores provided the water depth exceeds the depth of the effective wave base. Finally, it has been clarified that an ultimate equilibrium shoreface profile may be a rather complicated morphological feature. Omitting the profile of the accretion terrace, we turn our attention to the shape of the bench profile (Fig. 17). After 4000 waves this profile may be approximated by a concave shape. However, such an approximation will evidently not be adequate for ultimate profile because a pronounced linear shape characterizes the upper part of this profile (approximately up to 125 cm from the origin of the coordinates), whereas the lower part of the profile has a horizontal trend. Thus, in this particular case, the statement of DEAN (1997) that the validity of equation (1) is proved experimentally is not confirmed.

Examination of the Laptev Sea shoreface profiles at our disposal shows that all of them are poorly approximated by the power relationship of equation (1). An example of such an approximation is presented in Figure 18 for a shoreface profile in key section 4. The points of the measured profile, displayed on a logarithmic scale in Figure 18A, do not fit a straight line. The linear regression for these points produces the equation (1) of the next form

$$h = 0.13\,x^{0.56} \qquad (2)$$

The graph of equation (2) is illustrated in Figure 18B. It clearly deviates significantly from the measured profile which, instead, is almost perfectly described by a polynomial equation of the fourth degree.

Some indirect evidence supports the data on shoreface erosion in key section 3 near Cape Terpyay-Tumsa (Fig. 9A) and on sediment accretion further to the east (Fig. 9B). The coast, a 30-40 m high cape, retreated during the last decades at a mean rate of 4.8 m/year and evidently transfers a large amount of sediment to the sea. According to the calculations of SOVERSHAEV (1980), the longshore transport of sediments from the cape is directed both to the west and to the east. The low accretion shores of the Terpyay-Tumsa Peninsula east of the cape and parallel to the offshore ridge, which increases in height towards the east (Fig. 9), support the reliability of the measured accretion of sediment on the shoreface in this area.

Shoreface off the Lena Delta accreting shores

According to ALPHA & REIMNITZ (1995) the Arctic river deltas are typically framed by vast shallows with a maximum water depth of about 2 m along their outer edges. This depth approximately coincides with the maximum thickness of the ice cover which adfreezes with the bottom and thus provides bottom sediment freezing.

According to our investigations, a shallow and up to 18 km wide area with a seaward dipping inclination of its surface in the range of 0.0002-0.0004 occurs along the entire coast of the Lena Delta. For brevity we will call this area the prodelta „bench“.

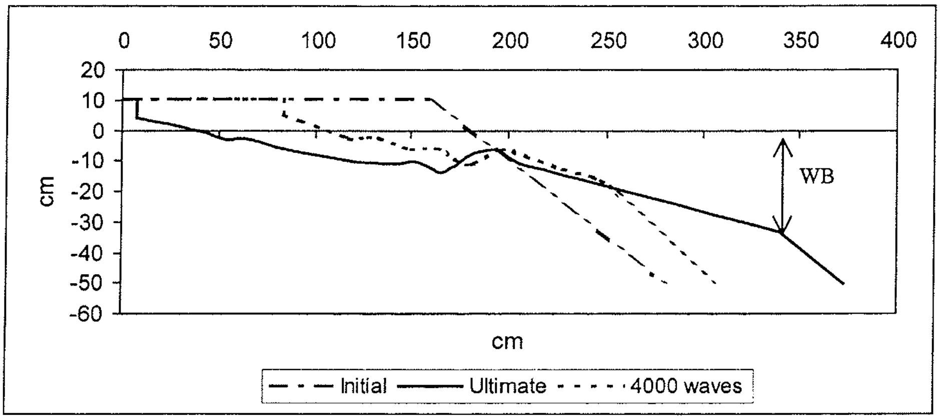

Fig. 17: Development of an ultimate equilibrium shore face profile in fine-grained sand. Tank experiment (SIVAKOV 1961). WB: effective wave base.

Abb. 17: Entwicklung eines equilibrierten seewärtigen Küstenprofils in feinkörnigem Sand im Tank-Experiment (SIVAVOV 1961). WB: effektive Wellenbasis.

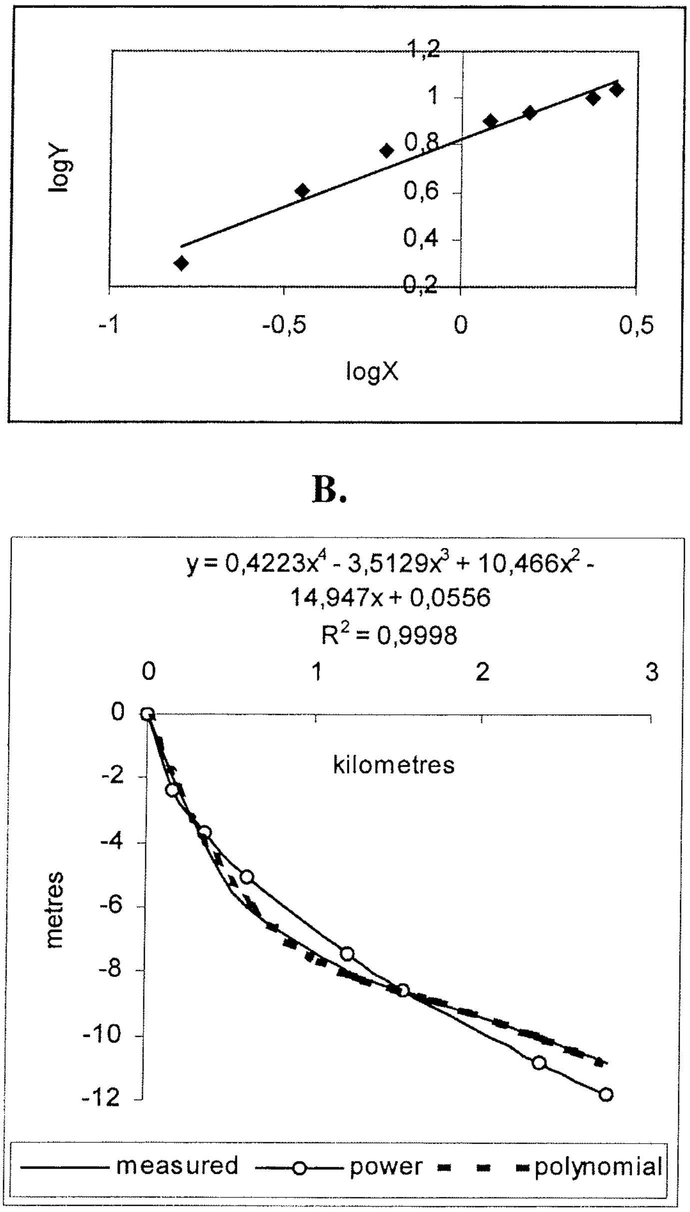

Fig. 18: Approximation of a sandy shore face profile, measured on the key section 4. (A.) Point diagram of the measured profile and its trend line at the logarithmic scale. (B.) Comparison of the measured profile approximation by power and polynomial functions.

Abb. 18: Mathematische Näherungsrechnung eines seewärtigen Küstenprofils in sandigem Substrat, Schlüssellokalität 4. (A.) Punktdiagramm des gemessenen Profils und der berechneten Trendlinie bei logarithmischer Skalierung. (B.) Vergleich zwischen gemessenem und berechnetem (mit Potenz- bzw. Polynom-Funktion) Profil.

The outer boundary of the bench is clearly defined by a sharp increase in the sea floor inclination by an order of magnitude (0.001) in the depth range of 2-3 m. The steeper slope extends up to water depths of 15-25 m and distances as far as 35 km from the shore (Figs. 10-12). We propose that the observed shoreface profile, which consists of two sections with different inclinations, forms the limit of the underwater part of the delta. Both sections have generally flat slopes, but some negative relief forms may occur on the bench near the delta channel mouths. These depressions are probably excavated by strong water flows penetrating under the fast ice during spring floods. A slightly elevated underwater bar is observed along the outer edge of the bench in some sections.

We cannot explain the origin of the bench and its clearly outlined outer boundary. It should be noted that such benches also frame the Yana River delta (GRIGORIEV 1966) and the deltas of the Alaskan rivers (ALPHA & REIMNITZ 1995). It is noteworthy that benches of similar form occur along the accretional shores of the Vankina Guba Bay (key section 13, Fig. 2) and in the lakes on Arga Island (Fig. 10).

A comparison of the delta shoreface profiles (presented in Figs. 10 and 11) testifies that bathymetric surveying is a promising technique for the investigation of the Lena and other Arctic river sediment discharge and dispersal.

Even the limited data sets of this study show the complicity of delta interaction with the sea. Besides general delta progradation, erosion of the delta occurs along some sections of the coast. The shoreface profile along eroded sections is characterized by convex shape.

The amount of Lena River sediment entering the sea and consumed in delta construction has so far not been reliably determined (ARE 1999). Direct sediment discharge measurements in the mouths of the numerous Lena River interdistributary channels are unacceptable because of technical complexity and high costs. Instead, bathymetric surveys and comparison with older hydrographic data provides a much simpler, cheaper and more reliable solution for the assessment of sediment input and underwater delta formation. Coupled with investigations of sedimentation rates on the delta floodplain it will provide good estimates of Lena River sediment discharge and its partitioning between delta construction and input into the sea.

Shoreface off rocky coasts

Our visual observations and measurements on the shores composed of bedrock show that some of these supply a considerable amount of sediment to the sea. Rocky coasts should therefore not be neglected in calculations dealing with shore erosion and sediment input into the Laptev Sea. Shoreface profiles off the Cape Tsvetkova (key section 1) and in Vankina Guba Bay (section 13), presented in Figures 15 and 16, document that the shape of the shoreface may be used for a preliminary assessment of the intensity of rocky coast erosion. The classical profile shape comprising a clearly pronounced bench and underwater accretion terrace suggests shore stability. The absence of the bench and accretion terrace, and especially a concave shape of the shoreface profile (Fig. 15), point to active erosion and considerable sediment supply into the sea.

CONCLUSIONS

The shoreface evolution of erosional shores depends on water depth and effective wave base relationships. The position of the lower shoreface boundary is evidently determined by the water depth in shallow seas where the water depth is less than the maximum possible effective wave base. These conditions prevail in the Laptev Sea everywhere off the lowland coasts.

During the last transgression the sea flooded a vast lowland and the surface of this lowland now lies 5-10 m below sea level in the southern part of the sea. The analyses of the Laptev Sea bottom profiles at our disposal showed that the position of the lower shoreface boundary along the retreating lowland coasts is actually determined by the water depth and in most cases may be easily recognized by a pronounced order of magnitude decrease in the mean inclination of the seabed.

All retreating shoreface profiles off coasts composed of unconsolidated sediments have a concave shape. This shape is best described by polynomial functions. It is poorly correlated with power functions, which is in disagreement with the generally accepted model for equilibrium shoreface profiles.

The shoreface inclinations depend on particle size and ice content of sediments composing the coast. In general the inclinations increase with increasing grain size and reduction of ice content.

The shoreface profile shape off the retreating shores did not change much over the last 20-30 years, thus suggesting continuous retreat.

The shoreface profile off the modern Lena River delta in general has a convex shape and consists of two flat sections. The upper one is as wide as 18 km and extends from the shore to the 2-3 m isobath. It is characterized by an inclination of 0.0002-0.0004. Further offshore it sharply dipps into a lower section with a rather constant inclination of about 0.001. The offshore limit of the lower section is clearly defined by a marked decrease in inclination at distances up to 35 km from the shore.

Extremely vast and shallow benches, as observed along the Lena Delta coast, with water depths <2-3 m is a typical feature of the Arctic rivers. The origin of the bench is not well understood. Oceanographic as well as geocryological processes may be responsible for its formation. An explanation of Arctic delta bench development is a task of future investigations.

The measured changes of the Lena Delta shoreface point to the complexity of its evolution over past decades. In some sections the delta prograded rapidly into the sea, whereas in others it stayed stable or underwent erosion.

Our investigations have shown that a comparison of measured shoreface profiles with old bathymetric data allows to quantify the underwater changes of the Lena Delta over past decades and may hence contribute towards a quantitative sediment budget of the river-sea system.

All our echograms indicate a very smooth nearshore seabed relief in the Laptev Sea. Any signs of ice gouging, typical for the Beaufort Sea, are absent in the area between the shore and the 10 m isobath.

Negative relief forms occur on the delta bench. Their origin may be explained by strudel scour caused by spring floodwaters flowing down through cracks in the fast ice.

Some sections of the Laptev Sea coast are composed of bedrock having comparatively low resistance to wave erosion. These sections may supply a considerable amount of sediment into the sea, especially if the cliffs are high. A good example is the Cape Tsvetkova coast on the Taymyr Peninsula. Shores of this type must be taken into account when evaluating the contribution of shore erosion to the Laptev Sea sediment budget.

We conclude that a concave shoreface profile is a sign of continuous retreat of the shore. The persistence of concave shorefaces in the Laptev Sea suggests continued intensive erosion of the Laptev Sea lowland coasts in the 21st century.

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References

Alpha, T.R. & Reimnitz, E., (1995): Arctic delta processes. A computer animation and paper models.- U.S. Geological Survey Open-File Report 95-843 A and B.

Are, F.E. (1996): Dynamics of the littoral zone of the Arctic seas (State of the art and goals).- Polarforschung 64 (3): 123-131.

Are, F.E. (1999): The role of coastal retreat for sedimentation in the Laptev Sea.- In: H. KASSENS, H.A. BAUCH, I. DMITRENKO, H. EICKEN, H.-W. HUBBERTEN, M. MELLES, J. THIEDE & L. TIMOKHOV (eds.), Land-ocean systems in the Siberian Arctic: dynamics and history, Berlin: Springer: 287-295.

Are, F.E., Grigoriev, M.N., Hubberten, H.-W., Rachold, V., Razumov, S.O. & Schneider, W. (2000): Coastal erosion studies in the Laptev Sea.- In: V. RACHOLD & M.N. GRIGORIEV (eds.), Expeditions in Siberia in 1999. Rep. Polar Res. 354: 65-74.

Bruun, P., (1954): Use of small-scale experiments with equilibrium profiles in studying actual problems and developing plans for coastal protection.- Trans. Amer. Geophys. Union 35: 445-452.

Danilova, N.S. (1965): The peculiarities of modern frozen sediment formation in Lena Delta.- Transactions of Acad. Sci. USSR, Geography Series No. 5: 63-71 (in Russian).

Dean, R.G. (1997): Models for barrier island restoration.- J. Coastal Research 13(3): 694-703.

Flemming, B.W. (1999): On the concept of „wave base“ in sedimentary facies analysis and paleo-environmental reconstruction: a critical comment.– In: L.B. CLEMMENSEN (ed.), Abstract Vol. 19th Regional European Meeting of Sedimentology, Copenhagen 1999: 86-87.

Grigoriev, N.Ph. (1966): Permafrost in the seaside zone of Yakutia.- Moscow: Nauka 180 (in Russian).

Grigoriev, M.N. (1993): Cryomorphogenesis of Lena River mouth area.- Permafrost Institute SD RAS, Yakutsk 174 (in Russian).

Larson, M. (1991): Equilibrium profile of a beach with varying grain size.- Coastal sediments '91. New York, ASCE: 905-919.

Rachold, V. & Grigoriev, M.N. (2000): Russian-German Cooperation System Laptev Sea 2000: The Expedition LENA 1999.- Rep. Polar Res. 354: 1-269.

Rachold, V. & Grigoriev, M.N. (2001): Russian-German Cooperation System Laptev Sea 2000: The Expedition LENA 2000.- Rep. Polar Res. 388, 135 pp.

Reimnitz, E. & Kempema, E.W. (1983): High rates of bedload transport measured from infilling rate of large strudel-scour craters in the Beaufort Sea, Alaska.– Continental Shelf Research, Vol. 1, No. 3, Pergamon Press: 237-251.

Reineck, H.-E. & Singh, I.B. (1990): Depositional sedimentary environments.- Springer-Verlag: 549 pp.

Sivakov, I.K., (1961): Formation of in-shore shoal outer edge by waves.- Transactions of Oceanography Commission of USSR Acad. Sci. Vol. 8: 129-135 (in Russian).

Sovershaev, V.A. (1980): Factors forming the shore, and shore zonation of the Laptev, East-Siberian, and Chukchi seas on the dynamic principle.- Abstract of dissertation, Moscow State University, 24.

Thieler, E.R., Pilkey, O.H., Jr., Yuong, R.S., Bush, D.M. & Fei Chai (2000): The use of mathematical models to predict beach behaviour for U.S. coastal engineering: a critical review.- J. Coastal Research, 16(1): 48-70.

Zenkovich, V.P. (1962): The fundamentals of sea shore evolution teaching.- Moscow, Publishing House of the USSR Academy of Sciences 710 (in Russian).