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An Overview of the Lena River Delta Setting: Geology, Tectonics, Geomorphology, and Hydrology

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ABSTRACT

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The Lena River Delta, largest in the Arctic, occupies 32,000 km². It has a complicated structure caused by neotectonic block-movements, which formed an island archipelago with elevation differences as large as 60 m of distinct geological units. The modern active delta occupies spaces between older islands of the archipelago, and is just beginning to protrude into the open sea. The hydrologic pattern in the delta also shows the influence of tectonism. Numerous earthquakes during last century with magnitudes as large as 6 suggest that tectonic movement is continuing. Radiocarbon dating shows that the modern delta has been built during the second half of the Holocene. The total advance of the delta during this time was 120–150 km. The Lena River is considered the main sediment source for the Laptev Sea. The latest investigations give the suspended sediment load in the lower Lena River at 21 Mt/y, but only <30% of this load is thought to reach the sea. The bed load transport is considerable but its value is unknown. The active sub-aerial delta is bordered by a shallow platform as wide as 18 km, which turns into a relatively steep slope at the 2 m isobath. This feature, corresponding in depth to the thickness of the seasonal ice cover, is observed only off Arctic rivers and is not understood. Some sections of the modern delta have morphological features characteristic for advancing shores, others show signs of retreat. However no measurements of delta shore dynamics are available. Thus the general direction of the process is disputable. The western part of the Lena Delta is formed by a large, 20-m-high sand island fringed by a unique lace coast formed by narrow estuary-like bays deeply penetrating the land. This unique coast undergoes intensive erosion not only on promontories but also inside of estuaries due to storm surges reaching to >2 m height. The sand island is characterized by typical lake-thermokarst relief, but no volumes of underground ice large enough to explain this relief are known. The elongated lake depressions and lakes are oriented about 2–8° True. In the middle of generally 1- to 2-m-deep lakes are equally oriented hollows as deep as 25 m. The lakes are degrading because of erosion by stream channels draining them. The lake-thermokarst relief on the north slope of the island is partly or totally destroyed by erosion processes. Thus the Lena Delta is characterized by several unique features that are either poorly understood or unexplained.

ADDITIONAL INDEX WORDS: *Siberia, Laptev Sea, Lena River, Arctic deltas, sediment budget, permafrost, ice complex, lake thermokarst, storm survey, tectonism.*

INTRODUCTION

Concerns with global change resulted in growing interest of geoscientists in Land-Ocean interactions in the Arctic, including coastal dynamics. Several large international programs are devoted to this problem. Intensive and comprehensive studies of the Laptev Sea system are being conducted within the frame of a Russian-German bilateral project. The Lena River Delta is a key area in these investigations because its water discharge of 520 km³/year and sediment yield of 21 Mt/year (ALABYAN *et al.,* 1995) is the major terrestrial source of water and sediment for the Laptev Sea.

This delta, the largest in the Arctic (WALKER, 1998), is characterized by a complicated structure, and is poorly studied and unique in many respects. The Lena River drains into the sea at a pronounced protuberance in the coastline that occupies an area estimated at between 28,000 km² (REINECK and SINGH, 1980) and 32,000 km² (ANTONOV, 1967; MIKHAILOV, 1997 Figure 1). On small-scale maps this huge bulge truly appears like a delta protruding far into the sea, but remnants of Pre-Holocene plains and Devonian bedrock outliers actually occupy about 40% of the area. The modern delta occupies only the area between a group of older islands of various origins and relatively small areas prograde into the open sea. The pattern of main distributaries evidently is controlled by the underlying geology. The delta is characterized by high seismicity (AVETISOV, 1975; KOZMIN, 1984; IMAYEV *et al.,* 1996). Although the sediment load has been measured for many years, the percentage actually reaching the sea is controversial. Intensive erosion and accretion is observed within the delta (ARE, 1985), but whether it actually is advancing today is unknown. The origin and age of older parts of the "deltaic bulge" are debatable. One part—the Arga-Muora Sise Island, for brevity Arga Island (Figure 1), is characterized by typical lake-thermokarst relief. But the underground ice needed for formation of such relief still has not

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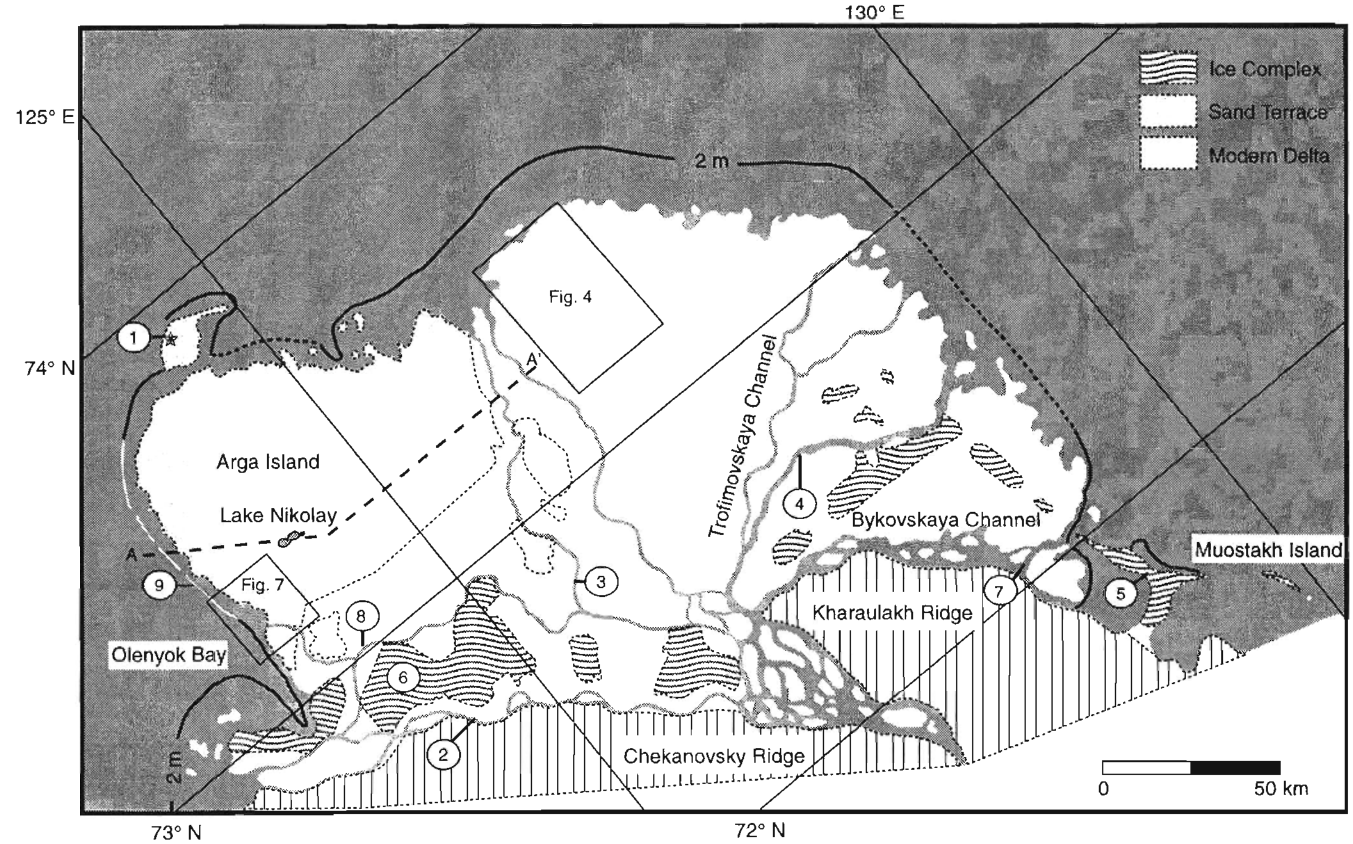

Figure 1. The Lena River Delta, showing the location of the Arga Island water shed and topographical profile A-A′ (see Figure 9). Numbered items are: (1) Dunay Island polar station, (2) Olenyokskaya Channel, (3) Tumatskaya Channel, (4) Sardakhskaya Channel, (5) Bykovsky Peninsula, (6) Khardang Island, (7) Dashka Crossover, (8) Arynskaya Channel, (9) barrier islands.

been observed. The depth of lakes is much larger than that of typical thermokarst lakes.

In this paper we review all available geologic and hydrologic data on the Lena Delta and show directions and promising approaches for future investigations within the frame of Land-Ocean interaction studies.

GEOLOGICAL BACKGROUND

Three different, non deltaic geomorphological units are distinguished within the delta area (KOROTAEV, 1991; GRIGORYEV, 1993): A) Outcrops of Devonian bedrock, too small to be shown in Figure 1, B) Remnants of a 20–60 m high coastal plain composed of ice complex (perennially frozen fine-grained Quaternary sediments with large ice-wedges and very high ice content), and C) A sand terrace 20–22 m-high with low ice content (Figure 1).

The occurrence of unit B, crossing the delta in a zig-zagging chain of mesas of different sizes, is a striking visual phenomenon when seen on satellite images or as shown in Figure 1. The usual lake-thermokarst relief covers the surface of these islands. The unit is underlain by sands of Mid-Quaternary age (GALABALA, 1987). On Khardang Island (Figure 1), its base lies slightly below sea level, while 100 km to the South-East in the delta apex it lies 30 m above sea level. On Bykovsky Peninsula (Figure 1) the base of unit B is depressed at least 10 m below sea level (GRIGORYEV, 1993). A review of radiocarbon age determinations by GRIGORYEV (1993) indicates that unit B in the delta was formed during the Upper Pleistocene, most likely between 45 and 12 thousand years BP.

Unit C is represented by several islands in the north-western part of the delta area (Figure 1). The largest of these is Arga Island (100 × 75 km). The origin of unit C is debatable. According to prevailing viewpoints it is composed either of marine deposits (VASILENKO, 1963; IVANOV, 1970; LOMACHENKOV, 1971; KOROTAEV, 1991; MIKHAILOV, 1997) or alluvial plain deposits (GUSEV, 1960; LUNGERSGAUZEN, 1966; GALABALA, 1987; GRIGORYEV, 1993). The first viewpoint is based on geomorphologic considerations and has no geologic basis. The second one is supported by the facts that unit C is composed of freshwater sand lacking a marine microfauna, but contains freshwater diatoms (IVANOV, 1972; GALABALA, 1987).

GALABALA (1987) considers unit C typical for shallow deltaic deposits and emphasizes that its composition is very similar to that of the Bestyakh series, widely distributed in the

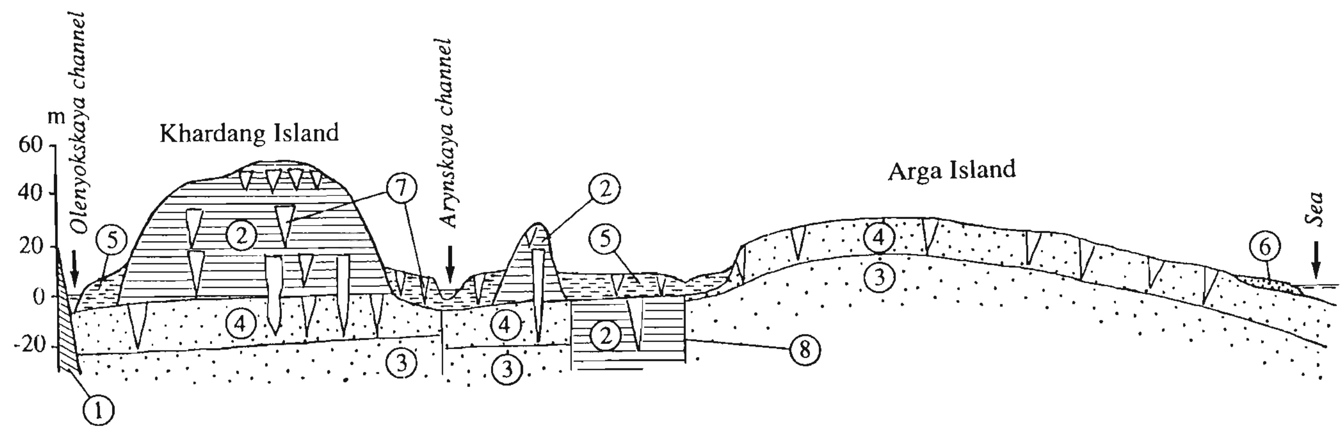

Figure 2. Shallow Quaternary stratigraphy of the western Lena Delta, simplified after GALABALA (1987). Numbered items are: (1) bedrock, (2) ice complex, (3) Muorinskaya series, (4) Turakhskaya series, (5) deltaic sediments, (6) Holocene marine sediments, (7) ice wedge, (8) fault.

lower and middle reaches of the Lena River. GRIGORYEV (1993) believes that unit C is of fluvial origin. Thus Arga Island and other smaller sand islands of the same elevation most probably are remnants of a Lena River alluvial fan.

Knowing the age of units B and C is necessary for understanding the modern structure of the delta. Early studies suggested that unit C is younger than unit B and is overlapping the latter (GUSEV, 1961; IVANOV, 1970, 1972). But the contact between these two geological bodies was never observed. Subsequently GALABALA (1987), based on aerial surveys and drilling, concluded that unit C is underlying unit B (Figure 2), and therefore is older.

The upper ~30 meters of unit C were investigated by GALABALA (1987). He divided this section into two sub-units. The lower one, never fully penetrated, he named Muorinskaya, the upper one, 15 to 20 m thick, he named Turakhskaya (Figure 2).

Muorinskaya is texturally rather homogenous with typical deltaic horizontal and inclined bedding. The Turakhskaya subunit differs from Muorinskaya by its non-homogenous texture, by the presence of layers with plant remains and peat, and by the presence of ice wedges. GALABALA believes that both units accumulated in the Mid- and Late-Pleistocene.

According to KOLPAKOV (1983), unit C occurs also far upstream of the delta in the Zigansk area, where it overlies morainal and periglacial eolian deposits of the Samarovo Glaciation (Riss), and in turn is overlain by Zyryanka (Würm) morainal deposits. This stratigraphy suggests that large amounts of denudation products were deposited in the Lena Basin during the Samarovo Glaciation. These were brought to the Lena River valley during interglacial time by increased precipitation.

GALABALA's conclusions, based on considerable geologic evidence, are rather convincing, but raise some questions. Thus we ask why unit B overlying unit C along the right bank of Olenyokskaya channel is absent on Arga Island? We also ask why the remnants of unit B are divided into a series of mesas by delta channels and why these mesas have such a peculiar aerial pattern? To answer these questions, tectonics of the area have to be considered.

ALEKSEEV (1961) noted that Olenyokskaya and Bykovskaya channels flow along a Cenozoic fault line. According to KIRYUSHINA *et al.* (1961), the Lena Delta with its high seismicity is characterized by vertical block movements. LUNGERSGAUSEN (1961, 1966) suggests that the modern structure of the Lena Delta was controlled by Late-Quaternary tectonic movements. The continuation of a sub-longitudinal rift occupied by the lower Lena River divides the western from the eastern delta. These viewpoints, at the time based mainly on geomorphologic evidence, now are supported by seismic data. Thus a map of earthquake epicentres and magnitudes in the Lena Delta area (Figure 3) shows their alignment with the Gakkel Ridge crossing the Arctic Basin. According to KOZMIN (1984), 26 earthquakes have been recorded in the delta and its vicinity from 1909 to 1980. Later compilations of seismic data (FUDJITA *et al.,* 1990; GORDEEV *et al.,* 1996), emphasise that earthquakes occur along the boundary between the North American and Eurasian tectonic plates. The latest compilation of seismic data by IMAYEV *et al.* (1996) shows pronounced clustering of mainly small earthquakes along a NW/SE trend crossing the delta (Figure 3). This clustering of seismic events generally coincides with the zone of mesas in which unit B crops out. It also coincides with two major river distributaries which occupied previously existing long estuaries (KOROTAEV, 1991). The strongest earthquake recorded in the delta region had a magnitude of 6. The modern seismicity indicates that tectonic movements are taking place now.

The active role of tectonism in the evolution of the Lena Delta recently was supported by drilling and outcrop studies conducted by GALABALA (1987) and GRIGORYEV (1993). These investigations suggest vertical movements locally exceeding 60 m. The continued involvement of tectonism in the evolution of the delta until the present is indicated by the linearity of a channel, recorded in a SPOT satellite image in 1996 (Figure 4). Under natural conditions, water flowing on

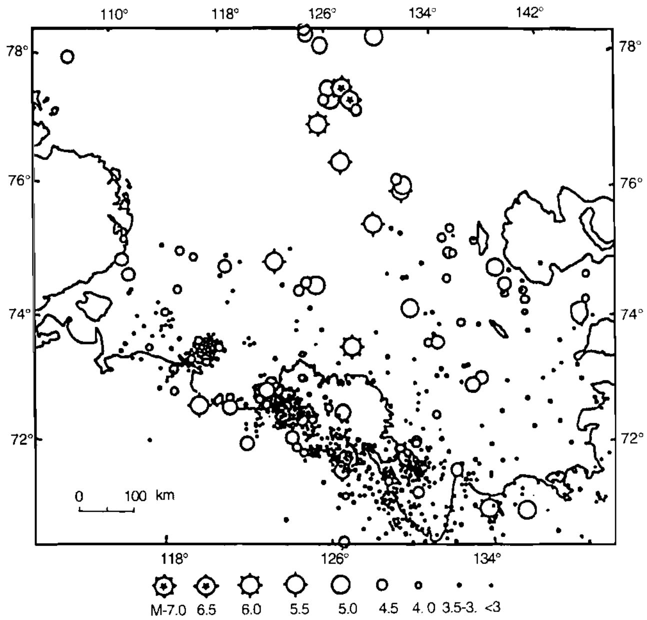

Figure 3. Earthquake epicenters in Laptev Sea area with magnitudes (M) identified (IMAYEV *et al.,* 1996).

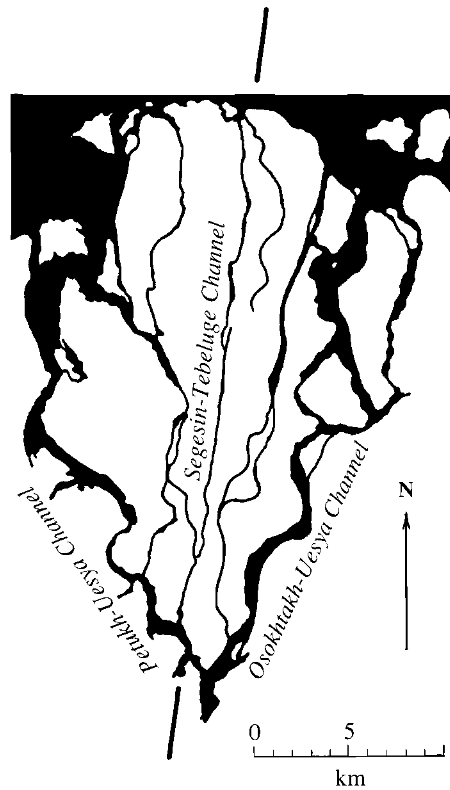

Figure 4. The rectilinear Segesin-Tebelyuge Channel, surrounded by freely meandering channels typical for the Lena River Delta, as traced from a SPOT satellite image of 7-10-96. The linearity of the channel suggests fault control. See location in Figure 1.

a horizontal surface does not follow such a straight course for nearly 30 km. Similar linear channels are observed elsewhere in the delta.

We believe that knowledge of the Lena Delta structure, though limited, may help understand the history and present conditions in the eastern Laptev Sea. Thus the origin of Dm. Laptev Strait, separating B. Lyakhovsky Island from the continent, can not be explained by activity of a paleo river, as there is no evidence for such a river. However, according to GRIGORYEV *et al.* (1984), the strait follows a graben. Most probably the existence of the New Siberian Islands overlain by an ice complex (unit B) is caused by tectonism. Semyonovsky, Vasilyevsky and other small islands, which were totally eroded during historical times, represent separate uplifted blocks. Zemlya Bunge, consisting of sand, seems to be an uplifted block like Arga Island. At Tiksi, near Muostakh Island (Figure 1), sealevel has been observed to be rising 1 mm/yr, while at the NW tip of the New Siberian Islands, near the shelf edge, a rise of 5 mm/yr was recorded over several decades (DVORKIN and MUSTAPHIN, 1989). These values were calculated from measured relative sea level changes, where the effects of meteorological tides and of water-density changes due to temperature and salinity variations have been eliminated. The change at Tiksi therefore corresponds to world-wide eustatic sealevel rise, indicating that this particular block of the delta now is stable.

LENA DELTA CONSTRUCTION—A LIKELY SCENARIO

Knowledge of unit B (ice complex) distribution on the emerged shelf during transgression is important to understand the most recent development of the Lena Delta area. Most scientists agree that ice complex developed on vast territories simultaneously, covering most of the shallow shelf at the beginning of the last transgression. Therefore, the highly variable regional pattern of unit B-elevations in the Lena Delta area was created by tectonic processes after the beginning of ice-complex formation and continuing until today. During Mid-Holocene the rapid transgression had flooded lower parts of the delta, while the submerged parts of unit B underwent thermal and mechanical erosion. As a result, only the remnants of elevated parts are preserved now. The zigzag pattern we discussed is due to differential vertical movement of separate blocks. For example, according to recent investigations, the near-longitudinal chain of small ice complex remnants near the eastern edge of the delta, including Bykovsky Peninsula and Muostakh Island, are located along the western edge of the Ust' Lena rift (DRACHEV *et al.,* 1999).

Much more problematic is the lack of unit B on Arga Island. We can think of only two possible explanations: (1) the ice complex was destroyed, and thereby eliminated from the island surface, or (2) it never formed there. With an Upper Pleistocene age, unit B should have been subjected to the transgression. To us, its total destruction by the transgression, leaving no trace even in the deep thermokarst lake depressions, followed by >20 m uplift in the second part of the Holocene, seems unlikely. More probable is that unit C on

Arga Island experienced uplift in the Middle Pleistocene and therefore could not be covered by unit B.

During middle Holocene time, when the transgression reached the flanks of Chekanovsky and Kharaulakh Ridges (Figure 1), flooding produced a large-scale, complicated multi-lobate estuary across the mouth of Lena River. Adjusting to the new sea level, the Lena River began filling the estuary with sediments and building its modern delta. Intensive erosion of islands composed of unit B also started at that time.

A detailed description of the Lena Delta evolution during Holocene is given by KOROTAEV (1984, 1991). The modern delta consists of four main, hydrologically separate parts. The Olenyokskaya channel area (Figure 1), between Chekanovsky Ridge and an uplifted massif of unit B, was an estuary 180 km long and 3–15 km wide when the transgression had reached the ridge. According to KOROTAEV (1984, 1991), it now is nearly completely filled with river sediments, and seaward migration of sand islands in its mouth occurs at an average rate of 15 m/yr. Progradation of the delta into Olenyok Bay should also begin, however, no advance of the sand bar across its mouth was observed during the last 30 years.

Another, about 100-km-long and 14 to 34-km-wide estuary existed between the flanks of Kharaulakh Ridge and a massif of unit B along modern Bykovskaya Channel (Figure 1). According to KOROTAEV (1984, 1991), this estuary is still not entirely filled with sediments. The delta in Bykovskaya Channel mouth today is beginning to protrude into the open sea.

The third and largest estuary was in the area of modern Tumatskaya-, Trophimovskaya- and Sardakhskaya Channels (Figure 1). This estuary was bordered by the uplifted massifs of units B and C in the west and by unit B massif in the south. This vast area is being filled by a multi-lobate delta now, prograding into the open sea.

The fourth part initially was a wide sound between the unit B massif situated along Olenyokskaya Channel and Arga Island. Now this sound is filled with sediments and drains through Arynskaya Channel (Figure 1).

Radiocarbon dating shows that the modern Lena Delta has been built during the second half of the Holocene. The total advance of the delta during this time was 120–150 km according to KOROTAEV (1984, 1991).

SEDIMENT DYNAMICS IN THE MODERN DELTA

The Lena River is considered the main sediment source for the Laptev Sea (ALABYAN *et al.,* 1995), but no direct measurements were made along the delta front.

Measurements of suspended sediment were made during last decades at Kyusyr about 150 km upstream from the delta apex. But the quantitative evaluations of suspended sediment transport made by different investigators using the same original data sets range from 11.8 to 21 Mt/yr (DORONINA, 1962; ALABYAN *et al.,* 1995; IVANOV and PISKUN, 1995, 1999; CHALOV *et al.,* 1995; GORDEEV *et al.,* 1996). We have no explanation for this diversity in transport estimates.

IVANOV and PISKUN (1995) point out the need for special investigations to determine the amount of sediments actually entering the sea. ALABYAN *et al.* (1995) state, only 2.1–3.5 Mt/yr of the total 21 Mt/yr of the suspended load measured at Kyusyr enter the sea, but do not document this extremely important statement. KOROTAEV (1991) believes that about 30% of Lena River suspended load reaches the sea, but again shows no supporting data.

ANTONOV (1967) and IVANOV and PISKUN (1995) report that water turbidity in the distributary channels of the delta is considerably higher than in the main channel up-stream due to shore erosion and eolian processes in the delta. However, later investigators contradict this. Thus ALABYAN *et al.* (1995) report water turbidity at Kyusyur to average 40 g/m^3, while GORDEEV *et al.* (1996) give the average as 34 g/m^3. According to KOROTAEV (1991) the water turbidity in the upper reach of Bykovskaya channel ranges from 21 to 24 g/m^3 and decreases down stream to as low as 10–12 g/m^3 due to intensive sedimentation, mainly approaching the Dashka shoal area (Figure 1).

No data on Lena river bed load transport are available, even though this component of the sediment supply may be important. Thus, SAMOYLOV (1952) reports that summer bed load transport is considerable because of high flow velocities, and therefore the islands in the delta are composed mainly of sand.

IVANOV (1967) studied sediment transport and bottom dynamics in Bykovskaya Channel for navigational purposes. He states that due to high flow velocities the channel floor along the fairway is composed of sand. Sand with a mean diameter of 0.58–0.74 mm prevails over the first 48 kilometres of the channel from the apex. The near-bottom velocities here range from 0.63–0.81 m/s. Still further downstream at a shoal, velocities increase to as high as 1.5 m/s and the floor is composed of gravel. Approaching Dashka shoal (Figure 1) between 54 and 70 km from the apex, sand with a mean diameter from 0.59–0.83 mm is observed where flow velocities are 0.53–0.93 m/s. Below Dashka Shoal, channel beaches are composed of silty sand having a mean diameter of about 0.01 mm. In Neelov Bay the floor is covered by silt and beaches are composed of silty sand.

ANTONOV (1967) believes that bed load exceeds suspended load in the Lena River, and MIKHAYLOV *et al.* (1986) state that the river mouth bars, composed of sand and silt, are mainly the results of bed load accretion. Furthermore, the mouths of the main distributary channels are bordered by bars along the 2 m isobath (KOROTAEV, 1991), which almost certainly are composed of sand. ANTONOV (1967) also believes that river ice transports considerable amounts of sediments, and therefore total sediment loads of the river based only on suspended load measurements underestimate the total load. But this may be true only for transport within the river because according to the same author almost all river ice thaws in the delta before reaching the sea.

Our short review of published data about Lena River sediment yield causes us to give support to the statement by IVANOV and PISKUN (1995): special investigations are needed to determine the amount of sediments actually introduced into the sea from this river.

Comparing information available on the sub-aerial Lena Delta and channels with general knowledge of low-latitude deltas does not indicate any major differences, except that

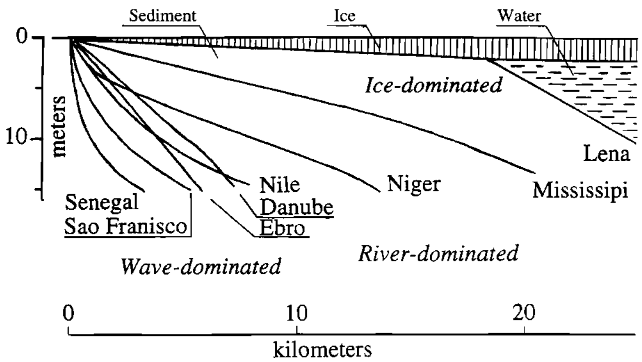

Figure 5. A comparison of prodelta profiles for ice-dominated Lena River and various open water rivers, ranging from wave dominated to river dominated (after ALPHA and REIMNITZ, 1995). Note the conformity of the shallow ramp to the base of the fast ice.

the delta plain has no natural levees along channels. However, the submerged parts of the active delta have a peculiar shape which is very different from those of mid- and low-latitude deltas, here having a pronounced break in slope at the 2-m isobath (Figure 5) as far as 18 km from shore (ALPHA and REIMNITZ, 1995). This <2-m deep terrace is referred to as the "ramp". KOROTAEV (1991) reports that the large Trofimovskaya channel delta is bordered by submerged and emerged bars along the 2-m isobath. A good example of a ramp in an ice-dominated delta is based on extensive drilling and bathymetric measurements made by GRIGORYEV (1966) for the Yana River Delta (Figure 6). The 2-m ramp has long been a puzzle to investigators in the Alaskan Arctic.

Ice bonded permafrost is known to underly Arctic shallows with less than 2-m water depth, because here at the end of winter 2-m thick fast ice rests on the sea floor. The active layer becomes frozen and ice fuses with the bed. Various types of satellite images of the Lena River Delta during Spring flooding of the adjacent fast ice clearly show that the ramp is well developed. Flooded ice on the ramp remains submerged for a week or longer, while ice over deeper channels has risen to the surface. We therefore conclude that the 2-m ramp is a typical feature of Arctic river deltas.

SEA-SHORE DYNAMICS

KOROTAEV (1984, 1991) reports that a 15–30-km-wide zone of islands 400–1000 years old and as high as 3 m above sea level represents the modern advancing front of the delta plane. The lowest parts of these islands, less than 0.5 m high, are sparsely vegetated. This evidence supports DANILOVA (1965), who wrote that at the mouth of Trofimovskaya Channel water depth do not exceed 1 m for several kilometres seaward. The shore and shore face are composed of silty sandy loam and fine-grained sand with sparse interbeds of loam, and advance rapidly. GRIGORYEV (1993) also notes rapid advance of the shore-line near the mouths of large distributary channels. But there is no reliable data on the rates of shoreline advance.

However, the 1:200,000-scale topographic maps do not give unconditional support for delta advance. For example, the mouth of Olenyokskaya Channel is bordered by a 15-km-wide belt of young sandy islands. Here the advance is convincing. But along the East and North-East coast of the Lena Delta the number of such accretion forms is small. Near the mouth of large Tumatskaya Channel, the map shows bluffs as high as 3 m, suggesting erosion. In some places huts of natives stand on the very coast, suggesting it can not be advancing rapidly. Here we cite HARPER (1990) writing about the Mackenzie Delta, a large sediment source for the Arctic Ocean: "major parts of the Mackenzie River delta front retreat at rates between 2.1 and 6.1 m/yr". Thus the question of advance and retreat of the modern Lena Delta front is disputable.

The configuration of Arga Island coast is extremely complicated because the floors of numerous coastal lakes are below sea level. As the sea occupied the chains of lakes at the end of the last transgression, an intricate "lace pattern" of bays and beaches penetrating deeply into the land developed (Figure 7).

Most of the marine energy of ocean shorelines is consumed in straightening these. While the capes are being truncated, bays are filled with sediments or transformed into lagoons. For example, the sea entered three lakes on the south coast of Bykovsky Peninsula with mean diameters of <2 km. Coastal erosion transformed these lakes into lagoons separated from the sea by spits that are cut by narrow tidal channels. The lagoons with stable shores trap driftwood.

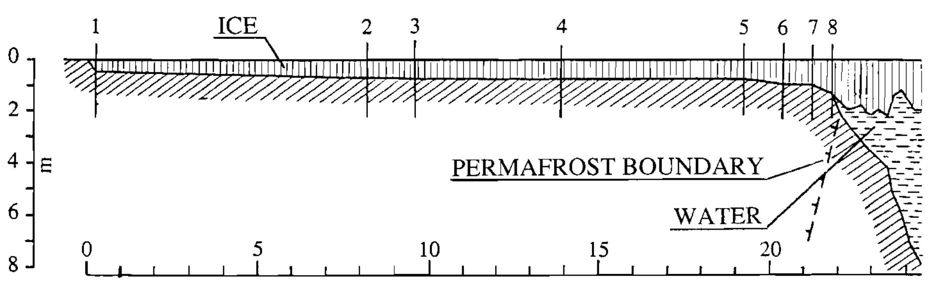

Figure 6. Yana River prodelta profile after GRIGORIEV (1966). 1–8 show boreholes. The thickness of ice and the water depths seaward of borehole 8 are based on 18 measurements.

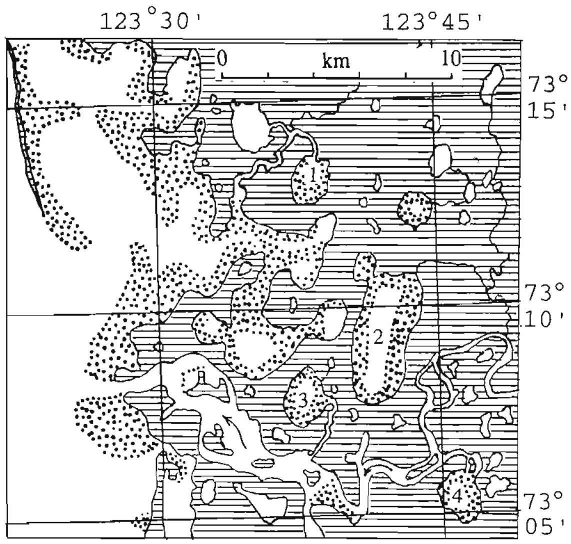

Figure 7. A section of lace-shore on the west coast of Arga Island (see location in Figure 1). The dotted areas represent shallows that probably are largely less than 1-m deep. Numbers 1–4 identify lakes discussed in the text.

Land-sea interactions along the Arga coast are quite different. No single lake breached by the sea has become a lagoon. Before the transgression, the chains of lakes were connected by rather narrow valleys occupied by small drainage streams. Now the borders of these former valleys are sandy beaches along estuaries undergoing shore erosion. The estuaries are transformed into wide sounds locally leaving no trace of the former lake pattern. Expansion of the bays of Arga may be explained by their special hydrological regime controlled by storm surges, while astrological tides are small. According to ASHIK *et al.* (1999), the amplitude of surges of northern Arga reaches 3 m and in Olenyok Bay 3.5 m. The maximum rise of sea level, recorded along the exposed coast at polar stations Dunay (Figure 1) and Terpiay-Tumsa (120 km W of Arga Island), is 1.9 and 2.3 m, respectively. A picture taken about 24 hours after a severe storm (Figure 8) shows a bluff with an erosional niche along Arynskaya Channel (Figure 1), 18 km upstream from its mouth in the western Delta. Using the 1.7-m-tall man as a scale, the height of the surge responsible for the niche is estimated at >2.5 m. Wind-driven surges at the heads of bays penetrating deep into Arga are probably higher. With surges continuing through the period of ice cover (ASHIK and VANDA, 1995), the bays of Arga undergo recurrent flushing. Strong currents occur in narrow straits, especially a drop of sea level after a surge, or when part of the channel cross-section is occupied by a thickening ice cover. The currents cause erosion of shores and sediment transport from bays into the sea. In spite of general sediment export from estuaries after surges, accretion also has to take place in the deep hollows of former lakes. The expanding sea surface inside the bays increases fetches and thereby wave erosion. The end result is that the Arga coast is being eroded not only on capes but also inside of bays. Since the eroded sediments are sand, these processes provide a large sand volume for the delta.

The western lace coast of Arga is separated from the open sea by a ~70-km-long chain of barrier islands with only five narrow tidal inlets. The very southern part of this chain is shown in Figure 7. The height of the barrier islands is mainly less than 2 m above sea level. According to topographic maps, what seem to be true barrier islands are only 100 to 250 m wide, but a number of the islands are several kilometer-wide sand flats. Therefore storm surges inundate all but the highest parts of the islands. Their seaward side is smoothed by waves and is located about 5 km from the lace coast. The sandy beaches along the mainland shore, like the islands, also are very wide (0.5 to 1 km) for Arctic conditions, indicating an excessive sand supply.

The 70-km long and as much as 5-km-wide lagoon has a very complicated form. Similar shores do not exist elsewhere in the Laptev Sea. For understanding the origin of these shores, the fact that elevations of an east-west profile along the water divide do not decrease toward the sea (Figure 9), is important. Here the height of bluffs is 20 m. However, seaward of the barrier chain and 10 km from the bluffs, the water depth reaches 10 m and continues to increase seaward. We believe that the 20-m-high sand bluffs with low ice content could not have retreated more than 5 km during the last 5000 years, when sea level had approached its present position. At that time, the sea started attacking a rather steep, sandy shore face backed by high cliffs of the tectonically uplifted Arga Island, thus introducing large amounts of sand into the sea. Long-shore transport was unable to remove all of this material, and therefore the wide barrier islands and beaches were created.

Figure 7 illustrates some of the processes described. Maps show water levels for lakes #1, 3, and 4 at between 0.2 and 0.8 m above sea level. The distance of these lakes from the sea or from a large estuary-like channel along the drainage streams ranges from 4 to 8 km. Storm surges therefore easily reach these lakes. As a consequence, drainage channels are eroded by the sea and have widths as large as 200 m. The valleys of the streams are widened correspondingly. The surface of lake #2 is 2 m above sea level, and the distance to the nearest estuary is 24 km and to the sea 37 km. Storm surges therefore do not reach this lake, and as a consequence the streams draining such lakes are not wider than 10–15 m and flow in correspondingly narrow valleys.

The sea along the north coast of Arga is shallow compared to the west coast. With the mean height of cliffs being only about 10 m, the amount of sand introduced by coastal retreat is less than along the west coast. This may be the reason why barrier islands are largely lacking here.

RELIEF OF ARGA ISLAND

After brief examination the relief on Arga Island seems typical for lake-thermokarst terrain, which is well known from arctic plains composed of unit B, still widely distributed between lakes. Thawing of excess ice in unit B between lakes would correspond to thaw settlement, which is similar to the depth of lake depressions. Relief of the depression floors is

Figure 8. Twenty-four-hour old and ~2.5-m-high storm-surge niche 18 km upstream from the mouth of Arynskaya Channel on the West coast of the Lena Delta (see Figure 1), August 1982.

rather low suggesting lateral uniformity within unit B. The deepest parts of lakes usually are characterized by stretched curvilinear forms that occur along the base of slopes bordering lake depressions.

The general floors of many large lakes on Arga Island, however, do not have low relief but instead deep central hollows. The depth of these hollows relative to the general depth of depressions below the island surface sometimes exceeds the latter. For example, the generalized floor of Lake Nikolay, the largest on Arga, is as much as 10 m below the island surface, but its central hollow lies 27 m below that (Figure 9). The surface area of lakes is always much larger than that of their hollows, which usually are surrounded by platforms as wide as 1 km covered by less than 1 m water.

The lake depressions, lakes, and the streams draining them, are oriented from about 2 to 8° T. This is normal to the general trend of the water divide A-A′ (Figure 1) or along the slope of the Arga surface. According to GUSEV (1960), the

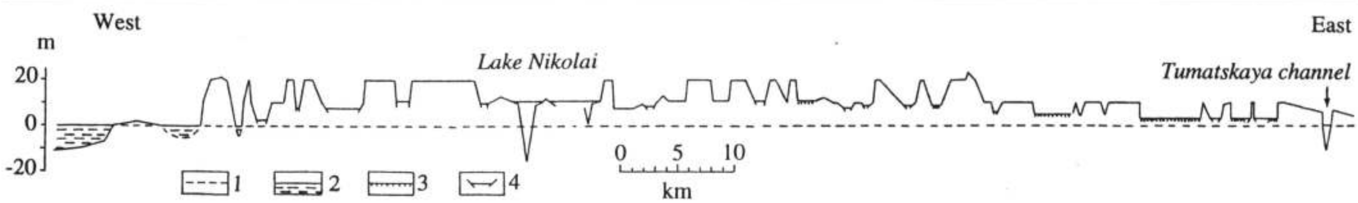

Figure 9. The topographical profile of Arga Island along the water shed A-A′ shown in Figure 1. Numbered items identify: (1) sea level, (2) Laptev Sea, (3) drained lake, (4) lake.

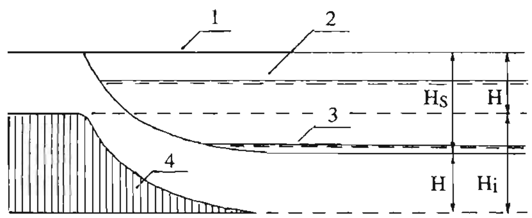

Figure 10. Evolutional scheme for a thermokarst lake depression. Numbers and letters identify: (1) initial earth surface, (2) water level in growing depression, (3) water level in drained, stabilized depression, (4) underground ice layer, (H_i) thickness of underground ice layer equal to thaw subsidence value H_s, (H) thickness of subsided sediment layer.

sides of hollows are as steep as 45°, but the latest depth profiles across Lake Nikolai (SCHWAMBORN *et al.*, 1999) show slopes of about 26°. GUSEV (1960) notes that the flanks of elongated hollows meet at their southern ends at acute angles, as observed on aireal photographs.

The geological causes for the relief of Arga Island and that of unit B (ice complex) on Arctic coastal plains are quite different. Arga Island sands locally contain single units <2 m thick of segregated ice layers 0.1–0.3 m thick interbedded with sand layers. Two systems of epigenetic ice-wedges occur together in the upper section. The largest one is represented by wedges about 10 m high and 0.3–1.0 m wide at the top. The surface polygons formed by these wedges are as much as 12–15 m across. Inside of this system there is a smaller set of ice-wedges <0.25 m wide at the top (GRIGORYEV, 1993). According to his calculations, the thawing of Arga Island sands can not cause subsidence of over 3.5–7.0 m, and therefore can not explain the formation of lake depressions 10–35 m deep.

The Arga area is not the only place where the described relief in sand is observed. Thus GUSEV (1960) notes that the remnants of similar sand terraces occur in the deltas of the Olenyok, Omoloy, Yana and Chondon Rivers. The same relief also is widespread on sand terraces of the Yamal Peninsula in West Siberia. Its origin remains a major puzzle of modern geomorphology.

To us the only likely mechanism for the formation of lakes on Arga Island is through thermokarst processes, either involving ice bodies that still remain to be found or large ice bodies of the past which have melted away. Lateral expansion of thermokarst depressions occurs due to erosion of shores and thaw subsidence of submerged permafrost (ARE, 1988). Once started, the growth of depressions may stop either because (1) the underground ice body or ice-rich sediments have thawed out, or (2) the thermokarst lake drained, the shoreline retreated from the base of bluffs and therefore the thermal and mechanical influence of lake water on permafrost stopped. In the first situation only small remnants of ice may be preserved. Figure 10 illustrates the second situation for the vast ice layer which stopped thawing because of lake drainage.

Geophysical methods probably are the most promising technique for finding such remnants of ice on Arga Island. The chances to find remnants probably are better on the slopes of Arga than along the water divide, because here most lakes already have drained.

GUSEV (1960) believes that platforms surrounding central hollows in the lakes are abrasion terraces, their area increasing with time. According to GRIGORYEV (1993), wave activity plays the main role in the process. We believe that Arga Island lakes are degrading. Precipitation in this area exceeds evaporation. Because the earth surface is nowhere horizontal, the water overfilling the lakes spills, and in the process erodes channels. As the sill over which a channel spills is lowered by erosion, the lake level begins to drop, its surface area decreasing. The relatively flat bottom of the lake emerges, as shown in Figure 10. The lakes on Arga Island fit various stages of the processes described.

Many large lakes occur along the Arga Island watershed. They occupy the largest parts of the lake depression area, with shorelines not far from the side slopes. This is due to poor drainage on nearly horizontal terrain (Figure 9). On the slopes away from the divide, especially the northern ones, many lakes have drained to the point that most of their bottoms are emerged and swampy during summers. Along the main streams flowing northward, the original lake-thermokarst relief already is partly to totally destroyed.

CONCLUSIONS

All available information reviewed suggests that the unique structure, shape, and relief of the Lena River Delta, setting it apart from other Arctic deltas, are caused by tectonism. The delta is a striking example of the influence of vertical tectonic movements not only on Upper Pleistocene depositional units but also on Holocene relief and the modern hydrological processes of a delta.

The absolute majority of investigators believe that ice complex accretion took place on the entire shelf. Until factual evidence becomes available, this remains the most probable assumption. Accepting this viewpoint would allow explaining the peculiar distribution of ice complex remnants in the delta area by vertical movements of separate blocks. We believe that accretion of the ice complex in the delta area, continuing until the beginning of the Holocene, occurred on a surface considerably below modern sea level. The ice complex never accreted on some uplifted blocks, like Arga Island. Some blocks capped by ice complex were submerged and buried under deltaic sediments, others were uplifted above modern sea level and therefore preserved. A large part of ice complex, located close to sea level, was eroded. To prove or disprove this hypothesis, establishing the age of the Muorinskaya and Turakhskaya Series would be necessary. Formation of the modern Lena Delta began during middle Holocene inside of an archipelago created by vertical tectonic block movements. The filling of the space between the islands with deltaic sediments is still incomplete, and the delta just begins to protrude into the open sea. During the second half of the Holocene the total advance of the delta within the archipelago was 120–150 km. The modern rates of advance into the open sea evidently are less, but not measured.

The values of suspended sediment load upstream from the delta apex calculated by different authors using the same basic data sets range from 11.8 to 21 Mt/yr. Nothing is known about bed load transport nor actual sediment discharge into the Laptev Sea. Some Russian investigators believe that 70–90% of Lena River suspended sediments load is deposited within sub aerial parts of the delta and on flood plains and only the small rest reaches the sea. But there is no reliable factual evidence for these statements.

The modern sub aerial Lena Delta is bordered by an up to 18-km-wide shallow platform which turns into a relatively steep slope at the 2 m isobath. This feature is observed only on Arctic river deltas and is not understood.

A unique lace coast, formed by the interaction of the sea with a sand body dotted by deep lakes, fringes Arga Island. Due to meteorological tides of over 2 m amplitude, coastal erosion occurs not only on the capes but also inside narrow bays penetrating inland by several kilometres. Therefore the usual straightening of sinuous shorelines by the sea is not taking place here. Coastal erosion supplies very large volumes of sand to the sea. Neither long-shore nor cross-shore transport can accommodate supply, and therefore the chain of barrier islands is created about 5 km from Arga Island. Considering the rather steep shore face of this barrier island chain, we suspect it is following the retreating Arga Island coast.

Arga Island relief is similar to typical lake-thermokarst relief, but so far no underground ice that could be responsible for the formation of this relief was observed. Also no evidence is available on the existence of corresponding amounts of ice in the past. Deep, uniformly oriented hollows in the center of lakes, surrounded by platforms as wide as 1-km that are covered by only 1 to 2 m of water, are not understood. The lakes on Arga Island are generally degrading and the thermokarst-like relief is undergoing denudational destruction, especially on the northward sloping island surface.

In summary, the Lena Delta is characterized by numerous unique features that are either poorly understood or remain unexplained. The delta therefore presents opportunities for answering a vast array of significant questions about continental margin geodynamics and land-ocean interaction in the Arctic.

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