

Morphodynamic Types of the Laptev Sea Coast: A Review

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Abstract: The Laptev Sea coast has a unique high-latitude and dynamic landscape. The presence of low-temperature permafrost (below -7°C) and its high ice content (up to 90%) determine a wide array of permafrost landforms and features. Under the actions of thermal abrasion and thermal denudation, high rates of coastal retreat are evident within this region. Local differences in the geological structure and sea hydrodynamic conditions determine the diversity of this sea coast's types. In this review, we present the results of a morphodynamic classification and segmentation of the Laptev Sea coast. The integrated approach used in the classification took into account the leading relief-forming processes that act upon this coastal zone. The research scale of 1:100,000 made it possible to identify and characterize the morphologies of the coast and their spatial distributions within the study area. The presented original classification can be considered to be universal for the eastern Arctic seas of Eurasia; it may be used as a basis for further scientific and applied research.

Keywords: Arctic coasts; thermal abrasion; thermal denudation; coastal dynamics; thermoterrace; permafrost; ground ice



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1. Introduction

The Arctic coasts are characterized by specific permafrost, hydrological and climatic conditions. Permafrost coasts are extremely dynamic natural objects that are highly sensitive to climate change in the Arctic [1]. Warming, including the summer air temperature rise, leads to an increase in the active layer thickness, resulting in intense destructive cryogenic relief-forming processes on the Arctic plains [2–8] and its coastal dynamics [9–12].

The Laptev Sea coasts on the north of Yakutia are located within an area of continuous permafrost, with a mean annual ground temperature below -7°C [13]. Ice-rich frozen Quaternary deposits, which contain significant amounts of organic matter and vast ice wedges, the so-called Yedoma Ice Complex [14], are patterned widespread [15,16] (Figure 1). The former plains comprising the Yedoma Ice Complex left remnants on its surfaces that have been eroded by thermal denudation, thermal erosion and thermokarst. The Holocene deposits are very widespread, and have different geneses. In river valleys, alluvial deposits form the floodplain and the first terrace above the floodplain; in the coastal zone, coastal-marine and lagoonal deposits form low marine terraces.

The high ice content, reaching 80–90%, and the significant thickness (10–40 m) of the Yedoma Ice Complex deposits cause rapid permafrost degradation. The melting of ground ice causes surface thaw subsidence [17], which results in declining elevations of up to several centimeters annually [10].

The permafrost coasts are more vulnerable to erosion than any of the other coasts of the world despite the fact that during most of the year, they are protected from wave action by sea ice. The reason for coastal retreat occurring within a short warm period results from

the action not only of mechanical wave erosion, also called abrasion, but also from thawing of the perennially frozen deposits, along with interactions with air and water temperatures above zero [9,10,18]. Therefore, there are two simultaneous processes acting on the coast: (a) thermal abrasion, as the combined thermal and mechanical impact of water on the foot of the coastal cliff, and (b) thermal denudation, as the thawing of permafrost deposits in coastal cliffs under the influence of air heat and solar radiation [9,10,18].

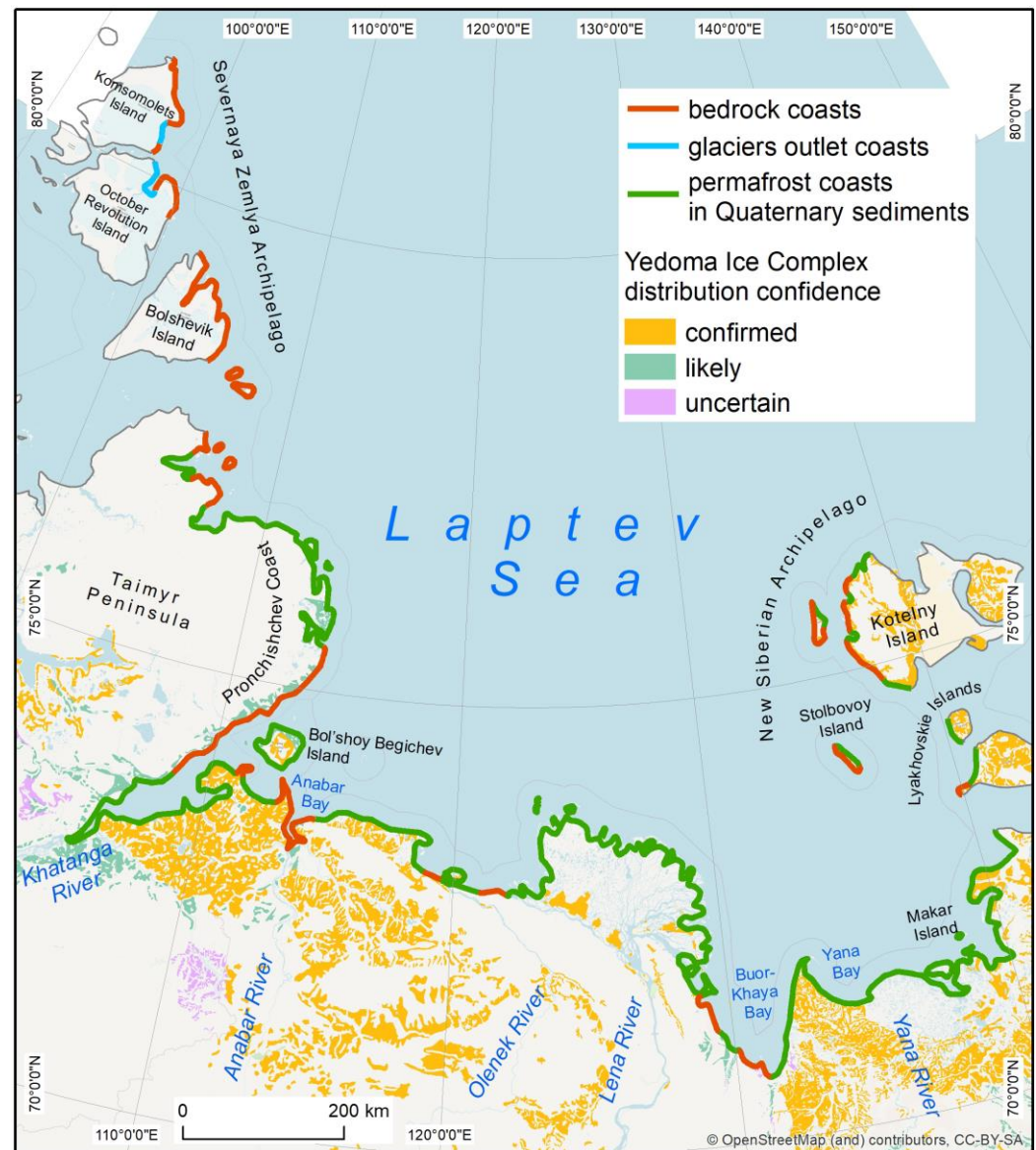


Figure 1. Map of the Laptev Sea coasts. Yedoma Ice Complex distribution areas and their confidences are indicated after [15,16].

Degradation of the ice-rich Yedoma Ice Complex results in the release of large amounts of previously frozen organic matter, carbon and nitrogen [19–23]. This, in turn, leads to local impacts on the riverine and coastal ecosystems, as well as global impacts through the release of greenhouse gases into the atmosphere [24,25].

The coastline of the Laptev Sea has a length of more than 10.5 thousand km, and includes the continental part and numerous islands that are located in the western and eastern parts of the sea. Coasts, formed both by bedrock and perennially frozen Quaternary un lithified sediments (Figure 1), are spread within the region [26].

Coastal erosion in the Arctic depends considerably on sea ice conditions. The waves are able to act on the base of the cliffs during the open-water season only, in summer and early autumn, when fast ice breaks down and the shoreface is free from ice [9,27–29]. At the same time, even in summer, drifting ice remains at some distance from the coastline, limiting the open water area, which limits the wave energy.

The maximum period of dynamic activity is confined to the eastern part of the Laptev Sea, where the warming effect of the river runoff is especially strong [2,27]. The longest open-water season in the western part of the Laptev Sea, comprising 20% of the year, or approximately 75 days. At the same time, there is a reduction in the extent of the sea ice as well as an open-water season increase in the Arctic and the Laptev Sea [30]. Sea ice reduction causes a growth in wave height and energy, which affect the coastlines [31,32].

The retreat rate of the Laptev Sea coasts in some parts of the coastline is up to the first tens of meters per year [9,10,33]. The coastal landforms are mainly determined by the presence of ground ice in coastal cliffs.

The peculiarities of the Laptev Sea coasts attract researchers and a wide range of readers. Widely known and discussed research topics include the disappearance of the Arctic islands of Vasilievsky, Semenovskiy, Diomed and Figurin, as well as the mystery of the existence of Sannikov Land. The search for this island was the goal of several polar expeditions [34–36].

The history of Laptev Sea research is also associated with the progress of navigation, and the search for and use of the Northern Sea Route. Among the most prominent historical research are the expeditions of the explorers Ivan Mercury Vagin, Yakov Permyakov, the Great Northern Expedition of 1733–1742, and the studies of Semyon Chelyuskin, Vasily Pronchishchev, Khariton Laptev, Ivan Lyakhov and Yakov Sannikov. Researchers noted the outcrops of permafrost in the coastal cliffs. A.E. Figurin, a member of the Ust'-Yana polar expedition under the leadership of P.F. Anzhu, related the vast ice-wedge bodies exposed in the coastal cliffs to the result of water freezing in frost cracks. A significant contribution to the pioneering research of the region was made by A.F. Middendorf, E. Toll and A. Bunge.

In recent decades, the most notable scientific results and new data in the study of the Laptev Sea coasts were obtained through long-term research conducted by the Melnikov Permafrost Institute of the SB RAS [2], complex research expeditions of the Faculty of Geography, Lomonosov Moscow State University in 1972–1978 [27,37], and a number of international expeditions within German–Russian Cooperation in the framework of multidisciplinary research program “Laptev Sea System” and “Lena Expeditions” [38] and “Arctic Coastal Dynamics” project, initiated by the International Permafrost Association and carried out on a cooperative basis with the International Arctic Science Committee [26].

Most of the research on the Laptev Sea coast was carried out on spatially separated local key sites. This limited the possibility of a comprehensive regional analysis that is necessary for segmentation and mapping the whole Laptev Sea coast as a system. The reasons for this are the inaccessibility and harsh climatic conditions of the region, which limit the possibility of studying the coast during the open-water season. The most studied sites are the coasts of the New Siberian Archipelago, Muostakh Island, Bykovsky Peninsula, islands in the Lena Delta, Vankina Bay, Mamontov Klyk Cape, Buor-Khaya Peninsula, etc. A number of these studies on the morphology and dynamics of the Laptev Sea coasts require integration and comprehensive analysis. A significant part of the coastline remains poorly studied in terms of its lithological, dynamic and morphological characteristics.

The aim of this study was to characterize the coastal morphology and relief-forming processes of the Laptev Sea on the basis of geomorphological segmentation and mapping of the entire regional coverage at a scale of 1:100,000. An important part of this study was the creation of an original morphodynamic classification that updates and unites the previous achievements.

2. Materials and Methods

The identification of permafrost processes spread over the Laptev Sea coastline, and their morphodynamic classification and segmentation, were based on the integrated use of the authors' own field materials over different years, on published literature and cartographic materials on the geomorphological structure, and on the lithodynamics of the coastal zone, as well as on remote sensing data from Sentinel-2 imagery [39] and the ESRI ArcGIS basemap [40]. The coast was divided into several types, based on the morphodynamic principles [41,42] of the inner and marginal sea coasts classification, considering the regional specifics of the Arctic region [43], and the geomorphology and lithodynamics of the Laptev Sea coastal zone [27,33,37,44]. In addition to the morphological and dynamic characteristics of a particular segment of the coast, the influence of geological, permafrost, fluvial and hydrometeorological factors, which determine the coast's evolution, were taken into account.

Data analysis and mapping were performed in ESRI ArcGIS 10.8 software. Geomorphological segmentation of the coastline was performed at a scale of 1:100,000. This allowed us to identify and characterize the morphology of the coasts and their spatial distribution within the study area. However, the chosen scale required a certain cartographic generalization. This was especially evident in the context of the widespread islands and the multichannel delta of the Lena River, which were considered to be one coastal type. In this regard, the determined relative lengths of coastal segments with different morphodynamic types may have differed from the results of other researchers who worked at other scales and based them on different coastline data.

3. An Overview of the Study Area

3.1. Geological Structure and Permafrost Characteristics

The Laptev Sea onshore was formed over a considerable extent by coastal lowlands that were composed of non-lithified Quaternary sediments. Mountainous areas with rock outcrops are common in the western part of the region, on the Taimyr Peninsula coastline, as well as between the Lena Delta and the Buor-Khaya Peninsula, on the periphery of the Verkhoyansk Ridge.

The upper part of the section of the coastal lowlands is a thick (up to 50–60 m) cover of frozen Late Pleistocene–Holocene sediments. Among the Quaternary sediments is the forementioned “Ice Complex”, which are syngenetically frozen Late Pleistocene sediments up to several tens of meters thick, predominantly of a silty composition with a high organic content, including vast ice wedges [14,45,46]. These sediments contain a large number of remains of the mammoth fauna complex. The first complete skeleton of a mammoth, delivered to scientists, was found in 1799 on the southern coast of the Laptev Sea. This Lensky mammoth was revealed from melting of the retreating coastal cliff of the Bykovsky Peninsula. Currently, valuable scientific findings of fossil mammals have been discovered in the coastal cliffs of the exposed Yedoma Ice Complex.

The volumetric ice content of the Yedoma Ice Complex is up to 40–90%, due to polygonal large syngenetic ice wedges; furthermore, the content of segregated ice is also high (up to 50%). The thawing of the Yedoma Ice Complex formed alas complexes [47]. On the coastal cliffs, specific microrelief features formed due to the thawing of ice wedges. In the cliff, networks of vast ice wedges are often seen as ice walls with rounded or slightly oval “windows” filled by sediments (Figure 2a). This pattern is the result of a projection of the section, including polygon centers with sediments, surrounded by ice wedges (similar to vertically elongated pyramids), onto the inclined plane of the cliff.

The central parts of polygons sometimes form figures resembling a pillar or a mushroom, the cap of which is composed of highly peaty frozen sediments (Figure 2b). Frequently, such peaty lenses form “noses” protruding from the cliff.

Thawing of the active layer begins in early June, and in mid to late June on the islands. The seasonal thawing depth reaches 0.2–1.9 m by the end of August, varying significantly

within the region, as well as depending on the local landscape conditions. In the second half of September, after the surface temperature drops below 0°C , active layer freezing begins.



Figure 2. Sea cliffs in the Yedoma Ice Complex: (a) cliff at Cape Mammoth Klyk. The sediment “windows” placed on the ice cliff. Such features are projections of the central parts of the polygons, surrounded by vast ice wedges on the inclined cliff; (b) inversion microrelief landforms, associated with thawing of ice wedges and the relative stability of central parts of the polygons, composed of sediments. The extensions and caps of these shapes are formed by lenses of peat-saturated sediments. After thawing, such forms collapse. Photos by M.N. Grigoriev.

The current challenge is to establish the boundaries of the distribution, thickness and state of permafrost offshore within the shelf area. The submarine permafrost includes both frozen ground and saline-cooled sediments, separated by sites of thawed sediments. According to the modeling results, the total thickness of the subaqueous permafrost can reach 600–900 m [48]. In the coastal zone, submarine permafrost is characterized predominantly by a continuous distribution in sea depth intervals from 0 to 50–60 m, and discontinuous and a sporadic distribution at depths of 50–100 m. The permafrost top gradually sinks towards the sea, which is associated with the gradual degradation of frozen ground under

the water. Permafrost is overlain by thawed and cooled sediments below 0 °C up to tens of meters thick. The depth and the slope of the submarine permafrost top are determined by the rate of coastal retreat [11]. Submarine permafrost degradation leads to sea floor morphological changes and surface subsidence, which affect the wave energy [11,31,49].

The permafrost top in the inner area of the Laptev Sea has a complex surface, similar to the onshore relief with uplands and thermokarst depressions [50]. The highest position of the permafrost top (1–5 m below the seabed) is presumably associated with the existence in the recent past on this site of islands, built of the Yedoma Ice Complex and destroyed by thermal abrasion. These are the very prototypes of the Sannikov Land.

The sites of permafrost aggradation are confined to the new forming wind-affected mudflats or windwatts. Syngenetic freezing of modern and Holocene marine sediments occurs in these areas [51]. On the windwatts, both frozen ground and saline sediments, cooled below 0 °C, are present. Thus, the permafrost is present at different depths in all of the bluffs of the considered coast types.

3.2. Hydrological and Sea Ice Conditions

High latitude location and connection with the Central Arctic Basin determine the harsh climatic and, as a result, sea ice conditions of the region. In the summer, Laptev Sea ice conditions are determined by the influence of two quasi-stationary areas of close and very close pack ice—the Taimyrsky and Yansky sea ice massifs. The Taimyrsky massif is a branch of the ice massif located in the central part of the Arctic basin. The Yansky ice massif is mainly formed by ice of local origin, and almost completely disappears by the end of the melting period.

In turn, the existence of sea ice determines the duration of the open-water season, when sea waves affect the coasts. The fast ice width varies greatly along the coast, and on shallow sites it ranges from several tens to hundreds of kilometers. The width of fast ice frozen to the sea bottom can reach 8–10 km in some areas [27].

The open-water season duration for the coast of the Laptev Sea increases from the west to the east: 1–1.5 months for the coast of Taimyr and the Severnaya Zemlya Archipelago (in the vicinity of vast Taimyr sea ice massif); 1.5–2 months in the southwestern part of the sea; and 2–2.5 months in the southeastern part of the sea [27]. The increase in the duration of the ice-free period is associated with the warming effect of river runoff, which spreads over the entire eastern part of the sea. East of the Lena River delta, during 70% of the open-water season, the maximum length of the wave fetch reaches 500 km [27].

3.3. Relief-Forming Processes

The Yakutian northern coastal lowlands, washed by the Laptev Sea, have been largely transformed by thermokarst. At the Pleistocene–Holocene confine (about 12–13 thousand years ago), the thawing of ice-rich sediments of the Yedoma Ice Complex was associated with the formation of numerous lacustrine–thermokarst basins—alases or als [52,53]. The reason for this wave of thermokarst activation was an increase in mean annual air temperatures and an increase in humidification [47,54].

The depth of thermal erosion and thermokarst dissection of the coastal lowlands is determined by the thickness of the Yedoma Ice Complex. At the initial stages, thermokarst on the yedoma (remnant uplands) forms flat depressions, flooded depressions that develop into thermokarst lakes when favorable conditions are combined. The final stage is associated with the drainage of lakes and the formation of alases.

The time of activity of destructive relief-forming processes onshore is limited by a short summer period, when the active layer thaws and the fast sea ice collapses. In the summer, thermal denudation and thermal abrasion act on the coast. The high volumetric ice content of the sediments in coastal cliffs determines the possibility of thermal subsidence, as well as the lack of sediments in the coastal zone, which leads to intensive coastal retreat. In areas with active thermal abrasion, the maximum retreat rates of coasts composed of the Yedoma Ice Complex reach tens of meters per year [2]. The retreat rate averaged for the

entire coastline has significantly lower values. In areas with a reduced intensity of wave impact, the thermal denudation of ice-rich sediments in the upper part of the coastal cliff begins to play a predominant role, which leads to the formation of thermoterraces [9,55].

4. Laptev Sea Coasts Classification

4.1. Morphodynamic Types of the Laptev Sea Coasts

The absence of a well-established classification of the Arctic coasts makes it very difficult to compare the results of the performed studies. Researchers use different classification approaches, which makes it challenging to reveal the regional features of coastal morphology and its relief-forming processes. Furthermore, it is often impossible to analyze the spatial distribution of coastal types and compare published data for isolated key sites. This leads to inconsistencies in the assessments of the ratio of the length of various coastal types within the study area.

The performed coastal segmentation (Figure 3) made it possible to clarify the current lengths of the various types of coast observed, and to illustrate their great variety of spatial distribution (Table 1). Such variety mainly results from the peculiarities of the geological and geomorphological structure of the coasts, which determined the conditions of the coastal dynamics in the Holocene.

Table 1. Laptev Sea coasts morphodynamic types.

Coast Type (by Prevalent Processes)	Index on Map (Figure 2)	Proportion in Length, %
1. Abrasional coast types		
1.1. Thermal-denudation cliffs formed by ice walls of outlet glaciers	1	1
1.2. Coastal cliffs in bedrock (lithified sediments):		
1.2.1. Abrasional cliffs	2	11
1.2.2. Abrasional-denudational cliffs	3	8
1.3. Coastal cliffs in unlithified sediments:		
1.3.1. Thermal-abrasional cliffs	4	5
1.3.2. Thermal-denudational cliffs	5	15
1.3.3. Abrasional coasts with stabilized cliffs, bordered by beaches or accumulative terraces	6	3
2. Accumulative coasts types		
2.1. Accumulative coasts with accumulative landforms	7	5
2.2. Accumulative coasts with shallow coastal zone and windwatts	8	6
2.3. Accumulative sheltered coasts in bays and gulfs	9	11
2.4. Deltas	10	34

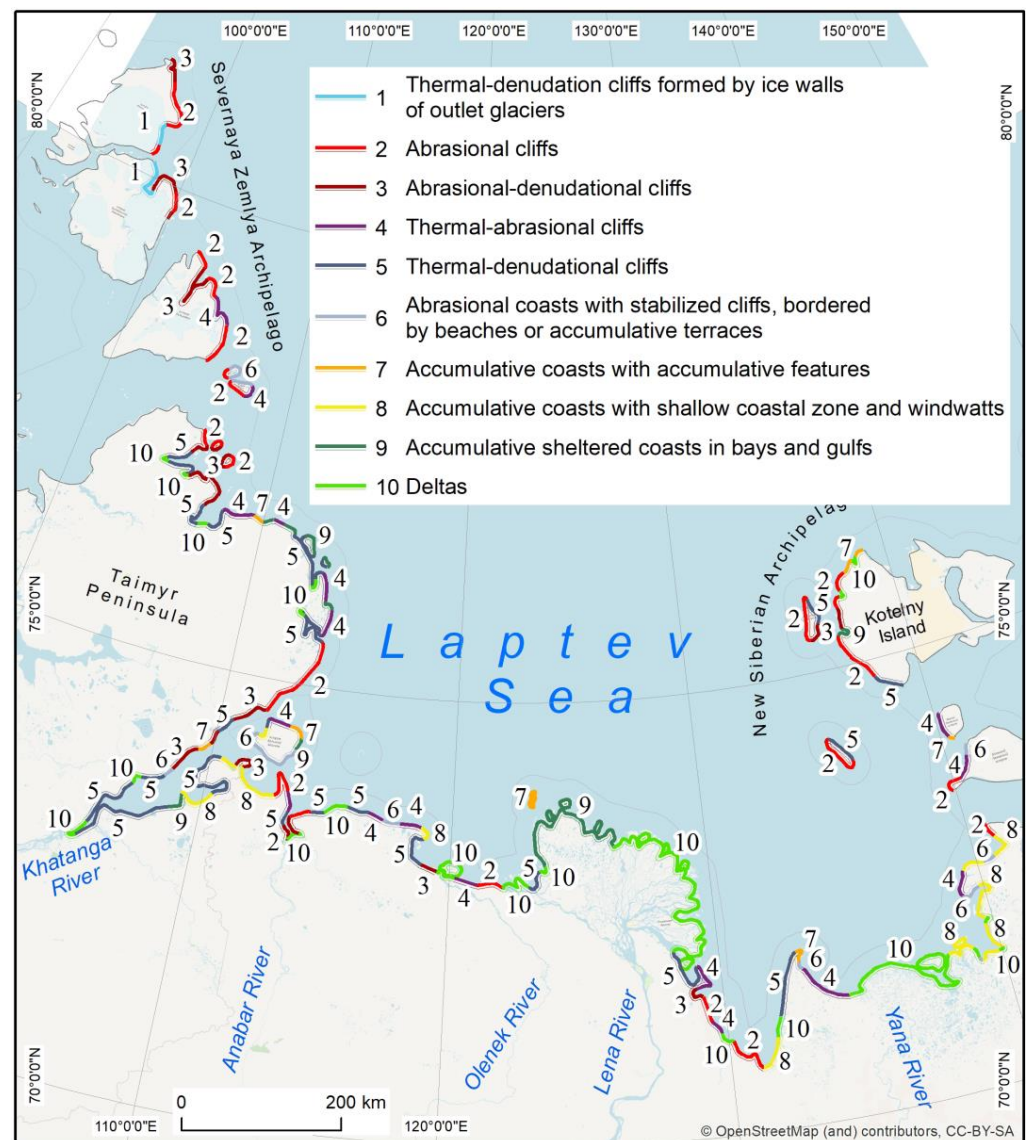


Figure 3. Generalized version of the Laptev Sea coastal segmentation map. Coastal types are indicated in accordance with Table 1.

4.2. Abrasional Coast Types

4.2.1. Thermal-Denudational Cliffs formed by Ice Walls of Outlet Glaciers

A specific and rather rare type of coast is represented by thermal-denudational cliffs formed by the glaciers extending into the coastal zone (Figure 4). Such sites are represented on the islands of Severnaya Zemlya. These icy coasts were formed by the glacier of the Academy of Sciences on Komsomolets Island, by Rusanov and Karpinsky glaciers on October Revolution Island, and by a fragment of the Semyonov–Tien–Shansky glacier on Bolshevik Island. The dynamics of such coasts proceeds mainly under the influence of non-wave factors, and the morphology of the cliffs formed by ice is quite diverse. Deep niches and grottos are formed at the base of ice cliffs under the warming effect of water, and icebergs formed as a result of the collapse of ice blocks.

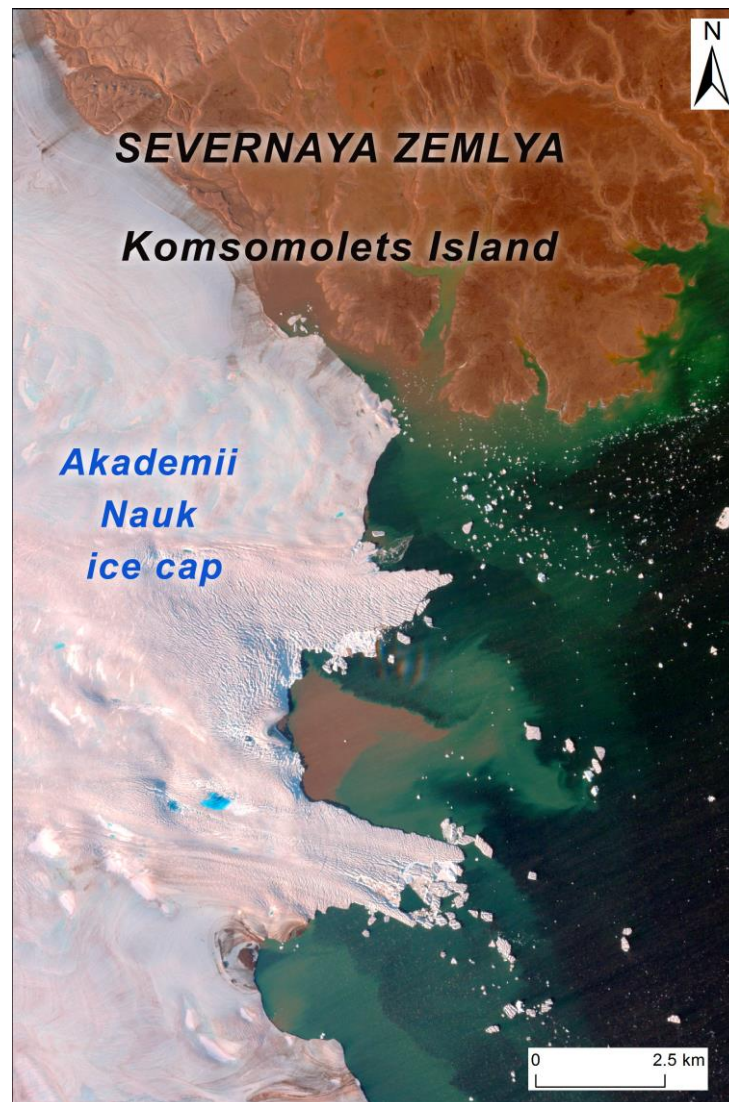


Figure 4. Thermal-denudational cliffs formed at the outlet of the glacier of the Academy of Sciences on the Komsomolets Island (Severnaya Zemlya archipelago). The formation of icebergs is associated with the collapse of ice blocks. To the north of the glacier, there is a bay with abrasional cliffs. Sentinel-2 image dated 23 August 2018 (synthesis of Red + Green + Blue) [39].

4.2.2. Abrasional and Abrasional-Denudational Cliffs in Bedrocks

Such coasts are limitedly distributed on the Laptev Sea, due to the geological structure of the region. The areas with above-sea-level outcrops of bedrock are characterized by a rugged coastline with bay coasts. The abrasional sites on capes and segments that are open to wave action alternate with sites of accumulation in the bays and gulfs.

Abrasional coasts can form steep cliffs up to several tens of meters high, or form low, gently sloping bedrock outcrops that pass directly into the bench surface. Often, there are no beaches at the foot of the cliffs, and the waves directly affect the cliff. Wave-breaking niches of various sizes, grottos and kekurs are formed (Figure 5).

Abrasional-denudational coasts are located on sites that are sheltered from intense wave action. The appearance of such coasts, as a rule, does not differ much from the exposed abrasional coasts; however, the ratio of the processes involved in the formation of the above-water part of the coastal cliff and the lower hydrodynamic activity in the coastal zone determine the specifics of this type of coast. The dynamics and morphological features of these coasts are determined by the leading role of denudation processes. The

physical and cryogenic weathering of rocks and slope processes leads to the destruction of cliffs and the movement of debris.

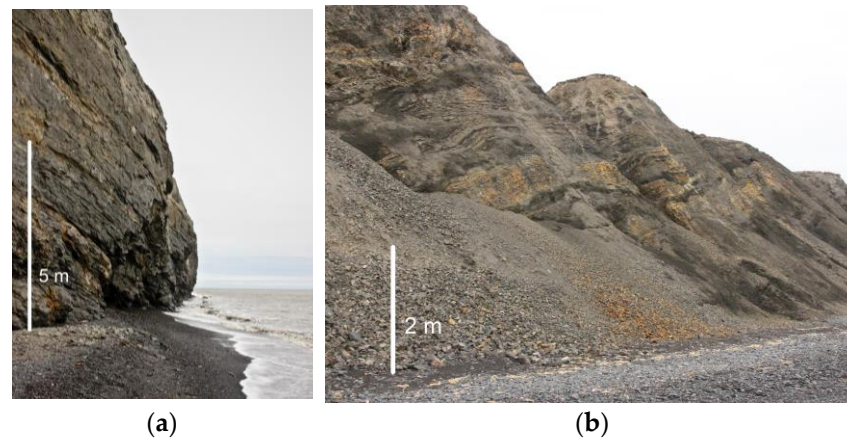


Figure 5. Abrasional-denudational coasts. Coastal cliffs, cut in bedrocks, on the south of Kotelny Island near the Medvejiy Cape: (a) abrasional cliff with a wave-breaking niche and a narrow beach; (b) abrasional-denudational cliff with talus cones of weathered rocks at its foot. Photos by A.I. Kizyakov.

The destruction of lithified coastal cliffs leads to the influx of coarse-grained material into the coastal zone. These sediments are transported by longshore drift; they participate in the formation of accumulative landforms such as gravel and pebble spits and beaches in neighboring sites.

Abrasional and abrasional-denudational coasts are mainly located in the western part of the Laptev Sea—on the islands of the Severnaya Zemlya archipelago, on the northern and southeastern coasts of the Taimyr Peninsula. On the Taimyr, this is the Pronchishchev Coast from the Maria Pronchishcheva Bay to the Siberian Cape. Coasts of this type are distinguished in separate areas of Anabar Bay, on the capes of Nordvik Bay and in Olenek Bay. On the western coast of Buor-Khaya Bay, the spurs of the Kharaulakh Range (Nunga and Naybinsky Ridges) approach the sea, and along the coastline there are cliffs 15–25 m high, and near the capes there are separately standing kekurs. In the eastern part of the region, the same coasts are on Cape Svyatoy Nos and on some sites of the New Siberian Islands, such as Belkovsky Island, the western and southern coasts of Stolbovoy Island, the Kigilyakh Peninsula of Bolshoy Lyakhovsky Island, and the capes of the western coast of Kotelny Island.

The total length of abrasional and abrasional-denudational coasts constitutes approximately 18.5% of the Laptev Sea coastline.

4.2.3. Thermal-Abrasional Coasts

Thermal-abrasional cliffs are widespread on coastline sites that are exposed to wave action. The lifetime cyclicity of a thermal-abrasional coast includes the forming of a wave-cut niche up to 10–15 m at its cliff base, the collapse of the overhanging block of frozen sediments and its washout on the beach face. Such retreating thermal-abrasional sites are also located near river mouths, due to the warming effect of river runoff.

Separate segments of thermal-abrasional coasts are located in Khatanga Bay, on Bol'shoy Begichev Island, within the Anabar-Olenek lowland, including parts of Anabar and Oleneksky Bays; on the Bykovsky Peninsula; on the western coasts of the Yana Bay; in bays of Selyakhskaya, Vankina, Ebelyakhskaya, Buor-Khaya; on the Shirokostan Peninsula; on the New Siberian Islands, Muostakh Island and others.

The retreat rates of active cliffs vary widely, from 1 to 15 m/year and more [2]. The maximum rates are observed on cliffs, cut in the Yedoma Ice Complex.

The solution to the mystery of Sannikov Land and other islands that disappeared has been associated with high rates of coastal retreat. During the period of relative cli-

mate warming in 1940–1950, Semenovskiy Island, located in the southwestern part of the New Siberian archipelago, eroded at an average rate of 17 m/year, and in some years up to 30–55 m/year [2]. Currently, this island has completely disappeared, and only the Semenovskoe shoal has been preserved.

Another site, widely known among Arctic researchers, is Muostakh Island, where the rates of coastal retreat have been studied for decades (Figure 6). Such studies have been carried out since the 1960s [56] to the present time [10]. Due to abrasion, the area of the island has decreased by 25% from the 1950s to the present. The average rate of thermal abrasion in 1951–2012 was 1.8 m/year, and in 2010–2013 it almost doubled, up to 3.4 m/year [10]. The ratio of the contribution of thermal abrasion and thermal denudation to the coastal dynamics is mainly determined by the spatial variability of the cryolithological structure, and the interannual variability of air temperature and hydrodynamic conditions of the sea. It is assumed [10] that the modern intensification of coastal retreat rate will lead to the disappearance of this island in less than 100 years.

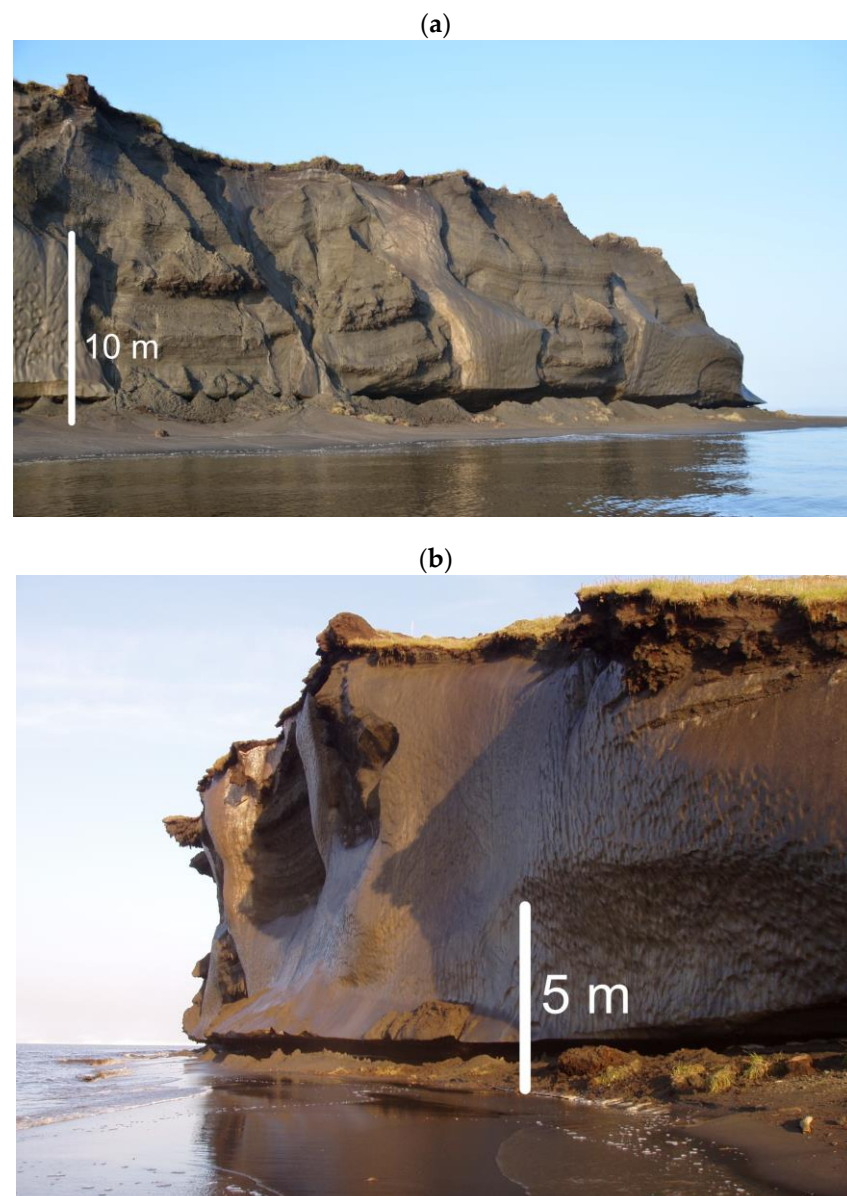


Figure 6. Thermal-abrasional coastal cliffs on Muostakh Island: (a) cliffs up to 25 m high cut into the Yedoma Ice Complex on the northeastern coast of the island; (b) wave-cut niches with a depth of up to 3–4 m at the foot of the cliffs. Photos by M.N. Grigoriev.

On the coastal cliffs of the Yedoma Ice Complex, large-block collapse is observed; the sizes of the collapsing blocks correspond to the sizes of the ice-wedge polygons, along which the separation cracks appear. A similar morphology of coastal cliffs with high rates of coastal retreat caused by river erosion are also found in the Lena Delta islands, built by the Yedoma Ice Complex. Such a cliff, eroded by a powerful Sardakhskaya channel of the Lena River delta, is located in the north of Sobo-Sise Island (Figure 7). Erosion rates vary widely and reach 22 m/year [25].



Figure 7. High cliffs cut by river erosion on Sobo-Sise Island in the Lena River delta: (a) cliffs up to 22 m high cut in Yedoma Ice Complex; (b) large blocks cliff collapse. Photos by A.I. Kizyakov.

4.2.4. Thermal-Denudational Coasts

On thermal-denudational coasts, in contrast to the thermal-abrasional type, waves do not play a decisive role in the formation of the morphology and dynamics of these coasts. In areas that have a gentle coastal slope and low-intensity waves, the formation of deep wave-cut niches at the base of the cliff and block collapse of the cliffs does not occur. These coastal cliffs, which are composed of ice-rich deposits, are retreating mainly as a result of thermal denudation through the flow, and the sliding of thawed deposits. The rate of coastal retreat on sites with the Yedoma Ice Complex noticeably exceeds the rate on sites with lower ice content deposits.

The special features of the thermal-denudational coasts are large denudational land-forms called “thermoterraces” (Figure 8). They are formed when the rate of thermal denudation of the outcrops of the Yedoma Ice Complex in the upper part of the scarp exceeds the rate of abrasion retreat of its lower part [55].

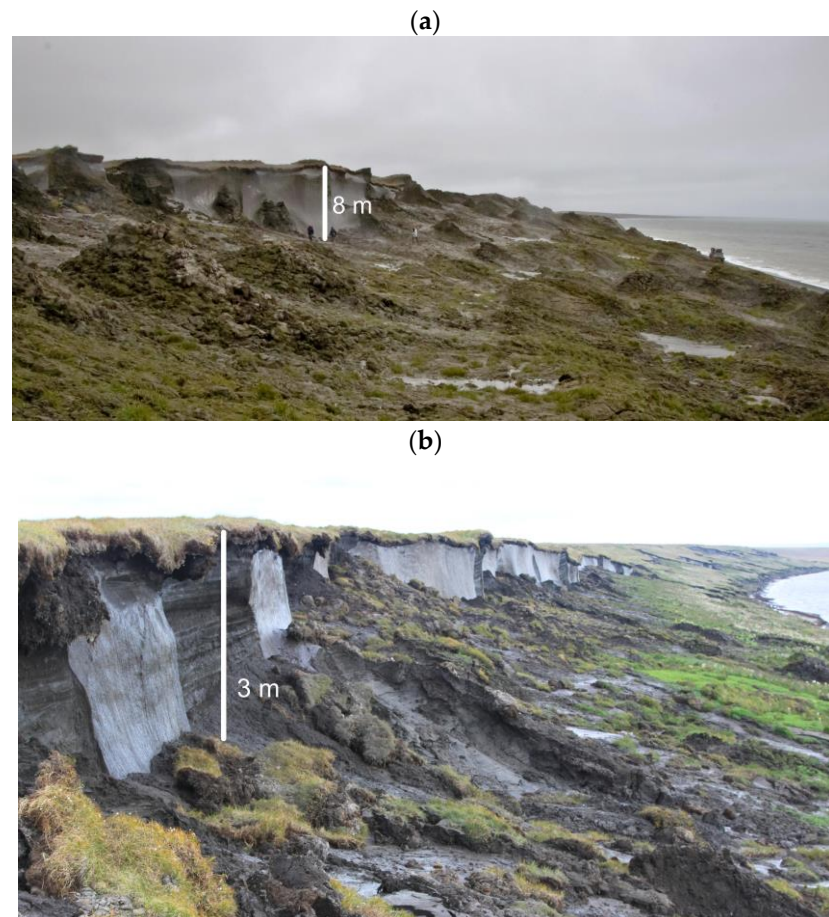


Figure 8. Thermoterraces forming on coasts with outcrops of Yedoma Ice Complex deposits: (a) an inclined surface of a thermoterrace with baydzherakhs on the southern coast of Kotelny Island. The height of the backwall cut in Yedoma Ice Complex is up to 10 m high; (b) the upper part of the thermoterrace on the western coast of the Bykovsky Peninsula, facing the Neelov Bay. The height of the Yedoma Ice Complex outcrop is up to 8 m. The lower part of the thermoterrace is partially stabilized with fragmented vegetation cover. The foot of the thermoterrace is eroded as a result of thermal abrasion. Photos by A.I. Kizyakov.

The length of thermoterraces along the coastline can be the first hundreds of meters, while the width of the inclined surface of the terrace is tens of meters. Thermoterraces, as a rule, are complicated by cones of baydzherakhs (residual thermokarst mounds left by the thawing of the ice wedges).

Thermal-denudational coasts are found on the Buor-Khaya (Figure 9) and Bykovsky Peninsulas, the New Siberian archipelago, in Anabar Bay and on other parts of the coastline.

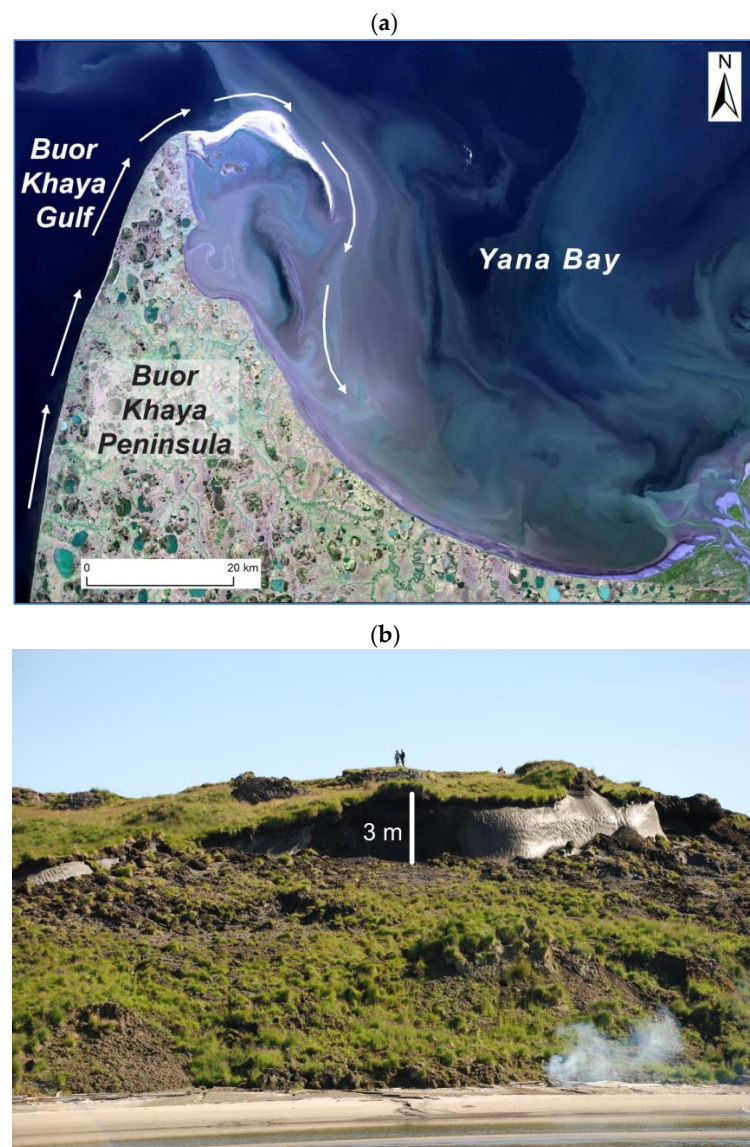


Figure 9. Buor-Khaya Peninsula: (a) location of the eroded and accumulative sites on Buor-Khaya Peninsula. The accumulative sand bank, attached to the northern edge of the peninsula, has a crescent shape with a length of more than 27 km. This accumulative landform protects the eastern coast of the peninsula from wave action, where stabilization of the previously retreating coasts is observed. To the southeast of the sand bank, hydrodynamic conditions are favorable for sediment accumulation. White arrows indicate the direction of the alongshore sediment drift. Sentinel-2 image, dated 28 July 2018 (synthesis of Red + Green + Blue) [39]; (b) thermal-denudational cliff, cut in the Yedomia Ice Complex deposits, on the western coast. Photo by M.N. Grigoriev.

4.3. Accumulative Coast Types

The accumulative coasts of the Laptev Sea are represented by the following main types: coasts with a shallow coastal zone and windwatts; coasts with accumulative landforms, terraces; and coasts within bays, lagoons and deltaic coasts. The distributions of these types of accumulative coasts, as well as their lengths, are very uneven within the region, and are determined by a combination of a number of lithodynamic factors.

The deltaic coasts are located in the mouths of large and medium-sized rivers—Lena, Olenek, Yana, etc. The largest protruding delta is formed in the mouth of the Lena River. Currently, the main river runoff and sediment transport with the formation of accumulative landforms occurs in the eastern low-lying part of the delta. In the west, the Lena Delta

is protected by bars that stretch in the submeridional direction, forming a lagoon type of coasts.

To the east of the Lena River delta, material is supplied with river runoff; as a result of coastal abrasion, it is transported eastward, and fills the reentry corner of Yana Bay, where the largest accumulative features are formed [27]. The areas with sediment accumulation are associated with permafrost aggradation.

The well-defined morphologically expressed accumulative coastal landforms attached to the endings of abrasional sites are one of the typical features of the Laptev Sea coast. For example, the divergence of alongshore sediment drifts near the western coast of the Buor-Khaya Peninsula leads to an increase in drift to the northern edge of the peninsula. As a result, a large sand bank has been formed to the east of Cape Buor-Khaya (Figure 9a). The coastal zone behind the sand bank is becoming increasingly shallow, and watt forms.

The wind-driven fluctuations in sea level led to the formation of specific accumulative windwatts, which are quite widespread in the Laptev Sea. These landforms have significant lengths in the eastern part of the sea, which is characterized by a coastal slope with a very low gradient, and significant volumes of sediment supplied from river runoff material. Watts are confined to areas of convergence of alongshore drifts, or in areas where they sharply weaken in the wave “shadow” of peninsulas and islands. To the east of Yana Bay, one of the largest accumulative forms is located. This is the Makar Island watt, which partially isolates Selyakhskaya Bay (Figure 10). The size of the windwatt that is located between the Makar Island and the Shelonskie Islands is currently 26×36 km. The western coast of Makar Island is abrasional. From the north and south, the island and the windwatt are surrounded by accumulative sand banks. The island and sand bank surface heights gradually decrease to the east.

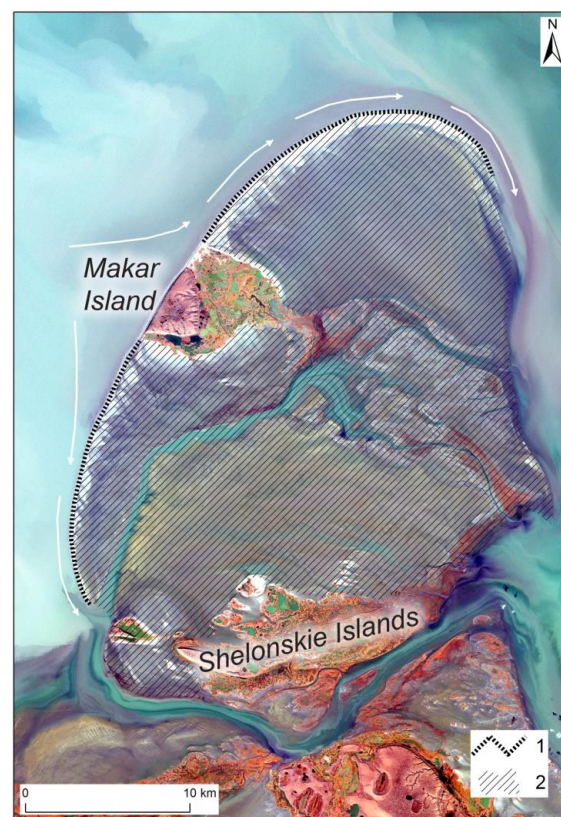


Figure 10. Accumulative coastal landforms of Makar Island: (1) accumulative sand banks surrounding the island, (2) windwatt area. White arrows indicate the direction of alongshore sediment drifts. Sentinel-2 image, dated 13 September 2018 (synthesis of Red + Green + Blue) [39].

In addition to accumulative windwatts, some sectors of the Laptev Sea coast are flooded during periods of wind-induced surges [27].

5. Discussion

One of the most important comprehensive researches on the Laptev Sea coasts was undertaken by V.A.Sovershaev [27]. It included a classification of coasts based mainly on dynamic characteristics. Studies [2,9,10,29,31,33,55–57] are devoted to the permafrost and coastal dynamics within the key sites of the coastal zone. The coastal classifications used in these studies did not cover the whole variety of coasts; therefore, in their current states, they cannot be extended to the entire coast of the Laptev Sea with regional coverage.

International databases, such as the ACD [26], contain layers of geospatial information for the entire coast; however, in terms of dynamic characteristics, the coasts were divided into only three types: erosive, accumulative and stable. The ACD database systematized all data available at that time, based on the structure and dynamics of all Arctic seas coasts. However, due to a lack of actual data on a number of sites, as well as the need to combine information that is heterogeneous in terms of methodological approach and detail, appropriate simplifications were made.

The proposed classification was developed on the basis of an analysis of coastal morphology (including cliff and beach morphology, lithology of sediments, permafrost), the complex of active relief-forming processes and dynamics characteristics (destruction of cliffs and retreat of the coast, sediment accumulation, sediment transit, etc.). The adopted approach will make it possible to expand local field data along the coast to longer parts of coastline, by taking into account regularities in the structures of the coasts, their morphologies, and associated with trends in their evolution.

We consider it very important to separate revelatory relief-forming processes on coasts. In permafrost areas, the process of thermal abrasion combines with mechanical wave erosion and the thermal action of water and air on the cliff and beach face [2,9,28,31].

Coastal retreat that is under the action of only the thermal energy of air and solar radiation is called thermal denudation, and is more typical for areas of ice-rich permafrost [9,27,28,31]. Another process is the deformation of beach surface and underwater slope as a result of the degradation of ice-rich permafrost, the so-called thaw subsidence [31].

In terms of practical applications, the proposed classification can be used for assessing a sea coast's vulnerability to oil spills. Coastal vulnerability is assessed based on the international Environmental Sensitivity Index system [58]. The segmentation of coastline according to coastal morphology, dynamic type and sediment lithology can be used as a basis for this expert assessment. We have already performed a similar study that used a geomorphological approach in segmenting the coastline of the Laptev Sea [41].

Two points should be highlighted as limitations of the proposed classification. The first limitation is the absence of numerical characteristics for coastal dynamics. The regional data on coastal dynamics were used in the ACD database, but it was based on very discrete points of actual observations. In addition, modern coastal change rates may differ from those provided in the database due to modern climatic changes. It is necessary to expand the monitoring network on coastal dynamics, update the database with modern data, and extend the time series of observations.

The second limitation of the proposed classification is related to the level of scale for which the study is applicable. Applied to field expeditionary or monitoring research in key sites, the classification can be expanded depending on the differentiation of sediments, permafrost, relief-forming processes and the morphology of the coast within the studied areas. Nevertheless, this does not cancel the proposed approach; it should be adapted and detailed.

Further studies of the Laptev Sea coast will be aimed at solving a number of issues related to the evolution of the inland and submarine permafrost. Under global climate change and the reduction in sea ice cover of the Arctic, the intensity of permafrost processes on the coast will increase. A high rate of coastal retreat causes dangers to economic facilities. This undermines the need for the further study of coastal dynamics in changing climatic and

anthropogenic impacts. Coastal retreat due to thermal abrasion and thermal denudation cause permafrost degradation, which is associated with greenhouse gases release and organic matter flux to the coastal zone.

6. Conclusions

The Laptev Sea coastal analysis is an excellent example that illustrates the variety of different types of the Arctic coasts with distinctive morphological features. The study of the mosaic structure and trends in dynamics of Arctic coasts is an important task in the context of modern climate change.

Studies of permafrost and geomorphological conditions of the region, as well as coastal dynamics, began a long time ago; however, a systematic study of the region is complicated by its remoteness and inaccessibility. Modern Arctic coastal studies rely on field observations at a series of key sites, along with interpolation on the basis of remote sensing data analysis.

The proposed morphodynamic classification made it possible to characterize the entire coast of the Laptev Sea, and to assess the distribution of different coastal types within its region. According to our segmentation analysis, accumulative coasts slightly prevail, while abrasional coasts occupy approximately 43% of the Laptev Sea coastline's length. Accumulative coasts are spatially adjacent to abrasional sites, since they are formed near sediment sources, or in areas of alongshore sediment drift discharge.

The coastal dynamics are determined primarily by a combination of the following factors: the presence of ice-rich permafrost deposits with vast ice wedges in the coastal cliffs; a short sea open-water season; and relatively low summer air temperatures. The coastal cliffs in non-lithified permafrost are formed under the complex interplay of thermal denudation and thermal abrasion, acting together during the warm season. The thermal-abrasional cliffs and thermoterraces, formed in the Yedomia Ice Complex, are retreating at a high rate. Within the widespread accumulative landforms, including windwatts, new permafrost aggradates preserve the newly formed accumulative coastal features.

The research scale of 1:100,000 made it possible to provide a detailed description of the coasts of the mainland and the islands of the Laptev Sea. While the scale of mapping was changed, classification can be expanded and detailed, taking into account regional specifics. The proposed classification can be considered to be universal for the coasts of the Arctic seas of the eastern sector of Eurasia.

On the basis of the presented classification, geomorphological segmentation of the Laptev Sea coast was undertaken. Such segmentation could form the basis for further scientific and applied research, and could be applied to assess and model various characteristics of coastal evolution, relief-forming processes distribution, and to assess a coast's environmental sensitivity to oil spills.

Future directions of the Laptev Sea coast studies will be focused on submarine and inland permafrost, and geo-ecological implementation. Other important tasks involve defining estimates of the mineral and organic matter flux into the Arctic Ocean as a result of coastal erosion. These fluxes have a significant effect on coastal ecosystems, as well as on the global cycles of organic carbon and greenhouse gases.

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