

Vyacheslav Krylenko

Abstract

The seas of the Arctic (Barents Sea, White Sea, Kara Sea, Laptev Sea, East-Siberian Sea, Chukchi Sea) wash over Russian territory from the North. Almost 70 % of Russian territory falls within the Arctic Ocean basin. Despite the necessity of monitoring instances of natural and technogenic changes in the Arctic, many segments of the Arctic coast are still “blank spots” for researchers. The main reason for the poor knowledge in regard to this region is its inaccessibility. Its lagoons and estuaries are among the most difficult for the study of natural geosystems, each of them distinguished by both natural features and their response to changes in external conditions.

The variations of accumulative shores (lagoon, delta) are widely spread within the Barents and Laptev Seas. They form a great many lagoons. The biggest estuaries are the Kola Gulf, situated near the city of Murmansk, and the Khatanga and Anabar estuaries. There are not that many full scale lagoons along the coasts of the Kara Sea, a fact which is related to the geological structure of the shores, the peculiarities of which do not facilitate the development of accumulative bodies. But the largest estuaries of the Russia Arctic coast are the estuaries of the Kara Sea: Obskaya Guba, Taz Guba, Yenisey Gulf, Baidaratskaya Guba and Gydanska Guba. A characteristic peculiarity of the East Siberian Sea is a long extension of the accumulative coasts (about 40%), especially on the islands. The accumulative-lagoon systems are distinguished for their peculiar internal partition into a number of round basins. Accumulative bay-bars separating the shallow lagoons from the Chukchi Sea extend parallel to the continental coast over hundreds of kilometers. The bay-bar of the Tenkergynpilgyn Lagoon is approximately 100 km long, and the length of the Kuvetpilchin Lagoon exceeds 50 km. The abundance of coastal accumulative structures and the lagoons that they form is a consequence of the geological structure of the adjacent coast and the topography of the submarine slope.

The major portion of the lagoons of the Russian Arctic coast is formed by accumulative bodies: bars, bay-bars, and spits. The influence of the changes in external conditions on the accumulative coastal bodies is different depending on their type of feeding and formation. Over recent decades, changes in all climatic parameters have been observed throughout the planet, especially in the Arctic regions. This natural global process inevitably influences the state of geosystems along the entire Arctic coast, including lagoons and estuaries. At present, it is impossible to say with certainty how large the positive or negative consequences of the Arctic's climate changes will be. Human activities in the Arctic almost

V. Krylenko (✉)
P.P. Shirshov Institute of Oceanology of Russian Academy of
Sciences (IO RAS), 1-g, Prostornaya, Gelendzhik 353467, Russia
e-mail: krylenko.slava@gmail.com

always have a negative impact upon the environment. Environmental protection measures may decrease this impact but are not capable of preventing it in full measure. Fortunately, the severe natural conditions do not allow for a large scale development of the coast, as has happened in more favorable regions.

Keywords

Lagoon • Arctic seas • Ice conditions • Accumulative coast • Estuary

2.1 Introduction

The shore and continental slope of the Arctic are gradually being developed economically. In the course of this development, all the countries in the region have conducted research on the resources of the Arctic Ocean. Scientific researches of the coasts of the Arctic Seas represent an important part of this works (Dobrovolsky and Zalogin 1982; Alekseevsky 2007). In the twentieth century, large research institutes carried out researches in the Arctic Seas of Russia; these were the State Oceanographic Institute (GOIN), the Arctic and Antarctic Research Institute (AARI), and the Shirshov Institute of Oceanology (IO RAS). After the disintegration of the USSR, economic activity in the northern seas decreased by several orders of magnitude, which led to a sharp decrease in scientific researches, especially in the multidisciplinary researches. The actual available data, in both amount and time distribution, is not currently sufficient to serve as the basis for a comprehensive characterization of the geosystems of the coasts of the Arctic Seas. The greatest problem is extreme non-uniformity in the studies of the Arctic coasts, many parts of which still remain “white spots” for investigators (Dobrovolsky and Zalogin 1982).

The fundamental work by A.D. Dobrovolsky and B.S. Zalogin “Seas of the USSR” (Dobrovolsky and Zalogin 1982) became the basis for the physical-geographical description of the coasts of the Russian Arctic Seas. The resources of the global Internet also play a significant role in the information provision of the researches. Actual information on the state of the most remote and poorly studied coasts of Russia is located on the sites of state and public organizations (administrations of the regions, ministries and agencies, protected areas, WWF, etc.). We studied the data and analytically selected that which would determine the current state and dynamics of the lagoon coasts of the Russian Arctic Seas to the greatest extent.

The Seas of the Arctic (Barents, White, Kara, Laptev, East-Siberian, Chukchi) wash over Russian territory from the North. All these seas are marginal, with only the White Sea being enclosed. The total area of the Arctic Seas, adjacent to the coast of Russia, is more than 4.5 million km² and the sea water volume is 864,000 Km³. Almost 70 % of Russian territory falls within the Arctic ocean basin.

The Arctic Seas are separated from each other, and from the Central Polar basin, by archipelagos and islands: Franz Josef Land, Novaya Zemlya, Severnaya Zemlya, Wrangel, Vaygach, etc. If there is no clear boundary, it is carried out conventionally. The greater portion of the seas is situated in a shelf and is therefore shallow. Mean sea depth is 185 m. Only the northern part of the Laptev Sea occupies the Nansen abyssal hollow. Its seabed goes down to 3385 m. Because of this, the average depth of the Laptev Sea is 533 m; it is the deepest sea of the Arctic Ocean (Dobrovolsky and Zalogin 1982). The Barents Sea (average depth of 222 m, maximum – 600 m) is in second place in terms of depth. The East Siberian (average depth 54 m) and the Chukchi (71 m) are the most shallow (Dobrovolsky and Zalogin 1982). The bottom of the seas is smooth. The Barents and Kara Seas are characterized by the greatest broken bottom relief.

All the Arctic seas are open. There is free water exchange between them and the center of the Arctic Ocean. In the west, the warm waters of the North-Atlantic Current flow in through the wide and deep strait between the Scandinavian peninsula and Spitsbergen in the Barents Sea, which annually brings in about 74 thousand km³ in Atlantic water. In the northeast of the Barents Sea, the warm and salty (34.7–34.9‰) waters of the Atlantic fall below the cooler and less salty, and therefore less dense, Arctic waters. In the east, the Arctic Ocean is connected to the Pacific Ocean by the narrow (86 km) and shallow (42 m) Bering Strait, so the impact of the Pacific Ocean is much less than that of the Atlantic. The shallow depth of the strait complicates the deep water exchange. About 30,000 km³ of surface water is received into the Chukchi Sea from the Pacific Ocean (Dobrovolsky and Zalogin 1982).

The Arctic Seas experience considerable river run-off from the mainland (2735 km³ per year). The inflow of river water drastically reduces the salinity of the seas and forms currents from south to north. In summer, warm river water contributes to sea ice dissolution, and in autumn and winter, desalinating sea water promotes the formation of solid ice (Dobrovolsky and Zalogin 1982). The year-round presence of ice is the most vivid feature of the region. Most parts of the Arctic Ocean are icebound all year. In winter, only the western part of the Barents Sea is ice-free. Young stationary ice (fast ice) forms in the winter along the coast. It has its

maximum width (several hundred kilometers) in the shallow East-Siberian Sea. Ice-holes become situated within fast ice. They are formed from year to year in the same places, to the extent that they even have their own names according to the geographical objects that are located nearby (Cheshskaya, Pechora, West Novaya Zemlya, Amdermink, Jansky, Ob and Yenisei etc.). Drifting long-term ice (the Arctic pack) forms after the ice-holes. It consists of large ice floes, separated by fissures, sometimes by ice-holes. The average thickness of the Arctic pack is 2.5–3 m and up. The surface of the pack ice is smooth or wavy. Sometimes, there are ice hummocks with a height of 5–10 m. They form as a result of ice floe collisions. Ice hummocks up to 20 m occur on the border of the pack and first-year (Dobrovolsky and Zalogin 1982). In summer, the ice area of the Arctic Seas is reduced, but their edge does not go beyond marginal seas, even in August. Local blocks of drifting and fast ice are conserved in the marginal seas, except in the Barents Sea, during the summer. Besides, sea ice icebergs are found in the polar seas as well. They break away from the ice sheet of the archipelagos of Franz Josef Land, Novaya Zemlya and Severnaya Zemlya (Dobrovolsky and Zalogin 1982). Arctic sea ice conditions vary from year to year. In recent decades, a reduction in sea ice area has been due to a general warming of the Arctic. Ice cover on most of the seas significantly reduces wave action on the beaches.

The salinity of the sea water decreases from the northern to the southern sea borders. In the northwestern part of the Arctic basin, the salinity of the sea water is 34–35‰, in the northern and north-eastern regions, it is 32–33‰, and near the major river mouths, it reduces to 3–5‰. Salinity affects the formation and characteristics of the ice cover.

The severe climatic conditions of the northern seas, the polar night and the ice cover are all unfavorable for the development of phytoplankton and zooplankton, so the total biological productivity of the seas is not high. Organism and species diversity is relatively small. With the increasing severity in natural conditions from west to east comes a parallel change and decline in species composition in the same direction. In the Chukchi Sea, the diversity in animal species increases due to the penetration of warm Pacific Ocean waters, with the Pacific Arctic boreal species joining those indigenous to the area.

For the last several decades, changes in all climatic parameters have been observed throughout the planet, especially in the Arctic regions. The general Arctic “warming” is manifested by a decrease in the area of the ice cover and a change in the facets of its existence. The air and seawater temperature rises and the direction of prevailing air currents changes, influencing the formation and interaction of water masses. These natural global processes inevitably influence the state of geosystems along the entire Arctic coast, includ-

ing lagoons and estuaries. At present, it is impossible to say with certainty how large the consequences, positive or negative, of the climate changes in the Arctic will be.

Unlike the natural influences, human activities in the Arctic almost always have a negative impact upon the environment. Environmental protection measures are only capable of decreasing this impact; they cannot prevent it in full measure. Fortunately, the severe natural conditions do not allow for accomplishing the sort of large scale development of the coast as has happened in more favorable regions. As a consequence of the permafrost and severe climatic conditions, there are no large cities along the Arctic coast of Russia. Most of the settlements were founded during the period of the USSR, when field development was carried out and military bases were established. After the disintegration of the USSR, economic activity in the northern seas stopped almost completely. Many people left the settlements after the closing of industrial enterprises, quarries, and military bases. At present, only economic activities yielding the highest return are conducted in the Arctic regions, which allow for compensation of the large expenses needed to “fight” against nature. As a rule, transportation (mainly hydrocarbon transportation, as well as extraction of natural minerals (also mainly hydrocarbons, i.e., oil and gas)) can be considered to be such an activity.

The Northern Sea Route connecting the northwestern and eastern regions of Russia and the mouths of the navigational rivers in Siberia runs along the seas of the Russian Arctic Ocean. In addition to transportation of loads providing for the economic development of the north of Russia, the development of international transportation of loads in the West – East – West direction will be possible in the future. Construction of a transport infrastructure (ports, roads, pipelines) will have the strongest and quickest effect on the coasts and coastal water areas including lagoons and estuaries.

In addition to transportation activities, exploration and production of raw hydrocarbon material on the coast and shelf of the Arctic Seas has become considerably more intense in recent decades. The activity results in strengthening the technogenic impact on the environment that has become evident in the transformation and pollution of the ecosystems. The coast and shelf of the Barents and Kara Seas, where considerable fields of oil and gas have been explored and their production carried out, have undergone the most severe impact.

Despite the necessity of monitoring occurrences of natural and technogenic changes in the Arctic, many segments of the Arctic coast are still “blank spots” for researchers. The lagoons and estuaries there are among the most difficult for the study of their natural geosystems, each of them distinguished by both natural features and their response to the change in external conditions.

2.2 Peculiarities of the Lagoon Coasts of the Russian Arctic Seas

Similarly to the other regions of the World Ocean, the appearance and development of the modern lagoons and the accumulative bodies of the Arctic that form them is related to the Holocene transgression. Nevertheless, these processes in the Arctic were significantly different, first of all, as the result of the climatic conditions. The presence of permafrost and thick ice cover along the entire coastline during a significant part of the year and seasonal variations in the discharge of rivers introduced significant changes in the shores and the processes that occur there. The natural factors facilitating the formation of the lagoon shores include the peculiarities of the tectonic-geological structure of the shore (configuration of the coastline, topography of the underwater slope, lithologic composition) and peculiarities of the coastal hydrodynamics (regime of wind and waves, thermal and ice regime, tides, and currents). Variety in the combinations of these factors led to significant diversity in the lagoons existing along the Arctic coasts. We can distinguish the following types of lagoon according to their origin, structure of the bay-bars, and the dynamics of the coastal processes (Kaplin 2010):

Ordinary lagoons, which appeared as a result of the separation of the basin by one or two spits.

Typical lagoons, formed in the curves of the coastline, which are separated from the sea by a bar that appeared as a result of the transversal transport of material.

Complex lagoons, formed as a result of flooding of hilly lowlands, and hence, having complex boundaries; they are separated from the sea by the remains of bedrock structures connected by accumulative multi-genesis crossbars.

Firth lagoons, separated by spits from the sea; they have the same configuration as the firths and are separated from the sea by accumulative bodies that originated as a result of the transport of deposits along the shore.

Typical firth lagoons, which have the configuration of the firths; they are separated from the sea by a bar that was formed owing to the transversal transport of material.

Complex firth lagoons, one part of their basins has a configuration of an ordinary lagoon and the other is a firth; they are separated from the sea by a bar or spit.

Lagoon bays, which are separated from the sea not by accumulative bodies but by bedrock land parts; according to their hydrological regime and configuration, they can be considered lagoons.

According to the combination of geological conditions (topography, lithology, lithodynamics), we can distinguish the most widely spread types of coast for which special properties of lagoon development are typical.

Bedrock Coasts of Hard Rocky Material The beaches of a portion of the Russian arctic coasts are formed of hard rocky material, which are stable in the face of wave forcing. Usually, the underwater coastal topography in such regions is distinguished by steep slopes and rapidly increasing depths. Such coasts include the Kola Peninsula, the Novaya Zemlya and Franz Josef Land archipelagos (the Barents Sea); the northwestern coast of the Taimyr Peninsula (the Kara Sea). The structure of the coasts does not facilitate the formation of large accumulative bodies, which evidently causes an almost complete absence of lagoons. Small lagoons are formed here only at the tops of deep shallow bays. The accumulative bodies separating these lagoons from the sea are frequently a result of the glacier, but not wave forcing. However, the area of Lake Mogilnoye located on Kildin Island at the Murmansk coast of the Barents Sea is only 0.09 km². This is actually a lagoon separated from the sea by a bar approximately 70 m wide, which is permeable for seawater (Fig. 2.1). This lagoon is similar to a miniature model of the Black Sea, owing to the presence of a few water layers of different salinity, from almost fresh at the surface (salinity does not exceed 3‰) to a salinity greater than 30‰ at the bottom; conditions for hydrogen sulfide formation exist in the bottom layer. Each water layer is characterized by its own set of organisms, including the endemic ones. The lagoon-lake Mogilnoye is recognized as a natural hydrological monument protected by the state.

Low shores are formed by loose deposits. The longest Russian Arctic coasts are swampy lowlands formed by loose deposits, with a greater or smaller proportion of fossil ice. Such deposits are rapidly destroyed, even under weak wave forcing. Two main types of beach are formed depending on the composition and grain size of the loose deposits and the inclination of the underwater slope: beaches with pronounced accumulative bodies and those without them.

Lowland Shores with a Barrier Beach A combination of lengthy sand accumulative beach bodies, clearly seen in Fig. 2.2, with lowland swampy beaches is a specific feature typical of many Arctic coasts (Ogorodov 2001). Such beaches with similar origin and structure are widely spread throughout the eastern part of the Barents Sea (the Pechora Sea) (Varandey Islands, Pesyakov, Gulyaevskiye Koshki). A common mechanism for the formation of such accumulative bodies caused their similar structure, as shown in Fig. 2.3. The frontal marine side terminates with a dune belt (foredune), which reaches the height marks of 4–10 m. The marine slope of the foredune is adjacent to the beach (20–100 m), which transforms into a regular foreshore. The rear part of accumulative bodies located beyond the dune belt is usually a laid

Fig. 2.1 Lagoon-lake Mogilnoye on Kildin Island in the Barents Sea (Modified from Kosyan 2013)



or setup/setdown foreshore with height marks within 2.5–3.0 m (Popov et al. 1988).

Aeolian processes play an important role in the formation and development of such accumulative coastal bodies (Ogorodov et al. 2003). The sand transported from the underwater slope is then transported by the wind from the beaches and foredunes and precipitates within the dune belt. Vegetation on the foredunes prevents deflation and facilitates intense Aeolian accumulation. As a result, a powerful dune ridge is formed at the surface of the primary bars.

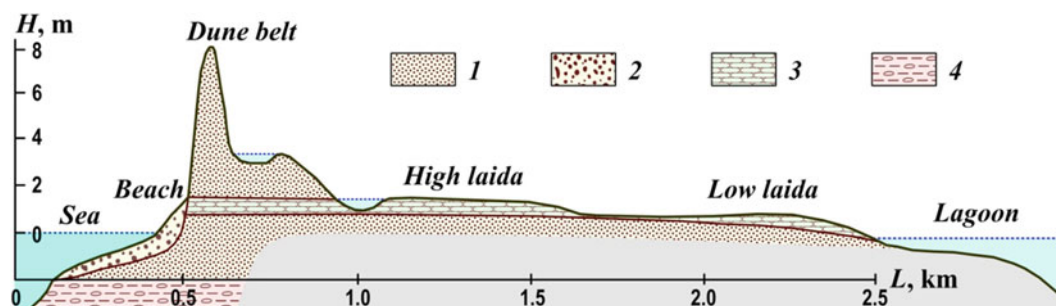
As the shore recedes, the entire accumulative body rapidly advances on the coastal laidas, river valleys, and shallow bays (Popov et al. 1988). Lagoons are formed in the flooded river valleys, which most frequently do not lose their connection with the sea, being maintained by the motions of the ebb tide. The lakes that appear in the influence zone of the sea are gradually filled with the deposits transported over the bars during storms, and then disappear as the sea advances.

Usually, a direct water exchange between such lakes and the sea does not occur.

Lowland Shores Without Formation of a Barrier Beach The accumulative coastal bodies are usually not formed in lowland regions of the gently sloping beaches where there is no transport of beach-forming deposits (abrasion products, solid discharge of rivers, or transport from the underwater slope). This usually happens on the descending parts of the coasts. An intermediate zone (laida) usually separates the tundra zone and the sea basin. Sometimes, it is a few kilometers wide. The laida is periodically flooded by the tides or setups. Specific vegetation (marshes) is typical of the laidas. Two levels are frequently distinguished in the laida morphology corresponding to the levels of low and high coverage, as one can see in Fig. 2.4 (Popov et al. 1988). Such conditions of shore development are not conducive to the formation of a real lagoon type. The existing lakes of river valleys are simply flooded by the sea.



Fig. 2.2 Extended accumulative body divides the lowland swampy tundra and the sea basin if the amount of deposits is sufficient. Eastern part of the Barents Sea (Modified from Kosyan 2013)



(1) - fine sands, (2) - sand pebbles, (3) - peat-grass "pillow", (4) - boulder clays and loams.

Fig. 2.3 1 Fine sands, 2 sand pebbles, 3 peat-grass "pillow", 4 boulder clays and loams. Transversal geological geomorphological profile across the accumulative body on Pesyakov Island (Popov et al. 1988)

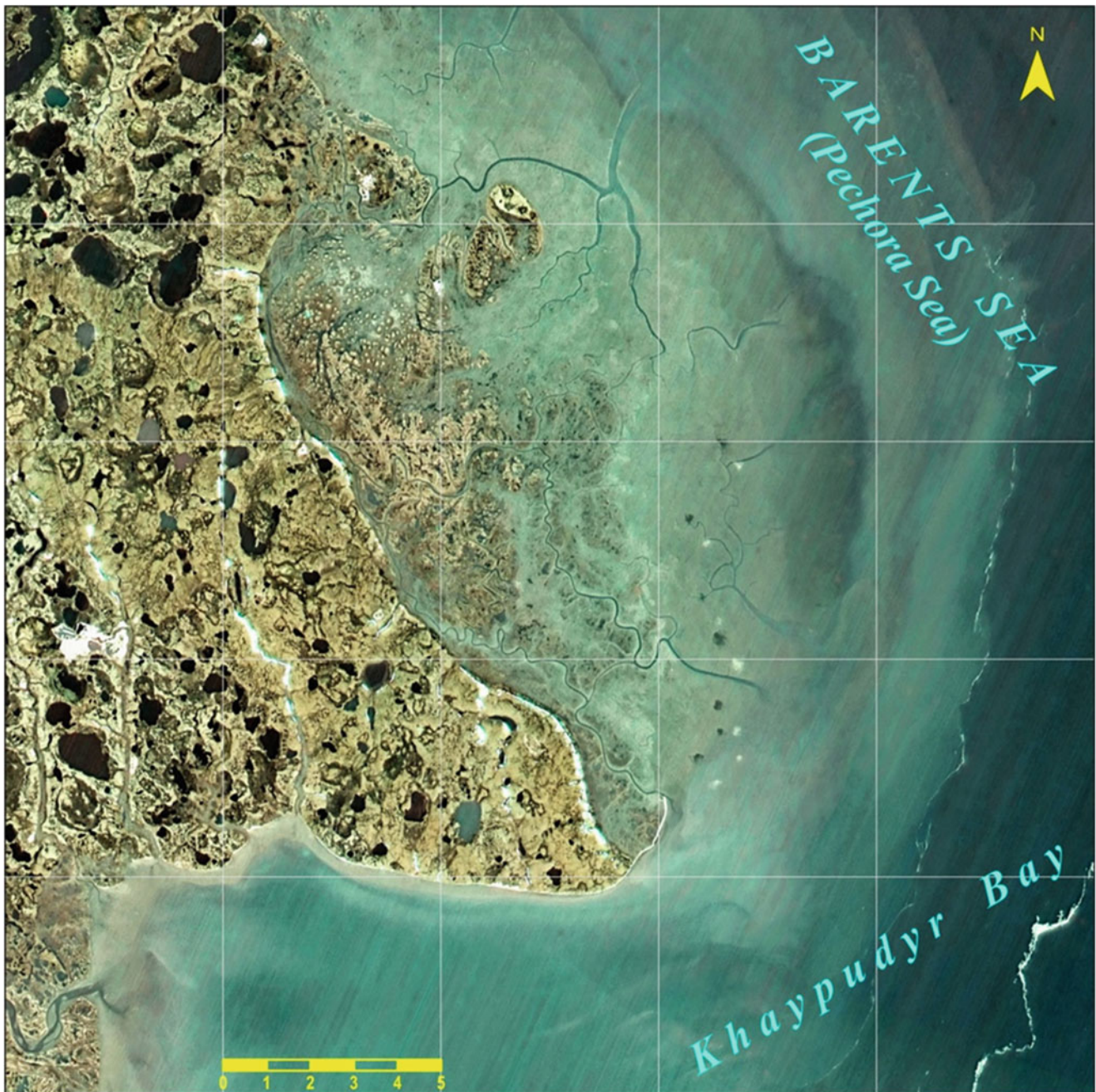


Fig. 2.4 If the amount of deposits is not sufficient for the formation of accumulative bodies, an intermediate zone (laida) separates the low wetland tundra and the sea basin. A laida is formed by tidal setup/set-

down fluctuations of the sea level. It can be a few kilometers wide. Eastern part of the Pechora Sea (Modified from Kosyan 2013)

Low Shores Without Formation of a Barrier Beach with Foreshore Zone An intermediate shore structure is formed when deposits accumulate in the coastal zone but their grain size and amount do not provide for formation of an entire thick accumulative body of a bay-bar or spit. Usually, such a shore structure is observed in regions where wave forcing at the bottom and shore is low (as a result of a very gently sloping bottom or when the ice cover period is long). Such shores

are characteristic of the western part of the East Siberian Sea and the eastern part of the Laptev Sea (Fig. 2.5).

Accumulative Bodies of Freezing Wave Origin If wave forcing is low, the rapid modern freezing of the deposits accumulated in the coastal zone facilitates stabilization of accumulative bodies formed under wave forcing, even if the amount of deposits is not high. Frozen organic remains,

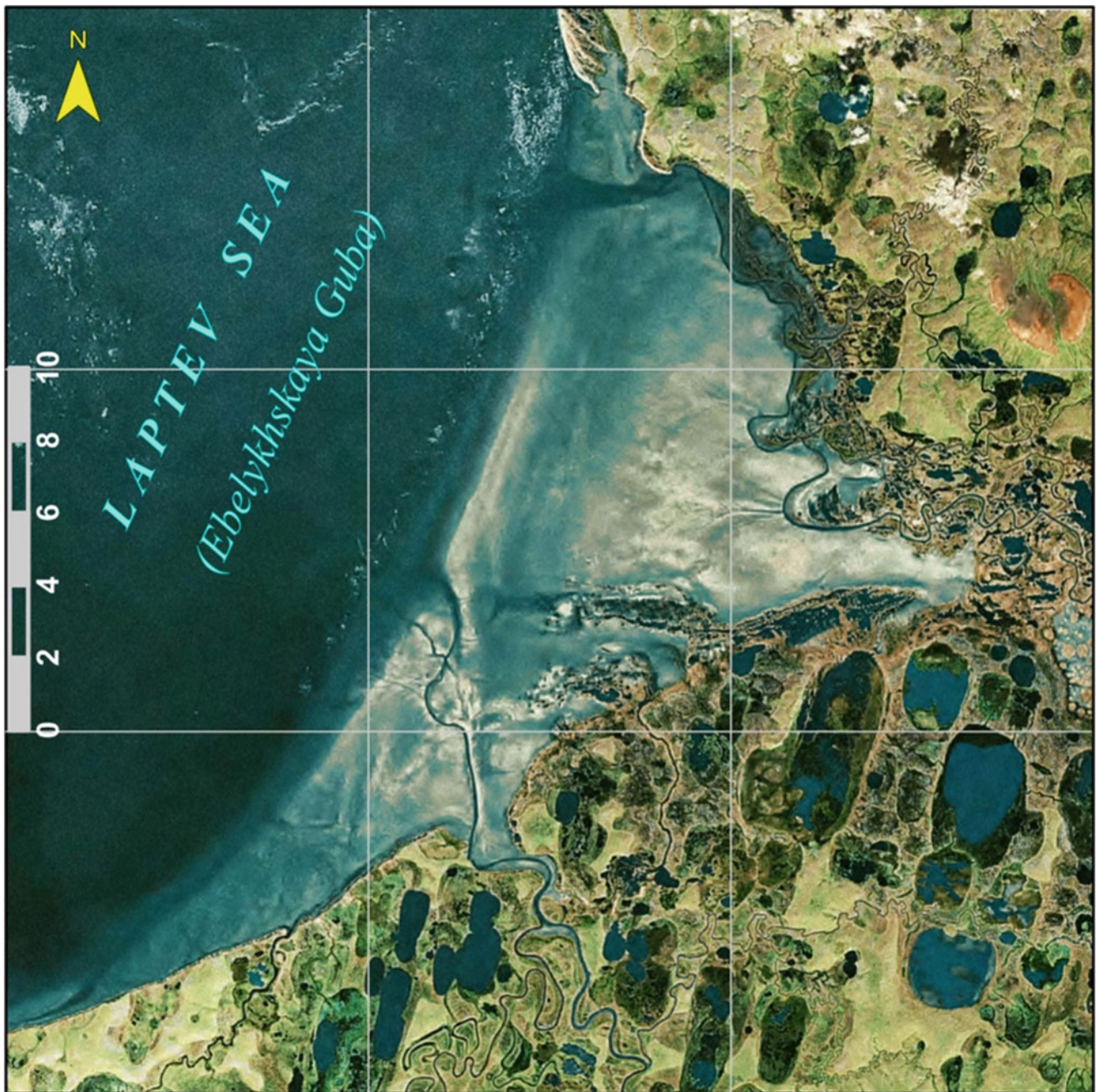


Fig. 2.5 Silt foreshore in the eastern part of the Laptev Sea (Ebelykhskaya Guba) (Modified from Kosyan 2013)

mixed with sand and silt, sometimes serve as the material for the formation of accumulative bodies. Such conditions are favorable for the appearance of lengthy accumulative bodies, which separate large water reservoirs from the sea. The Mogotoevo lagoon-lake, located along the coast of the East Siberian Sea (Fig. 2.6), is an example. This is a large (323 km²) brackish (13–19.5‰) reservoir formed by a large accumulative body located to the northwest of the Indigirka River mouth in Yakutia.

«Typical» Bars and Bay-Bars The largest accumulative bodies and lagoons are formed when the conditions of relatively steep bottom slopes, strong wave forcing, and an abundance of deposits of large granulometric size are combined. Such conditions are characteristic of a significant part of the shores of the East Siberian Sea and the Chukchi Sea. The inclinations of the bottom slopes there are usually 0.01–0.02 (reaching 0.08), which makes possible the development of powerful waves capable of transporting sandy pebble material from the underwater slope to the beach. The traces of wave impact at



Fig. 2.6 The East Siberian Sea. Accumulative body is located to the northwest of the Indigirka River mouth. Several large lagoons are formed, together with numerous small lagoons. Lake Mogotoevo is the largest of them (Modified from Kosyan 2013)

the bottom are sometimes observed up to depths of 35–40 m. However, the main condition for the development of high accumulative bay-bars is the abundance of mobile sandy pebble deposits on the submarine slope (Fig. 2.7). Usually, the material of the modern abrasion is not enough for the formation of large and stable accumulative bodies at the open coast. The discharge of the major part of the northern rivers is usually represented by deposits of sand-silt size. The major part of it precipitates in the deep bays (flooded river valleys).

Therefore, the only possible sources of the material applicable for the formation of large bars are silt and fluvio-glacial sediments on the shelf transported by water streams during the melting of mountain and valley glaciers flooded during the Holocene regression. Under the conditions of transgression and domination of the transversal motion of the sediments, part of these deposits formed a lengthy coastal ridge, which was slowly displaced to the coast during the transgression. This process slowed down simultaneous to the decelera-



Fig. 2.7 Lagoon coasts of the Chukchi Sea (Modified from Kosyan 2013)

tion of the transgression, but in some regions, where a relative increase in the sea level exists, the bars continue their inland motion (for example, the bay-bar of the Inchoun Lagoon in the Chukchi Sea). This process leads to an alignment of the coastline along a significant length of the shore, as one can see in Fig. 2.7. As the bar approaches the regions of the coast that are stable in the face of abrasion (mountainous massifs of hard rocks), protruding capes are formed. Accumulative arcs supported by the abrasion capes will be formed as the bars displace to the lowland beach.

2.3 Estuaries of the Russian Arctic Seas

The features of the tectonic-geological structure of the continental margin determined the configuration of the modern coastline of the Arctic seas. After completion of the Holocene transgression, the coastline of the Arctic coast was consider-

ably indented. Flooding of sea river valleys that had been greatly deepened during the previous regression formed deep ingressive bays.

The subsequent arrival of the river solid runoff and abrasion products changed the coast's configuration. Many bays were completely filled by river solid run-off or blocked by mouth bars. They transformed, respectively, into deltas or lagoons. However, some ingressive bays were preserved, forming special natural features – estuaries, where the combined influence of river runoff and sea is exhibited. The tectonic subsidence of near-coastal land or the deficiency of solid material to form deltas or estuary bars contributed to the preservation of the estuaries.

In modern scientific literature, the definition of an estuary is “a semi-closed water body, which is part of the river mouth area and characterized by active processes of the sea and river water mixing” (Mikhailov and Gorin 2012). The main feature of the estuary (besides a semi-closed form) is the

existence of a mixing zone for fresh river and salty sea waters and the existence within it of the “estuarine barrier” where salinity varies within 1–8‰ (Mikhailov and Gorin 2012).

Researchers have isolated a number of different types of estuary. The following are the usual criteria for determining estuary type: morphologic (shape and origin of the estuary); characteristics of the longitudinal changes in water salinity; characteristics of the salinity’s vertical distribution; tidal level oscillations; characteristics of the water circulation. In accord with the morphological and genetic features, all estuaries can be classified into four main types: sea type, river bed type, lagoon type and liman type (Mikhailov and Gorin 2012).

Semi-enclosed bays in which “estuarine barriers” (the mixing zones of river and sea water masses with changes in salinity from 1 to 8‰) are formed under the influence of river runoff are marine type estuaries. A close relationship with the sea and a relatively weak effect of river run-off are distinctive features of marine estuaries. The deep bays of the Barents and Kara Seas (Gydansky, Baidaratskaya, Khaipudyrskaya and the like) can be attributed to this type of estuary. Many small rivers flow into these bays. River run-off has little effect on their hydrological and hydrochemical regime. Perhaps the little-known fjords of the Novaya Zemlya archipelago are like estuaries.

River bed estuaries are formed in the lower parts of river beds under the influence of the opposite flows of river and sea water. Two subtypes of river bed estuary are determined according to features of the hydrological mode (Mikhailov and Gorin 2012): those with widening mouths and those without. Hydrological processes in the river bed estuaries without widening mouths proceed under the primary influence of river run-off. Often, there is estuarine water circulation when river water moves to the sea in surface layers and sea water moves towards the river at the bottom. Along the Russian Arctic coast, this type of estuary is available at the mouth of the river Yana. In river bed estuaries with widening mouths, their hydrological processes are characterized by the action of sea tides; river and sea waters actively mix, causing delicate water stratification in these objects. Estuaries of this type prevail on the coasts thanks to the presence of strong rocks, for example, the Kola Peninsula in the Barents Sea.

The origin and form of estuaries of the lagoon type are mainly related to waves and sediment motion in the mouth zone, where accumulative sea bodies (spits, coastal bars, barrier islands etc.) are formed. The main difference between lagoon estuaries and standard lagoons is the presence of river run-off in them. On the featureless coasts, the lagoon estuaries are water bodies extended or waterways

flowing along the sea coast, “pressed” by bay-bars to the land. Most lagoon estuaries are located at the mouths of small and medium rivers, a type quite prevalent along the Arctic coast. The main difference between lagoon estuaries and other types is that their hydrological processes are related to the dynamics of the accumulative form, separating these estuaries from the sea. This type of estuary is predominant along the coast of the East-Siberian and Chukchi Seas. Other types of estuary are practically absent, because the majority of river mouths are blocked by accumulative bodies or have deltas (Fig. 2.7).

Liman estuaries often form near the mouths of medium and large rivers and have an elongated form along the axis of the river valley. Liman estuaries are either unblocked on their seaside or are partially blocked by accumulative forms (spit, bay-bar, barrier islands). The water regime of liman estuaries is determined by river runoff. Liman estuaries’ salinity increases closer to the sea. In estuaries of this type, the majority of solid runoff settles near the mouth, forming deltas. In Russia, estuaries of the liman type are called “liman” or “guba”. In English language papers, such estuaries are called “coastal plain estuaries” or “drowned river valleys”. The largest estuaries of the Russian Arctic coast are of this type, in particular, those of the largest rivers of Russia – the Ob and the Yenisei Rivers, which flow into the Kara Sea, and the Khatanga and Anabar Rivers, which flow into the Laptev.

Estuaries are very interesting objects, scientifically speaking, because they are unique centers of biological activity in the system between the sea and the river. They have original hydrological, hydrochemical and hydrobiological conditions. Here, river runoff interacts with the salty waters of the sea, this interaction affecting the composition, distribution, quantitative indicators and living conditions of the biological organisms in the estuary. Furthermore, estuaries are often areas of human activity, as they have favorable locations for transport and other infrastructure. High sensitivity to natural and anthropogenic impact and slow reducing processes are features of the estuarine ecosystems of the Arctic Seas.

The intensity of interaction in the “river – sea” system is determined by the amount of river run-off (and its seasonal fluctuations), tidal processes, and surge phenomena. The influence of the Russian polar seas on inflowing rivers can be estimated from the data in Table 2.1.

It should be noted that poor knowledge of the Arctic coasts of Russia, including estuaries, creates difficulties for their economic use and protection. Most Arctic estuaries are of interest, not the least for their valuable natural objects, and need further study.

Table 2.1 Tide and surge influence on the regime of the Russian Arctic rivers

River	Run-off, km ³ /год	Max tide, m	Max surge, m	The maximum range of intromission of:		
				Tide, km	Surge, km	Salinity water, km
Pechora	128.4	1.0	2.4	180	160	10
Ob	357	0.7	3.0	51	358	200
Pur	28.4	–	1.5	–	100	0
Taz	33.5	–	1.8	–	180	0
Yenisei	624.4	0.7	3.0	566	990	253
Hatanga	104.5	0.8	2.5	227	–	–
Lena	521	0.4	2.5	25	56	–
Jana	35.1	0.2	1.5	10	133	60
Indigirka	49.5	0.3	2.0	24	137	–
Kolyma	123	0.1	2.5	–	283	–

Modified from Mikhailov (1997)

2.4 Lagoon Coasts and Estuaries of the Russian Arctic Seas

2.4.1 The Barents Sea

General Characteristics of the Sea

The Barents Sea is the westernmost sea among the seas of the Russian Arctic sector. In modern boundaries, the sea is located between latitudes 81°52' and 66°44' N and between longitudes 16°30' and 68°32' E. The sea has natural borders in the south and, to an extent, in the east. In the other parts, its boundaries are conventional lines (Dobrovolsky and Zalogin 1982). In the west, the Barents Sea borders the Norwegian Sea along the following line: Southern Cape (the southern tip of the Spitsbergen Archipelago) – Bear Island – North Cape (Cape Nordkapp). The southern boundary of the sea is the continental coast and the following line: Cape Svyatoy Nos – Cape Kanin Nos, which separates it from the White Sea. From the east, the sea is limited by the western coast of Vaigach and the Novaya Zemlya islands, and then by the line along the straits bordering the Kara Sea: Cape Zhelaniya – Cape Kohlsaas. In the north, the border is located along the northern edge of the Franz Josef Land archipelago and then from Cape Mary Harmsworth (Alexandra Land Island) through the Victoria and Belyi islands to Cape Leigh Smith on Nordaustlandet Island (Spitsbergen Archipelago).

The Barents Sea is one of the largest Russian seas; its area is 1424 th.km² (according to the other data 1405 th.km²), and its water volume is 316 th.km³ (Arctic and Antarctic Research Institute).

The southeastern part of the Barents Sea between Kolguev Island and the southwestern coast of Novaya Zemlya is called the Pechora Sea. The Kara Gates Strait and Yugorsky Shar Strait are not related to the Pechora Sea (Dobrovolsky and Zalogin 1982; Pavlidis et al. 2007). There are many islands in the Barents Sea, and large archipelagos are its boundaries.

Small islands are located near the coasts or close to larger islands; they are frequently joined into small archipelagos.

Characteristics of the Barents Sea Shores

The length of the coastline of the Barents Sea is 6645 km (Dobrovolsky and Zalogin 1982). Individual regions of the shores are related to different morphological types, which can be seen in Fig. 2.8. The Barents Sea is characterized by a wide variety of shores, which are strongly determined by the structural geological formation of the coast (Alekseevsky 2007). The main types of shore and their characteristics are presented in Table 2.2.

The variations in accumulative shores (beach, lagoon, delta, and foreshore) are widely spread within the Barents Sea (Alekseevsky 2007). Large accumulative marine bodies of different types are characteristic of these shores. The accumulative bodies are represented by the forms of transversal transport of sediments (including the relict bars) and by the forms of alongshore motion. The forms of transversal sediment transport are generally represented by bars and bay-bars (blocking the river estuaries or shallow-water bays) on the shores, formed by loose or easily eroded rocks. Elongated accumulative bodies are formed as a result of the alongshore transport of sediments on gently sloping low coasts of the Pechora Sea formed by loose rocks. These are shown in Fig. 2.9. The most interesting are the tombolos forming the Svyatoy Nos Peninsula, which has a double side supply of material and a large coastal bar (Timansky bereg) with a total length of 200 km. It separates a number of lagoons from the sea and continues to exist as partly flooded islands in the current period: Gulyaevskiye Koshki.

Tombolos are found on the shores of Vaigach Island (including double tombolo), connecting individual islands to each other or with the main coast, as one can see in Fig. 2.10. These tombolos frequently separate lagoons of small area from the sea.

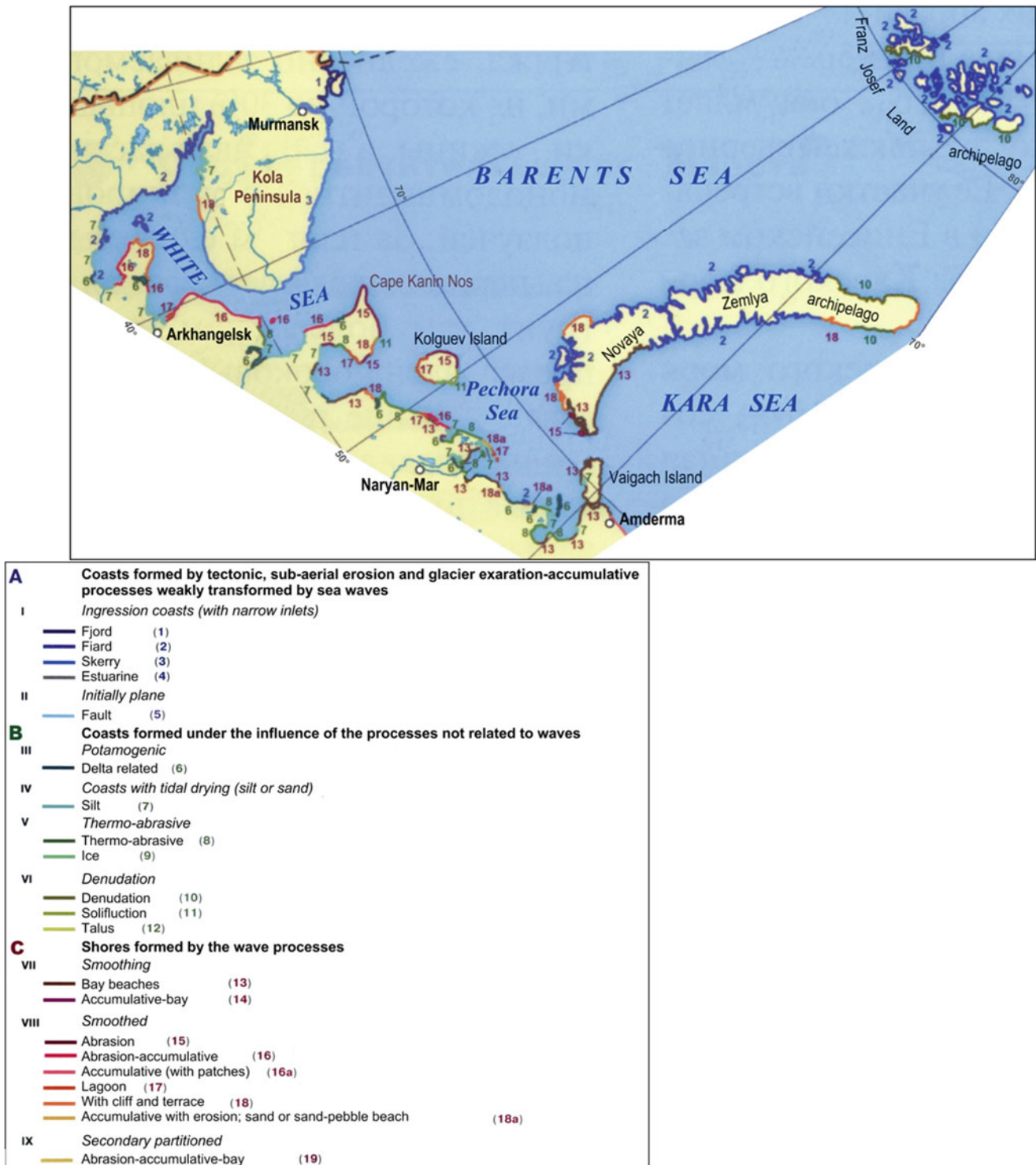


Fig. 2.8 Morphological types of the Barents Sea coasts (Spiridonov et al. 2011), A, B, and C are types of sea shore, I–IX (Roman numerals) sub-types of shore partitioning, 1–19 (Arabic numerals) primary causes of the initial partitioning of the shoreline

The city of Murmansk is situated in the deep Kola Gulf of the Barents Sea (Fig. 2.11). The gulf is 47 km in length and from 1 to 7 km in width and has a tectonic origin, i.e., it is a fjord and not a flooded river valley. The depths at the gulf

entrance are between 200 and 300 m. According to its geomorphological features, the Kola Gulf is conditionally divided into three parts: the south, the middle, and the north. The small Tuloma and Kola Rivers run into the southern part

Table 2.2 Proportion of the shore types in the Barents Sea (%)

Shore type	Continental coast	Islands	Total
Not affected by the sea	29.6	29.5	29.6
Abrasive-denudation	–	7.4	4.9
Abrasive	11.3	5.0	7.2
Abrasive fossil	1.7	7.6	5.6
Thermo-abrasive	16.0	43.2	34.0
Abrasive-accumulative	0.7	2.9	2.1
Accumulative: beach	5.0	2.0	3.0
Lagoon	14.0	2.4	6.3
Foreshore	16.7	–	5.6
Delta	5.0	–	1.7

of the gulf. The hydrological and hydrochemical processes in the Kola Gulf concurrently have features of marine, riverbed, and liman estuaries. This kind of structure and regime is characteristic of many fjord-like gulfs of the Kola Peninsula and the Novaya Zemlya archipelago.

The Kola peninsula is characterized by a great diversity of hydrological conditions. Tides in the gulf are semidiurnal, up to 4 m.

The salinity regime in the Kola Gulf is determined by the degree of desalination of the water of the Barents Sea when mixed with fresh waters. Salinity varies depending on river runoff, spring snow melting, liquid fallout, intensity of water exchange and mixing. The salinity degree quickly decreases with depth. Salinity at all levels beginning at 100 m remains within the range of 34.0–34.5‰ throughout the whole year. At a depth of 50 m in the middle of the Kola Gulf, desalination up to 33.8‰ can be observed. In the middle and northern parts at depths from 10 to 25 m, salinity is about 34‰ in winter and decreases to 32‰ in summer. At a depth of 5 m, salinity is from 32 to 33‰ in winter and decreases to 25‰ in summer. Salinity in the surface layer varies very much throughout the gulf, being no less than 30‰ in winter, and decreasing to a range of 15–20‰ in early summer. The most significant desalination is observed in the southern part of the Kola Gulf, with summer salinity in the surface layer decreasing at a rate of 10–15‰. At the 5 m level, salinity varies from 28 to 32‰ for the better part of the year; from June to August, it decreases to a range between 15 and 20‰. At the 10 m level, salinity remains fixed at no less than 25‰.

Ice phenomena in the Kola Gulf change significantly from year to year. In some years, ice is only observed in the Gulf from February to March; there are years when the southern and middle parts are entirely covered with ice of up to 30 cm thickness. In the most severe winters (1935–1936, 1965–1966, 1978–1979, 1997–1998, 2010–2011, 2014–2015), a complete freezing of the gulf has been observed.

The Kola Gulf coast is home to the largest cities and ports of the Russian Region of the Arctic: Murmansk and Severomorsk. The main sources of gulf water pollution are

industrial, agricultural, and the result of transport enterprises, marine vessels, and settlements. Wastewaters are discharged into the Kola Gulf by 60 large enterprises, about 1000 vessels are attached to the sea ports, and about 4000 port calls are registered every year. Since 2004, the largest Russian off-shore oil shipment terminal, holding 360 thousand tons of oil, has been functioning in the Kola Gulf. One hundred and twenty seven sunken vessels considered to be sources of pollution have been registered in there. Thus, the Kola Gulf ecosystem undergoes extremely severe technogenic pollution.

2.4.2 The Kara Sea

General Characteristics of the Sea

The Kara Sea is a wide open portion of the Arctic Ocean. The major part of the sea is located on a shallow continental shelf. It is related to the continental marginal sea type. The Kara Sea is one of the largest Russian seas. Its square is 883 th.km², the volume is 98 th.km³, the mean depth is 111 m, and the maximum depth is 600 m (Dobrovolsky and Zalogin 1982; Arctic and Antarctic Research Institute 2015).

The western boundary of the sea goes from Cape Kohlsaat (the Frantz Josef archipelago) to Cape Zhelaniya (Desire) (the Novaya Zemlya archipelago) and then along the eastern shores of the archipelago, stretching from the western boundary of the Kara Gates Strait from Cape Kusov Nos (the Novaya Zemlya archipelago) to Cape Rogaty (Vaigach Island) and then along the eastern shore of the island, and finally from the western boundary of the Yugorsky Shar Strait to the continent. The northern boundary goes from Cape Kohlsaat (the Frantz Josef archipelago) to Cape Arctichesky on Komsomolets Island (the Severnaya Zemlya archipelago). The eastern boundary goes along the western coasts of the Severnaya Zemlya archipelago and eastern boundaries of the Krasnoi Armii, Shokalsky, and Vilkitsky straits. The southern boundary goes along the continental coast. Within these limits, the sea occupies the basin between

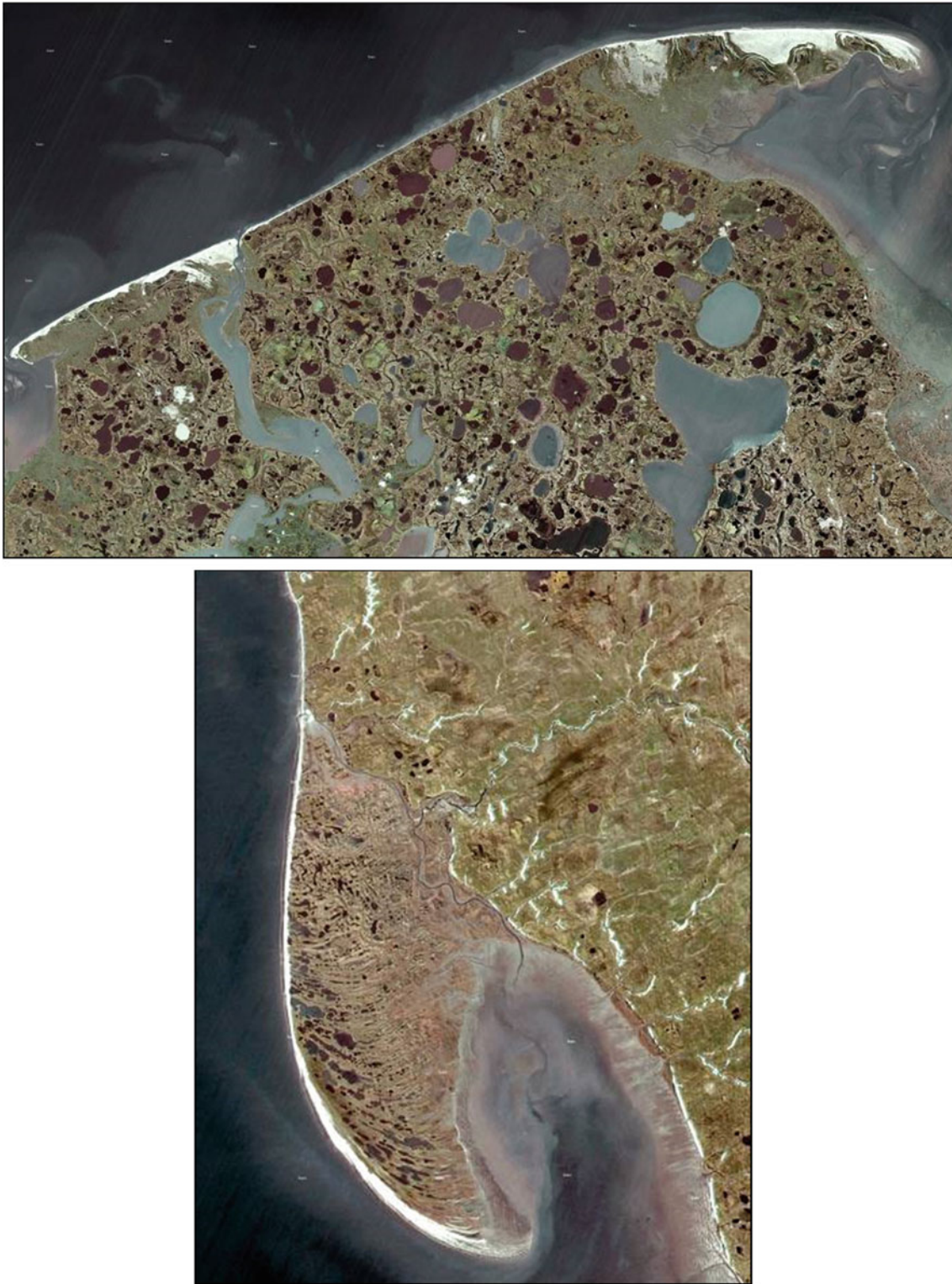


Fig. 2.9 Sand silts in the Pechora Sea (Modified from Kosyan 2013)

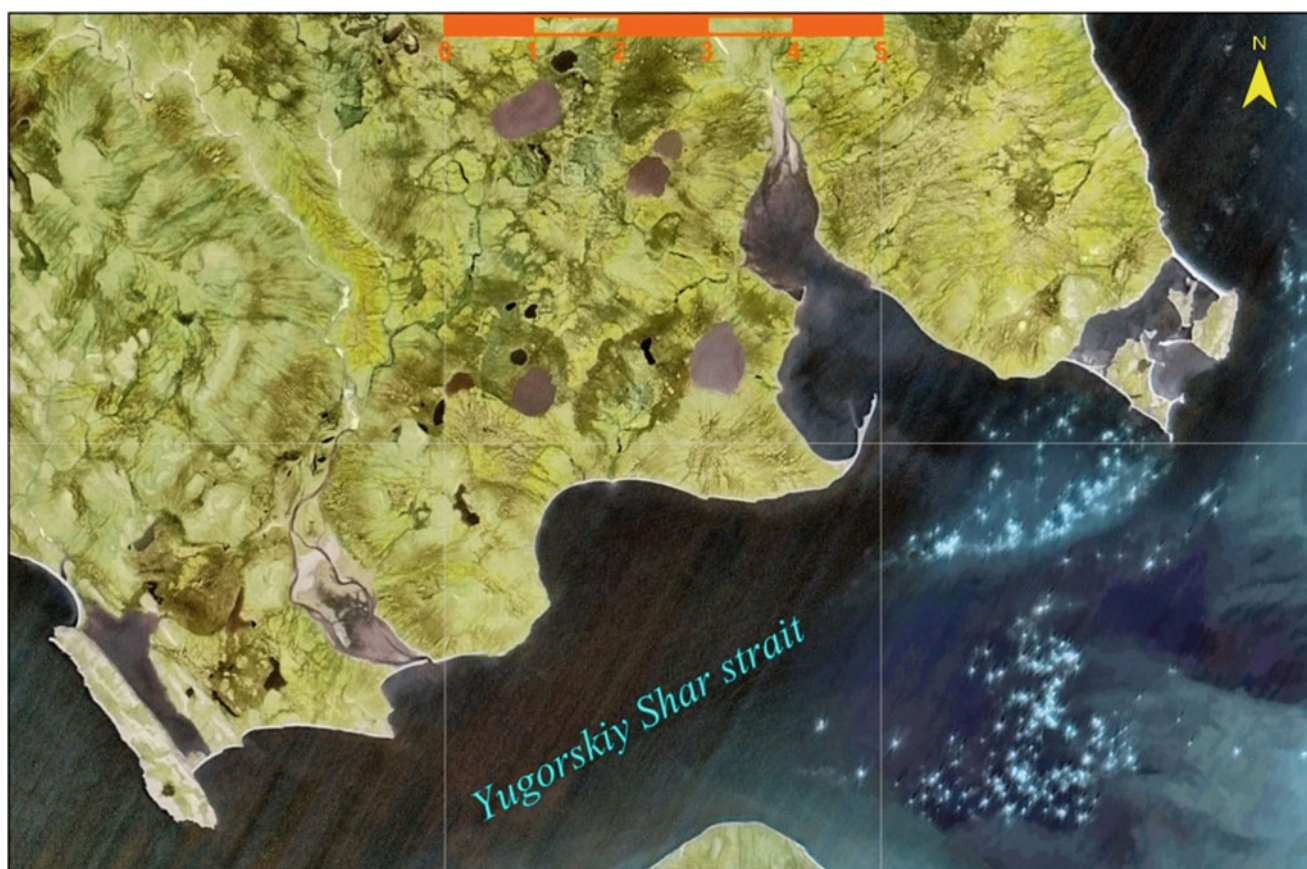


Fig. 2.10 Accumulative bodies; southern coast of Vaigach Island (Modified from Kosyan 2013)

the $81^{\circ}6'$ and $66^{\circ}0'$ N latitudes and the $55^{\circ}2'$ and $104^{\circ}1'$ E longitudes.

There are many islands in the Kara Sea. Most of them are small and located along the continent. The large islands are solitary and the small islands are grouped into archipelagoes.

Characteristics of Shores of the Kara Sea

The coastline length of the Kara Sea is 9790 km. The length of the continental part is 6025 km, and the island part is 3765 km. The abrasion and accumulative shores are almost equally developed. Abrasion shores slightly dominate (mostly thermal abrasion shores), as seen in Table 2.3 and Fig. 2.12.

Accumulative and abrasive-accumulative shores are widely spread in the bays and along the open coasts. They are frequently subject to strong wave erosion.

There are not that many full scale lagoons along the coasts of the Kara Sea, a fact related to the peculiarities of the geological structure of the shores, which does not facilitate the development of accumulative bodies. The domination of alongshore sediment transport, which facilitates the forma-

tion of unclosed accumulative bodies (spits), is another possible cause. We note the existence of several large bays along the western coast of the Yamal Peninsula, partly separated from the sea by spits. The largest is the Sharapov Shar Gulf, separated from the sea by the Sharapovy Koshki Islands, which are accumulative bodies (Fig. 2.13). Strong tides prevent the formation of continuous accumulative shores.

Lagoon shores are widely spread along the northern part of Belyi Island (Fig. 2.14), as well as the Olenyi, Shokalskogo, and Sibiryakova Islands, and on the Gydansky Peninsula. These lagoons are not large. Usually, they are the flooded valleys of small rivers separated from the sea by accumulative spits and bay-bars created out of the erosion material of low bedrock shores made up predominantly of sands, loams, and clays with numerous ice veins.

The largest estuaries of the Russia Arctic coast are the estuaries of the Kara Sea. Here are situated the liman type estuaries of the Ob River (with the adjoining estuary of the river Taz) and the Yenisei River (Fig. 2.15). In addition, the Baidaratskaya Guba and Gydanska Guba (“guba” – the local name for a deep sea bay) can be considered estuaries of the sea type. About 40 % of the Kara Sea water area is influenced by river runoff. The rivers carry 1290 km^3 of fresh water per



Fig. 2.11 Kola Bay of the Barents Sea (Modified from Kosyan 2013)

year into the sea, 80 % of which comes in during the period from June to October. The Yenisei brings 600 km³ of water per year, the Ob, 450 km³, the Pur and Taz, 86 km³ together, the Pyasina, 80 km³, and the others, about 74 km³ all together.

Ob River Estuary

The Ob River estuary (the Gulf of Ob, the local name of the Obskaya Guba) is the largest gulf of the Kara Sea. The gulf separates the coasts of the Gydan peninsula in the east and

Table 2.3 The types of the Kara Sea shores (%)

Shore type	Continental coast	Islands	Total
Lightly or weakly transformed by sea	16.3	35.0	23.5
Abrasive as a whole, including:	24.8	32.4	27.7
Abrasive	4.3	8.6	5.9
Thermo-abrasive	19.3	19.3	19.3
Abrasive-denudation	–	1.7	0.7
Abrasive with fossil cliff	1.2	2.8	1.8
Abrasive-accumulative	23	11.7	19.3
Accumulative:	25.4	20.9	23.6
Beach	10.5	14.9	12.2
Lagoon	3.2	6.0	4.3
Setup (foreshore)	11.7	–	7.2
Delta	10.5	–	6.4

the Yamal in the west (Fig. 2.15). The estuary is about 800 km in length (many researchers consider it to be the longest estuary in the world). The width of the estuary ranges between 30 and 80 km, the total area is 20,800 km², and its volume is 400 km³. The lowest depth of the estuary reaches 25 m, but throughout most of its area, it varies within a range of 10–15 m. Between the estuary and the main sea, there is the Ob bar, a sand-bar in the most active part of the estuary runoff cone resulting from river sediments deposited in the area where the river flows into the sea. The Ob estuary bottom is of firm mud, and only along the coast are there some sand banks.

The Tazovskaya Guba, i.e., the estuary of the Taz and Pur rivers, is on the same side as the Ob estuary in the east (Fig. 2.15). Besides the Ob and Taz Rivers, several small rivers run into the Ob estuary, sometimes forming island archipelagos near the estuaries. The Ob estuary coasts are steep in the west and flatter in the east. Islands only occur in the small river mouths, and there are few gulfs and bays. The Ob estuary coast is woodless, being dominated by marshy Arctic tundra.

The current look of the Gulf of Ob came about during the Holocene transgression, when the Kara Sea waters flooded the bed and floodplain of the lower Ob. Coastal thermoabrasion and erosion caused a significant widening of its lower valley, and the estuary deepening took place as a result of the river's thermic impact upon the bed permafrost. At present, these processes are still going on in the gulf.

The Ob estuary's hydrological regime is determined by the river Ob delivering 75.8% of the river runoff, i.e., 530 km³. The main feature of the Ob basin is a huge watershed of 2,770,000 km², 75 % of which is a heavy wetland. A minor slope of the river basin in its flat area leads to a high degree of natural regulation of the runoff. The Ob River has a prolonged high water in the spring and summer. Starting in

October and continuing throughout the entire winter, the river runoff sharply decreases. During the high water period, the greater part of the estuary has a hydrologic regime similar to that of a river; in the lower water period of winter, the regime is similar to that of a lake, and the importance of meteorological components, i.e., winds and related positive and negative setups, the amplitude of which can reach from 3 to 4 m, grows sharply at that time.

A tidal wave 0.5 m in height in the Kara Sea would first grow to two or three times its initial size when entering the estuary (the tide amplitude reaches 1.85 m), and then gradually decrease to zero in the Ob estuary. Positive setups in the Gulf of Ob are caused by the north, west, and northwest winds. Slight level rises can be observed under the southwest winds. Negative setups are caused by the east, south, and southeast winds.

The currents in the Ob estuary are generated by interaction between permanent, tidal, and windy currents. The permanent currents are formed by the Ob river runoff; they are directed to the north at a rate of 0.05–0.1 m/s. The tidal current at the estuary's entrance is semidiurnal, with reverse motion in the tidal cycle. The highest rates are observed in the northwest part of the Gulf of Ob and reach 0.6–0.7 m/s. In the surface layer, the rate of summary currents can reach 1.4 m/s, and at the bottom level (20 m), the maximum rate to have been observed is 0.5 m/s.

The Ob estuary stretches from the south to the north, a fact that has a significant effect on its ice regime. The greater part of the Gulf of Ob, excluding its southern part, freezes up in October. The estuary becomes completely free of ice in July.

In accordance with modern scientific classification, the Gulf of Ob is a microtidal, vastly stratified estuary of the liman type. The water in the greater part of the Ob estuary is fresh and contains a large amount of suspended matter. The area bordering the salt waters of the Kara Sea (the frontal

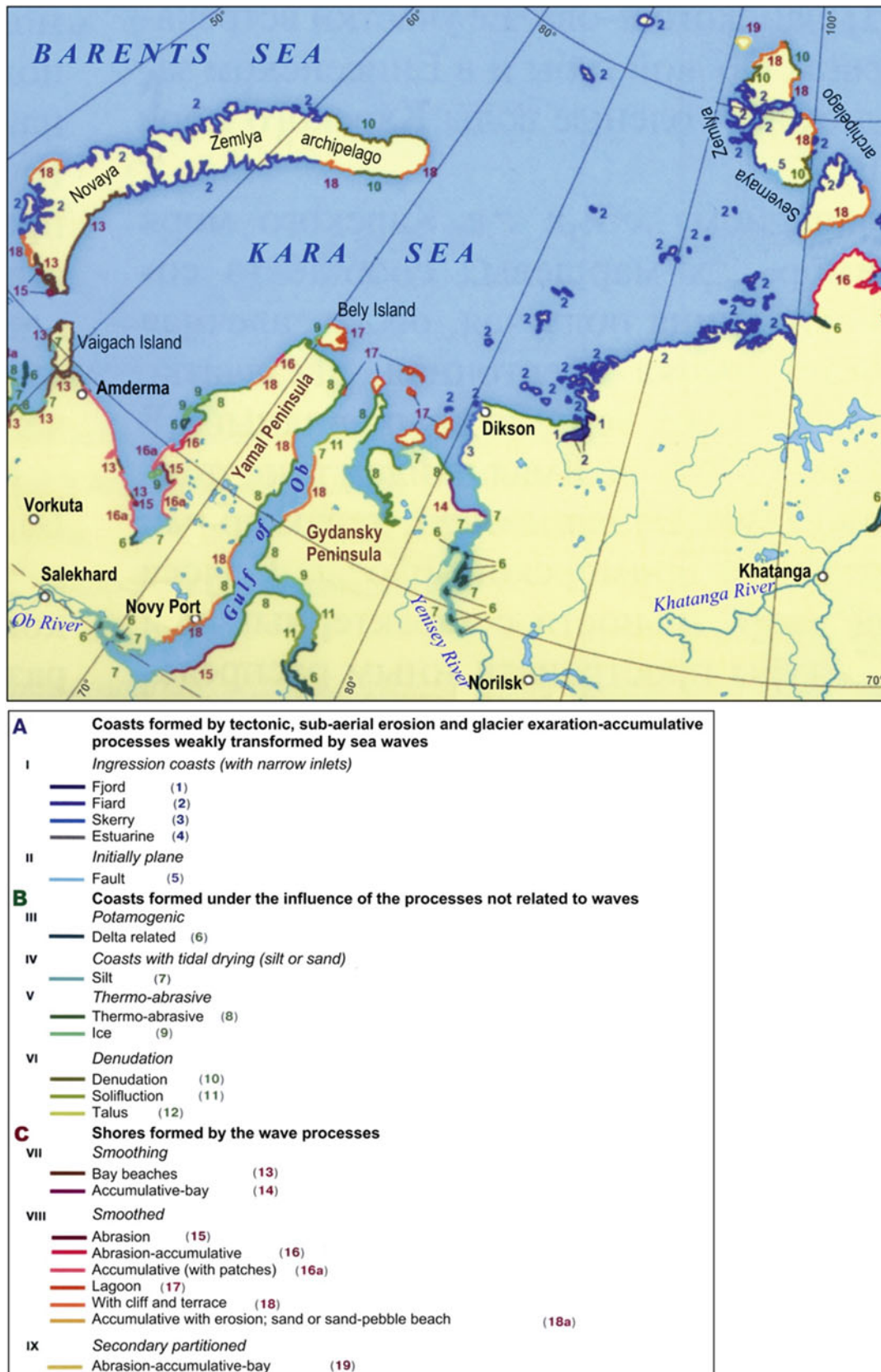


Fig. 2.12 Morphological types of the Kara Sea coasts (Spiridonov et al. 2011), A, B, and C are types of sea shore, I–IX (Roman numerals) sub-types of shore partitioning, 1–19 (Arabic numerals) primary causes of the initial partitioning of the shoreline

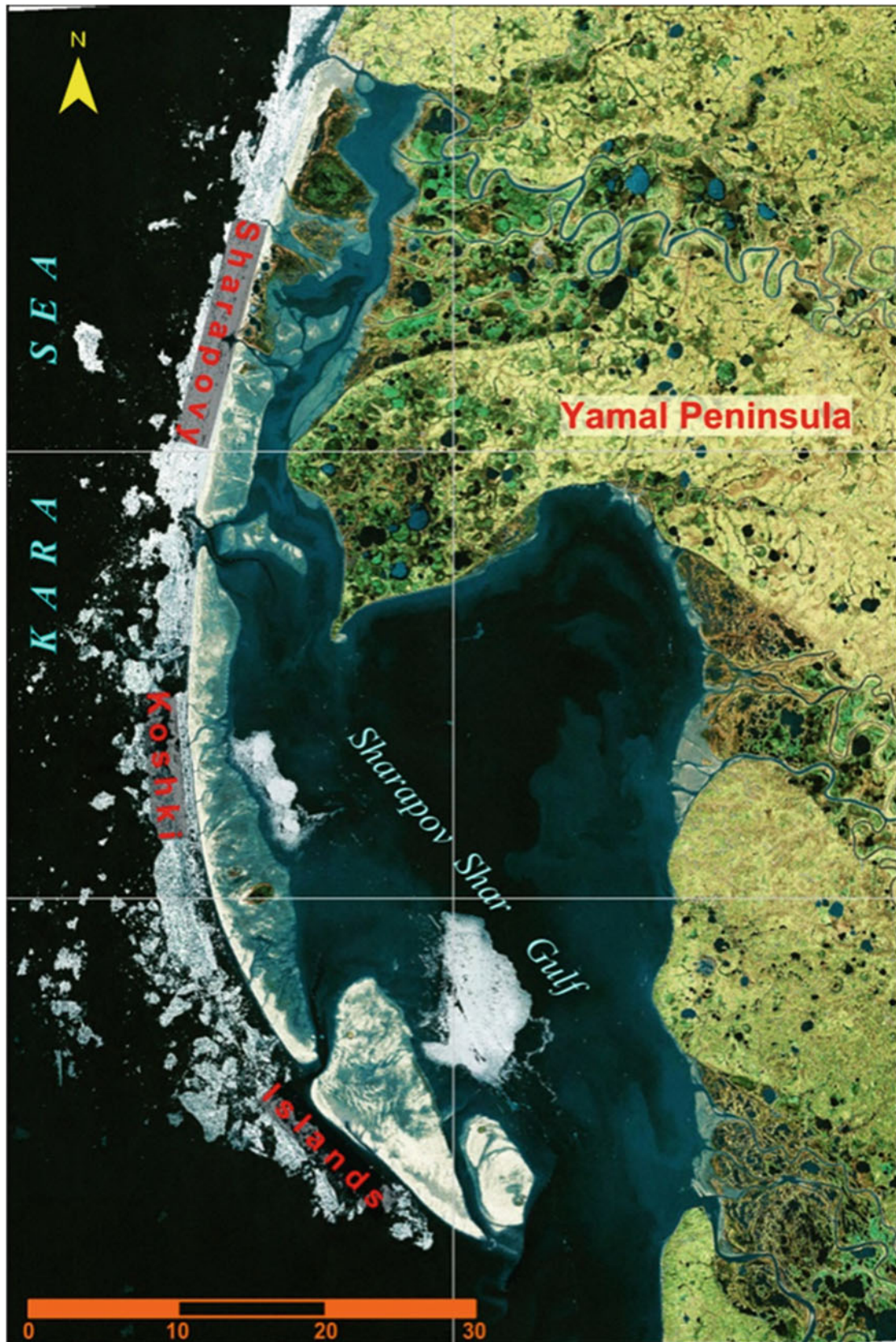


Fig. 2.13 Sharapov Koshki Islands formed by accumulative processes and the Sharapov Shar Gulf (the Kara Sea, Yamal Peninsula) (Modified from Kosyan 2013)



Fig. 2.14 Belyi Island and the adjacent coast of the Kara Sea (Modified from Kosyan 2013)

zone) is flexible: during the high water period, it is located at 50 km from the sea, and by the end of winter, it moves up to 300 km to the south. The complicated dynamic interaction between the fresh runoff and the Kara Sea salt waters takes place in the north gulf; and the physicochemical, biochemical, and biological processes occurring on the boundary between the fresh water biocenosis and that of the marine area also intensify here. The bioproductivity of the Ob estuary is higher than that of the Ob River itself. The Ob estuary *ichthyofauna* includes more than 60 sea and freshwater species and subspecies.

In the flood-land of the Gulf of Ob lies the Nizhne-Obsky reserve, with a total area of 128,000 ha. The reserve territory is included on the list of wetlands of international importance

(“Islands of the Kara Sea Gulf of Ob”, Ramsar Convention). The reserve was organized for the purpose of maintaining the safety of rare species of animals, as well as protecting the nesting places and habitats of the indigenous birds.

Some small settlements, such as Novy Port, Yamburg, and Mys Kamenny, are situated on the Ob estuary coast.

The water areas of the Ob and Taz estuaries, as well as the Ob River, are used for navigation. These waterways facilitate cargo delivery to and from the area of the northern regions of West Siberia (Yamalo-Nenets Autonomous Okrug) to the Taimyr peninsula and Krasnoyarsk Krai. Similar delivery and removal of necessities for the West Siberian oil and gas basin are accomplished through the Taz estuary to the Pur and Taz rivers. Navigation and cargo transportation are pro-



Fig. 2.15 Estuaries of the Kara Sea: 1 Obskaya Guba, 2 Tazovskaya Guba, 3 Yenisey Gulf, 4 Baidaratskaya Guba, 5 Gydanska Guba (Modified from Kosyan 2013)

vided by the Enisey ship company. This cargo transportation is realized by special vessels which have a permit to work under the coastal conditions of the Kara Sea. The terms of cargo transportation are determined by the ice conditions. The navigation in this region usually takes place from August until the end of September.

Over the last few decades, a large number of oil and gas fields were discovered on the coast close to the Ob estuary and on its bottom. The Novy Port field is located within 30 km of the Gulf of Ob coast. The recoverable reserves of the Novy Port oil and gas condensate field exceed 230 million tons of oil and 279 billion cubic meters of gas; it is one of the largest fields of the Yamal. By 2020, it is estimated that 6–9 million tons of oil will be extracted there per year. The field is located far from the existing overland transport infrastructure, so it is necessary to transport the oil by waterway. For loading ships, by the end of 2015, OJSC “Gazprom Neft” plans to put the marine terminal Novy Port in the Ob estuary near the cape of Kamenny into operation. By 2019, the marine terminal will ship 8.5 million tons of oil per year. The port is planned so as to be able to receive tankers of Arc6 ice class with maximum deadweight up to 55 thousand tons, draught up to 9 m (fresh water), and maximum width from 32 to 34 m. The tankers will accomplish year-round cruises for the purpose of transporting oil to the ports of Murmansk and Rotterdam (the Netherlands).

Port Sabetta is already being built on the west coast of the Ob estuary. Port Sabetta, with an annual freight turnover of 30 million tons, will become one of the largest in the Russian Arctic. When the port is put into operation, the freight flow through the Gulf of Ob and Northern Sea Route will grow. Port Sabetta will become a key element in the transportation infrastructure of the Yamal LNG project, which provides for starting up a liquefied natural gas plant (LNG) on the resource base of the Yuzhno-Tambey field. Terminals for loading LNG and gas condensate will be built. The plan provides for dredging in the area of the Ob estuary, including laying a marine canal through the Ob bar of 49 km length, 295 m width, and 15.1 m seabed level. The general volume of the dredging is about 70 million cubic meters. Port Sabetta will function all year round, despite the severe ice conditions in the Ob estuary. As the Ob estuary is free of ice for only 3 months a year, it is supposed that the year-round oil removal can be accomplished using icebreakers. The nuclear-powered icebreakers “Yamal” and “Taimyr” are already working on the route to provide for navigation. The open-sea icebreaker “Yamal” brings ships to the Ob estuary, where the shallow-draught nuclear-powered vessel “Taimyr” accompanies them to Port Sabetta. The nuclear-powered icebreaker “Vaigach” will lay and renew channels for vessels going from Port Sabetta to Port Dudinka in the Yenisei estuary.

Gas production is also planned in the Ob estuary water area. The Kamenny Mys field is located in the southern part of the Ob

estuary between the Kamenny and Parusny Capes. Specialists estimate its reserves to be around 534.7 billion cubic meters. Gas production, with drilling planned in 42 wells, will begin here in 2021. For the main multiwell pad, they will use an ice-resistant platform, a metallic construction of 100 m length and 60 m width. The platform will be fixed on piles to the bottom of the Gulf of Ob; there will be a drilling installation on it, and after drilling, there will be gas conditioning equipment. In addition to that, a living settlement and gas conditioning installation are planned for construction on the Parusny Cape in the Nadymsky District. The objects will be connected to the Yamburg settlement infrastructure by the 80 km gas pipeline. By 2030, the Gasprom company will produce, in total, 50 billion cubic meters of gas per year in the Ob and Taz estuaries.

Thus, the Ob estuary and its coasts will eventually become a busy navigable and oil and gas production zone. Human interference will adversely affect the ecology of the Ob estuary. A marine canal of 50 km length and 300 m width will be laid through the Ob bar, located in the area adjacent to the main sea. The canal is necessary for high capacity tankers to pass into the ports. The Ob bar (a shallow area of the Gulf of Ob at the river-sea boundary) is a natural obstacle for the Kara Sea salt waters on their way to the south towards the freshwater estuary area. The canal construction will lead to an increase in the penetration of salt seawaters deep into the estuary and to changes in the Gulf of Ob's ecosystem. As a result, the volume of the Ob estuary's fresh water portion, which forms the basis for biological productivity in the ecosystem of the entire Ob basin, will decrease.

Yenisei River Estuary

The Yenisei estuary has a total length of 500 km and its width at the entrance is about 200 km. According to the geomorphological features, the estuary is divided into the silt delta, the Yenisei liman, and the Yenisey Gulf (Fig. 2.15). The Yenisei delta is about 180 km in length and includes the river segment from the settlement of Ust-Port on Nasonovsky Island. The liman, at a length of 115 km, begins at the north part of Nasonovsky Island; its external boundary is the Sopochynaya Karga Cape. The north part of the Yenisei estuary is called the Yenisei Gulf; its marine border is a line between the Mattesal Cape (Yavai peninsula) and the Severo-Vostochny Cape (near the Dikson settlement). The marine boundary of the estuary is not exactly defined; some researchers draw it along the straits to the east and to the south of Sibiriyakov Island. Others set it as the entire water area within the line marked by the Shokalsky, Vilkitsky, and Dikson Islands, including the vast Gydan Gulf.

The depth of the Yenisei Gulf is 6–15 m; to the east of Sibiriyakov Island, the gutter of the flooded Yenisei River valley, with a depth of 20–35 m, can be observed. Tides are semidiurnal, up to 0.4 m. The thermic and salinity regimes are determined by the volume of the Yenisei river runoff. The frontal zone has seasonal dynamics; the deepest penetration

of seawater into the estuary is observed from February to March. In winter, the gulf is covered with fast ice and with drift-ice in the north. The Yenisei Gulf water freezes in October and the ice starts to break in June.

Sea routes to the ports of the lower Yenisei Dudinka and Igarka pass through the Yenisei Gulf. Port Dikson, providing navigation along the Northern Sea Route, is located on the eastern coast near the entrance to the Yenisei Gulf.

Within the northern part of the Gydan Peninsula and on the islands of the west Yenisei estuary, the Gydansky State Natural Reserve is situated. The reserve was established in 1996 to protect the undisturbed tundra ecosystems of West Siberia, and the coastal and marine ecosystems of the Kara Sea, as well as places of mass bird nesting.

2.4.3 The Laptev Sea

General Characteristics of the Sea

The Laptev Sea, in its modern boundaries, is characterized by the following measures: the area is 662 th.km², the volume is 353 th.km³, the mean depth is 533 m, and the maximum depth is 3385 m. The western boundary runs along the eastern coasts of the Severnaya Zemlya archipelago from Cape Arctichesky (Komsomolets Island) and then along the Krasnoi Armii Strait, then follows the eastern coast of Oktyabrskoi Revolyutsii Island to Cape Anuchina, through the Shokalskogo Strait to Cape Peschanyi on Bolshevik Island and along its eastern coast to Cape Vaigach, then spans the eastern boundary of the Vilkitskogo Strait and up the continental coast to the top of the Khatanga Gulf. The northern boundary of the sea goes from Cape Arctichesky to the crossing of the meridian of the northern edge of Kotelny Island (139° E) with the conventional edge of the continental shallow bank (79° N, 139° E). The eastern boundary goes from the above-mentioned point (79° N, 139° E.) to the western

coast of Kotelny Island and then along the western boundary of the Sannikov Strait, turning around the western coasts of Bolshoi and Malyi Lyakhovskiy Islands, and then continuing along the western boundary of the Dmitry Laptev Strait. The southern boundary goes along the continental coast from Cape Svyatoi Nos to the top of the Khatanga Gulf.

Within these boundaries, the sea is located between 81°16' and 70°42' N latitudes, and 95°44' and 143°30' E longitudes. According to its geographical location and hydrological conditions, which are different from those of the ocean, despite the sea being openly connected, the Laptev is related to the continental marginal sea type (Dobrovolsky and Zalogin 1982).

Characteristics of the Shores of the Laptev Sea

The length of the coastline of the Laptev Sea is 5900 km. The length of the portion along the continent is 3880 km, and the portion along islands is 2020 km. The coasts are related to different morphological types, which can be seen in Table 2.4 and Fig. 2.16.

Abrasive and accumulative shores in the Laptev Sea are almost equally numbered, with a slight domination of abrasive shores, as seen in Table 1.3 (Alekseevsky 2007). To the greatest degree, this is characteristic of the continental shores. Low shores are only a small part of the total length of the coastline of the sea.

A large amount of terrigenous material transported to the coastal zone from the rivers, as well as from the shallow submarine slope, facilitates the development of accumulative shores that form the edges of the plane. The rapid modern freezing of the sediments accumulated in the coastal zone and the intense formation of frozen columns facilitate stabilization of the sea shores, even if the relative amounts of the transported sediments is not high. Sea basins separated from

Table 2.4 The types of the Laptev Sea shores (%)

Shore type	Continental coast	Islands	Total
Lightly or weakly transformed by sea	1.7	20.5	8.2
Abrasive as a whole, including:	33.9	38.3	35.3
Abrasive	12.5	12.6	12.5
Thermo-abrasive	13.9	19.8	15.9
Abrasive-denudation	2.8	5.9	3.9
Abrasive with fossil cliff	4.7	–	3.0
Abrasive-accumulative	13.6	14.4	13.9
Accumulative:	32.8	26.8	30.8
Beach	9.2	9.7	9.3
Lagoon	6.7	8.9	7.5
Setup (foreshore)	17.0	8.2	14.0
Delta	17.9	–	11.8

Alekseevsky (2007)

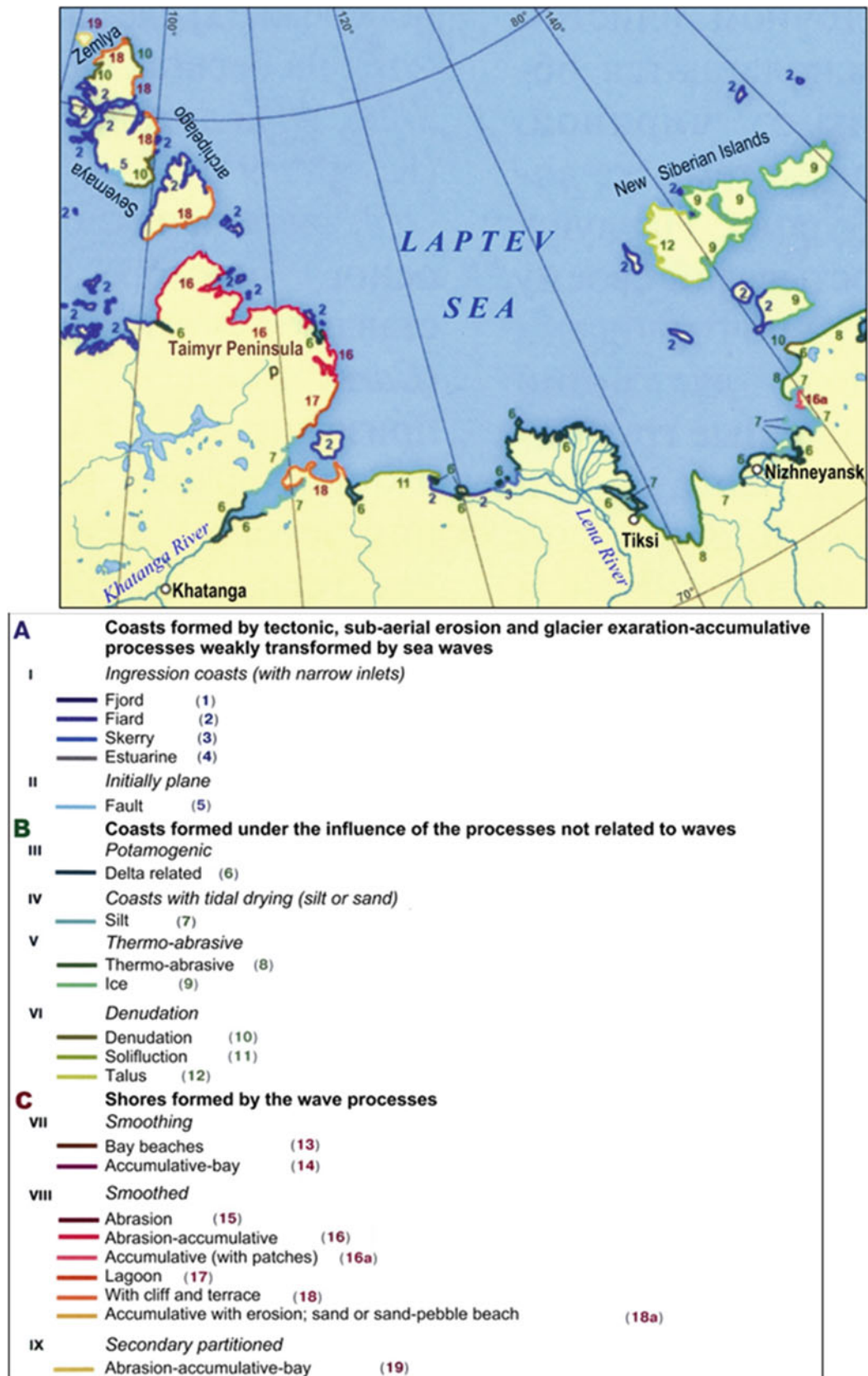


Fig. 2.16 Morphological types of the Laptev Sea coasts (Spiridonov et al. 2011), A, B, and C are types of sea shore, I–IX (Roman numerals) sub-types of shore partitioning, 1–19 (Arabic numerals) primary causes of the initial partitioning of the shoreline

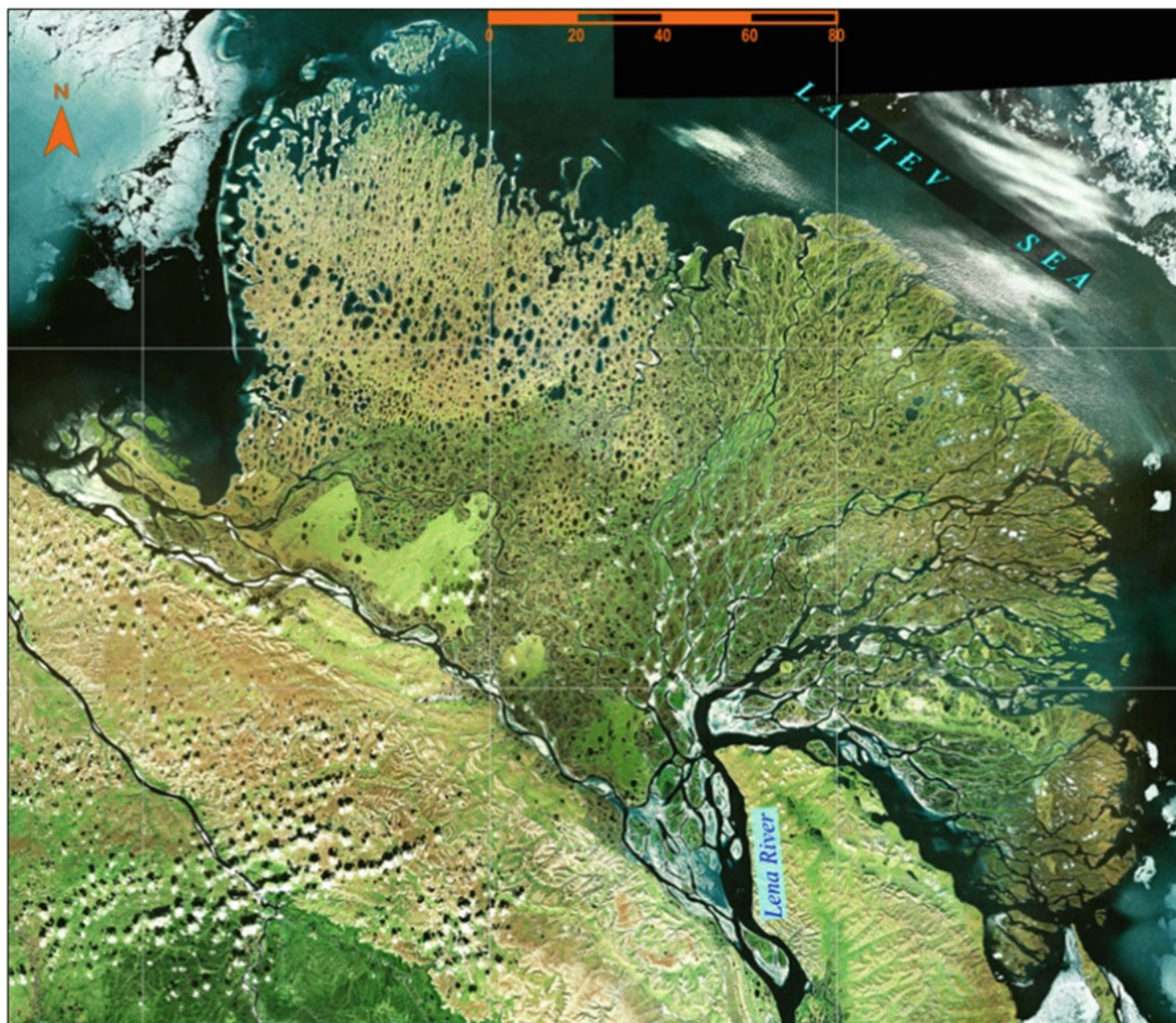


Fig. 2.17 The Laptev Sea, the Lena River delta (Modified from Kosyan 2013)

the sea occur under specific conditions, appearing in the deltas of the Lena and Yana, in shallow bays (Yana, Khromskaya Guba). In particular, the stable condition of a long sandy barrier that borders the northwestern part of the Lena River was recorded during the period 1969–2001 (Fig. 2.17) (Alekseevsky 2007).

Abrasive regions alternate with accumulative bodies along the eastern coast of the Taimyr Peninsula, where coastal steps are eroded in the sand-stone, schists, and also in loose Quaternary deposits. Edge bars formed of sand and pebble material separating small lagoons from the sea are observed most frequently (Alekseevsky 2007). Lagoons at the mouths of rivers are widely spread along the low shores of Khatanga Bay and the Begicheva Islands.

Several lagoons are located on the northwestern coast of Kotelny Island (the Novosibirskiye Islands archipelago) (Fig. 2.18), including the Stantsii, Reshetnikova, Eselyakh, Nerpalakh, and Durnays lagoons.

Khatanga and Anabar River Estuaries

The Khatanga river estuary (Khatanga Gulf) is in the southwest portion of the Laptev Sea. The gulf is about 230 km in length, and its maximum width is about 50 km (Fig. 2.19). The water exchange with the sea is realized via the Vostochny (8 km in width) and Severny (13 km in width) straits, separating the large Bolshoy Begichev Island. The Khatanga estuary includes the Kozhevnikov Bay and the Nordvik Bay situated in the west Khatanga Gulf. Throughout most of the



Fig. 2.18 Lagoons on Kotelnyi Island (the Novosibirskiye Islands archipelago) (Modified from Kosyan 2013)

gulf, the depths are from 8 to 20 m, while its central part features a gutter with a depth from 20 to 30 m that stretches towards the Severny strait, marking the location of the Khatanga river valley flooded by the sea.

The Anabar river estuary (Anabar Gulf) is located to the east of the Nordvik peninsula. The gulf is conical, widening in the direction of the sea, a shape similar to that of the “classic” estuary. The gulf goes 70 km into the continent and its

width near the entrance is 76 km. The greater part of the Anabar Gulf is less than 10 m in depth, but the flooded bed of the Anabar River can be seen as a gutter with a depth of up to 17 m.

The coasts of the Khatanga and Anabar Gulfs are mainly high and indented, destroyed as a result of thermoabrasion. Tides are semidiurnal, up to 1.4 m. For much of the year (from October to July), the Khatanga and Anabar gulfs are covered with ice.



Fig. 2.19 Khatanga estuary (1) Anabar estuary (2) and Nordvik Bay (3) (Modified from Kosyan 2013)

2.4.4 The East Siberian Sea

General Characteristics of the Sea

The East Siberian Sea, in its modern boundaries, is characterized by the following measures: the area is 913 th. km², the volume is 49 th. km³, the mean depth is 54 m, and the maximum depth is 915 m. The western boundary goes from the crossing of the meridian at the northern edge of Kotelnii Island with the edge of the continental shallow bank (79° N, 139° E) to the northern edge of this island (Cape Anisii) and then follows along its western coast to the eastern boundary of the Laptev Sea. The northern boundary goes along the edge of the shallow continental

bank from the point with coordinates 79° N, 139° E to the point with coordinates 76° N, 180° E. The eastern boundary goes from the point with coordinates 76° N, 180° E along the 180° meridian to Wrangle Island and then along its northwestern coast to Cape Blossom and further to Cape Yakan on the continent. The southern boundary goes along the continental coast from Cape Yakan to Cape Svyatoi Nos (the western boundary of the Dmitry Laptev and Sannikov straits).

According to its geographical location and hydrological conditions, the sea is related to the continental marginal seas (Dobrovolsky and Zalagin 1982).

Table 2.5 The types of the East Siberian Sea shores (%)

Shore type	Continental coast	Islands	Total
Not transformed by sea	—	—	
Abrasive-denudation	3.3	5.1	
Abrasive	4.8	15.2	
Abrasive fossil	1.9	1.0	
Thermo-abrasive	21.9	29.9	
Abrasive-accumulative	5.6	8.2	
Accumulative beaches	4.6	26.0	
Lagoon	3.3	1.0	
Setup (foreshore)	35.0	13.1	
Delta	19.6	0.5	

Alekseevsky (2007)

Characteristics of the Shores of the East Siberian Sea

The length of the coastline of the East Siberian Sea is 5090 km. The length of the portion along the continent is 3145 km, and the portion along islands is 1945 km (Alekseevsky 2007). A characteristic peculiarity of the sea is a long extension of the accumulative coasts (41.8 %), especially on the islands, which can be seen in Table 2.5 and Fig. 2.20.

Processes of setup-setdown accumulation, together with thermo-abrasion processes, dominate in the western (greater) part of the East Siberian Sea. In the eastern (smaller) part of the sea, the processes of wave accumulation, combined with abrasion, dominate (Alekseevsky 2007; Kaplin et al. 1991). The development of absolutely different forms within one sea were a consequence of the differences in the submerged slopes of the coastal zone, existence of the resources and sources of sediments, and peculiarities within the wind-wave regime.

Sediments of low granulometric size (fine grain sands and clays) dominate in the western part of the region. Such sediments are not capable of remaining within the coastal zone in the major part of the shores of the other seas, and are transported to the deep sea. The East Siberian Sea, among the other Arctic seas, is characterized by the greatest shallowness. The depths in many regions at a distance of 3 km from the coast hardly reach 1–2 m, while the slopes of the bottom within 0.0003–0.0004 continue up to a distance of 18 km from the coast (Alekseevsky 2007). A low gently sloping lacustrine-alluvial plane approaches the sea from the land side. The wave impact on the shore is decreased due to the low slopes of the bottom and the ice cover during the better (80 %) part of the year. Under such conditions, the main fac-

tor forming the coast becomes the setup-setdown phenomena. Wide (up to 4–5 km) silt foreshore regions were formed along the coastline of the sea (Fig. 2.21). The water edge within these regions migrates, depending on the synoptic situations. Vegetation is not formed here. Low current velocities facilitate the accumulation of clay particles. Fine sediments are transported along the surface of the foreshore regions by setup currents, gradually filling them (Alekseevsky 2007).

Large volumes of loose material (silt and fluvio-glacial) on the submarine slope in the eastern part of the sea and wave forcing that intensifies in the eastern direction facilitate intense accumulation.

Many of the accumulative lagoon systems are distinguished for their peculiar internal partition into a number of round basins. A complex bay-bar near Cape Billings, shown in Fig. 2.22, is the most interesting accumulative body of such type. The bay-bar of Cape Billings separates the basins of several oval lagoons from the sea: the Valkakinmanka-1 (western) and Valkakilmanka-5 (eastern) lagoons. The marks of the storm ridge reach 5.4 m and even 6.8 m, together with the dune (Alekseevsky 2007; Kaplin et al. 1991). V.P. Zenkovich suggested that such accumulative bodies were formed as a result of the formation of “mirror” series of spits of the Azov type (Kaplin et al. 1991). However, there is no commonly accepted opinion about the formation mechanism of such natural structures. Different researchers consider this accumulative body to be a spit, a double bar with remains of edoma in the rear part (Tarakanov et al. 1981).

Small lagoons are located at the southern edge of Wrangle Island: the Popova, Davydova, and Predatelskaya lagoons. The entire territory of Wrangle Island and the adjacent sea basin are natural state reserves.

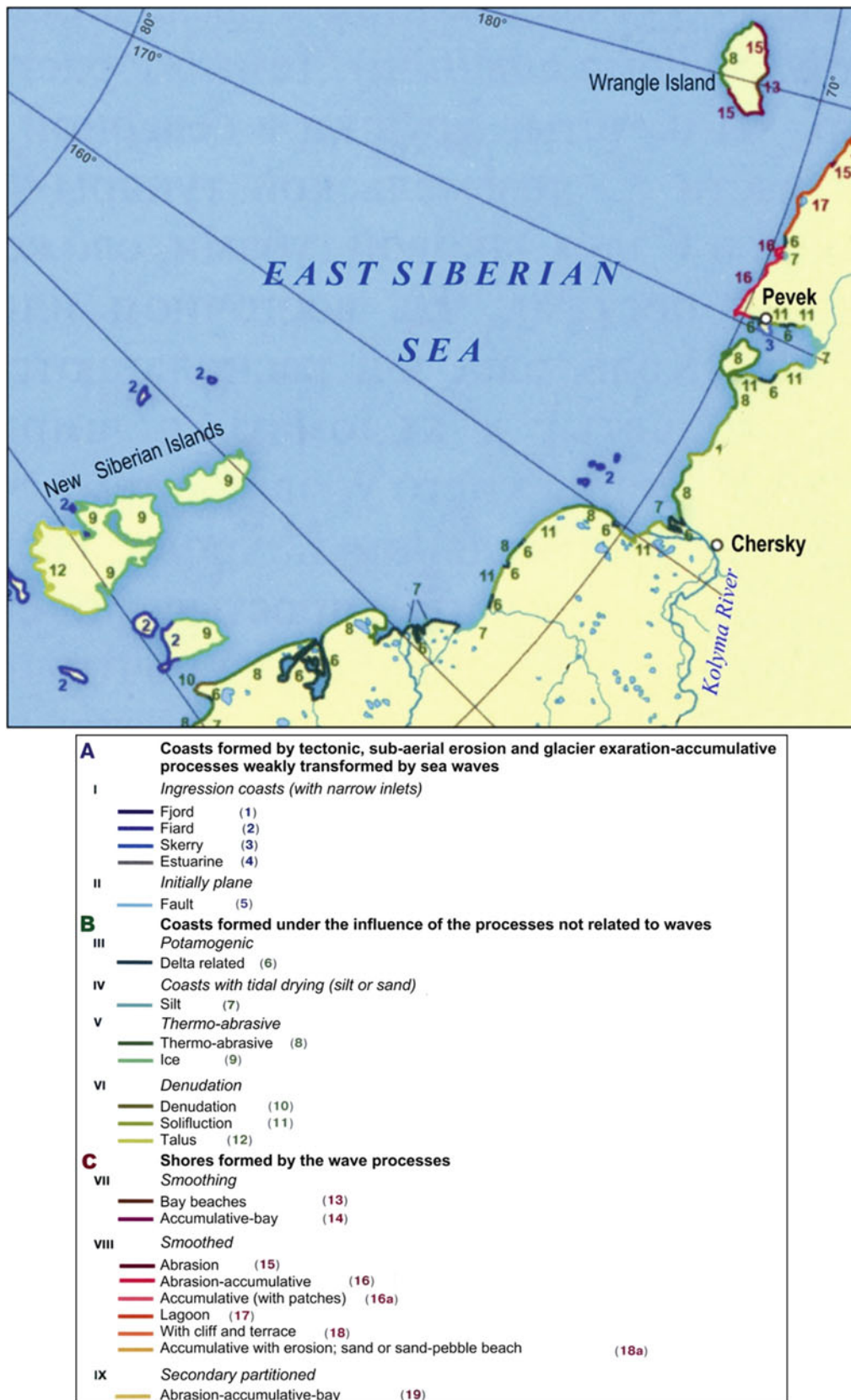


Fig. 2.20 Morphological types of the East Siberian Sea coast (Spiridonov et al. 2011). A, B, and C are type of sea shores I–IX (Roman numerals) sub-types of shore partitioning 1–19 (Arabic numerals) primary causes of the initial partitioning of the shoreline



Fig. 2.21 Silt foreshore regions in the western part of the East Siberian shore (Modified from Kosyan 2013)



Fig. 2.22 East Siberian Sea, complex bay-bar near Cape Billings separates the Innukay Lagoon (*left*) and Valkakinmanka-1 – Valkakinmanka-5 lagoons (*round*) (Modified from Kosyan 2013)

2.4.5 The Chukchi Sea

General Characteristics of the Sea

The Chukchi Sea is partly limited by land and partly by conventional lines. The western boundary goes from the point that crosses meridian 180° with the edge of the continental shallow bank (76° N, 180° E) along the 180° meridian to Wrangle Island and then along the eastern boundary of the East Siberian Sea. The northern boundary goes from the point with coordinates 72° N, 156° E to Cape Barrow in Alaska. The eastern

boundary goes along the continental coast of Alaska to the southern entrance cape of Sishmarev Bay (Cape Seward). The southern boundary of the Chukchi Sea goes along the northern boundary of the Bering Strait from the southern entrance cape of Sishmarev Bay (Cape Seward) to Cape Unikan (Chukchi Peninsula) and then along the continental coast up to Cape Yakan. The Longa Strait is also related to the Chukchi Sea, its western boundary stretching from Cape Blossom to Cape Yakan. The eastern boundary of the strait goes from Cape Pillar (Wrangle Island) to Cape Schmidt.

Within these boundaries, the sea occupies the basin between 76° and 66° N latitudes and 180° E and 156° W longitudes. The area of the sea is 595 th.km², its volume is 42 th.km³, the mean depth is 71 m, and the maximum depth is 1256 m. According to its geographical location and free connection with the Arctic Ocean, the Chukchi Sea is related to the continental margin sea type (Dobrovolsky and Zalogin 1982). The majority of Wrangle Island and the entirety of Herald Island are related to the basin of the Chukchi Sea.

Characteristics of the Shores of the Chukchi Sea

The length of the coastline of the Chukchi Sea is 1705 km. The length of the portion along the continent is 1300 km, and the portion along islands is 405 km. Accumulative processes dominate on the shores of the Chukchi Sea. Lagoon shores are in great abundance here. They occupy more than 49 % of the Asian continental coast and the coast of Wrangle Island, as seen in Fig. 2.23 and Table 2.6 (Alekseevsky 2007).

Accumulative bay-bars (dominating height is 0.5–3.5 m and width ranges from 0.1 to 1.5 km) separating the shallow lagoons from the sea extend parallel to the continental coast over hundreds of kilometers. The bay-bar of the Tenkergynpilgyn Lagoon is approximately 100 km long, and the length of the Kuvetpilchin Lagoon exceeds 50 km. Widely spread lagoon shores in the Chukchi Sea are related to the specific combination of natural factors.

First of all, the abundance of accumulative coastal structures and the lagoons that they form is a consequence of the geological (lithological) structure of the adjacent coast. The bay-bars are formed of sand and gravel-pebble material, whose composition is closer to the rocks of the internal portion of the continent than to those of the neighboring abrasion ledges (Kaplin et al. 1991). The modern abrasion regions are comparatively short and could hardly supply sufficient amounts of debris material to the coastal zone. It is likely that the resources of alluvial and fluvio-glacial sediments on the shelf were previously transported by water flows during the melting of the mountain and valley glaciers that subsequently flooded in during the Holocene regression. They could be the sources of transported material. Thus, the majority of the Chukchi Sea bay-bars are standard bars, i.e., the result of transversal sediment transport (Kaplin et al. 1991). During strong storms, the debris material is washed over the crest of low bars in the direction of land, which leads to the gradual displacement of the bar on the lagoon. A characteristic peculiarity of many bars in the Chukchi Sea is the inclusion of the remains of coastal edoma in their body, which are formed from frozen loamy sediments (Alekseevsky 2007).

The topography of the submarine slope is very important. Here, the inclinations of the submarine slope notably increase owing to the approach of the spurs of the Chukchi Rise towards the sea. The bottom slopes are usually 0.01–0.02 (in

the eastern part, they are as steep as 0.08), which makes possible the development of high waves capable of transporting sandy-pebble material from the submarine slope to the shore. The traces of the wave impact on the bottom are seen up to depths of 35–40 m. The abundance of submarine sediments on the shelf provides for the development of high accumulative bay-bars.

The increase in the duration of the ice-free season owing to the influence of warm Pacific waters propagating through the Bering Strait is important for the formation of the lagoon-bar complex. The proportion of ice-free time increases in the eastern direction, from 10 % near Cape Billings (the Longa strait) to 27 % near Cape Dezhnev (Kaplin et al. 1991). The waves from the northern and northeastern directions, which sometimes are as high as 6–7 m, transport sedimentary material from the coastal submarine slope and play a primary role in the formation and displacement of accumulative bay-bars in the direction of land.

Depending on the formation mechanism, we distinguish between long and narrow (cord-shaped) lagoons (Kuvetpilchin, Maaminpilgyn), bay-lagoons (Neskynpilgyn), firth-lagoons (Amguema, Pyngopilgin), and others. Many of these are distinguished by their peculiar internal partition into a number of round basins as a result of the formation of a series of spits belonging to the Azov type (Kaplin et al. 1991).

Unlike the overwhelming number of lagoons and accumulative bodies of the Arctic coast of Russia, the Chukchi Sea lagoons have been well studied (Kaplin 2010). Since many features of the structure and appearance of the accumulative bodies and lagoons of the Chukchi Sea are also found on the shores of the other Arctic Seas, the book we have cited is a reasonable source of information. The data from the investigation of the shores and lagoons of the Chukchi Sea (adopted from Kaplin et al. (1991)) are presented below.

Five coastal regions have been distinguished in the Chukchi Sea (Kaplin et al. 1991):

1. Dezhnev region (between Capes Dezhneva and Unikan), including the Uelen and Inchoun lagoons (officially, this coastal region is part of the Bering Strait coast (IHO 23-3rd 2002)).
2. Cape Serdtse-Kamen region (between Capes Unikan and Serdtse-Kamen), with well-pronounced abrasion forms.
3. Genretlen region (from Cape Serdtse-Kamen to the eastern edge of the Serykh Gusey Islands), which is distinguished by its peculiar lagoons and the zonal orientation of the coastline.
4. Vankarem region (from the islands of Serykh Gusey to Cape Vankarem), including various accumulative bodies and adjacent abrasion regions of different structure.

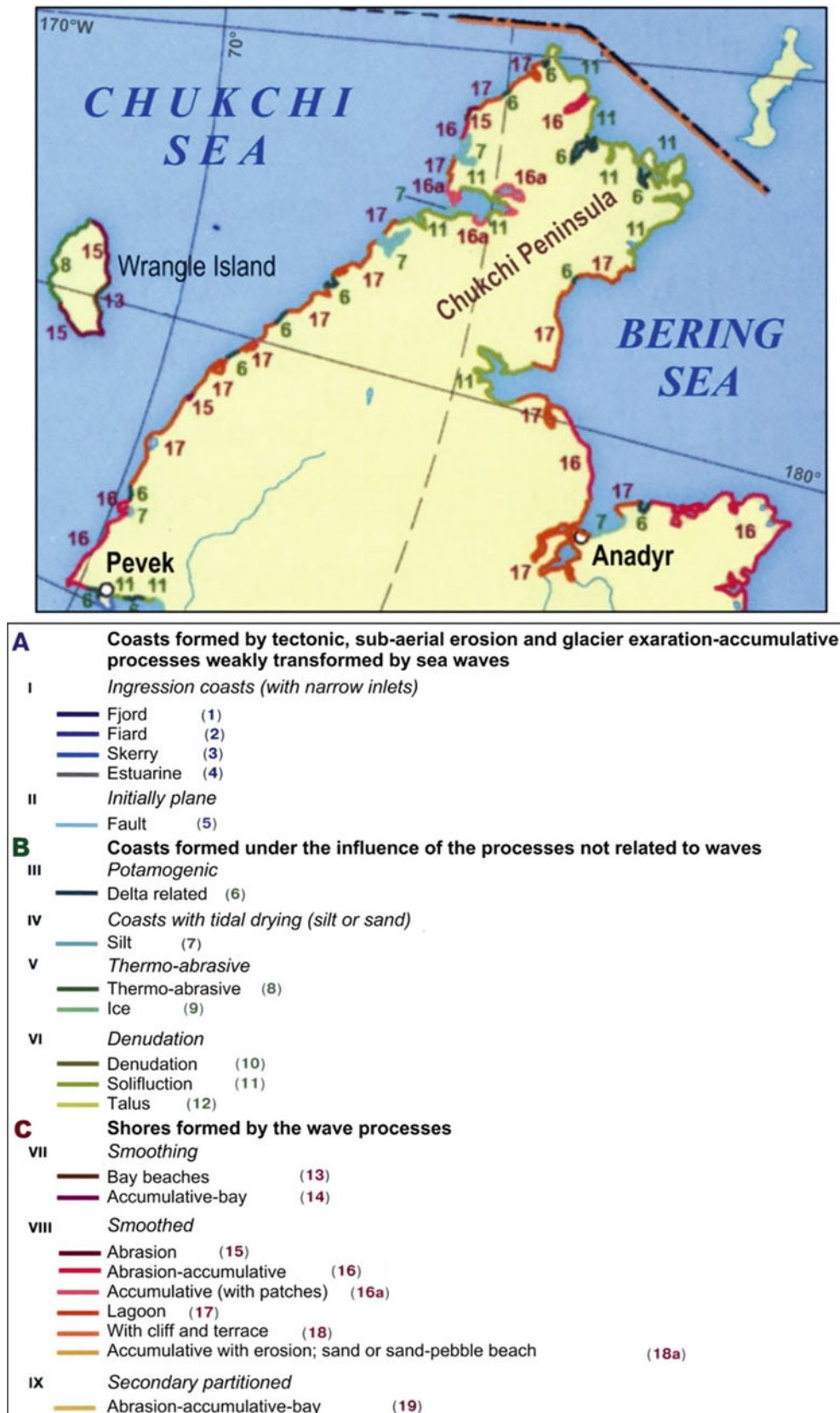


Fig. 2.23 Morphological types of the Chukchi Sea coasts (Spiridonov et al. 2011). A, B, and C are type of sea shores. I–IX (Roman numerals) sub-types of shore partitioning 1–19 (Arabic numerals) primary causes of the initial partitioning of the shoreline

Table 2.6 The types of the Chukchi Sea shores (%)

Shore type	Continental coast	Islands	Total
Not transformed by sea	–	–	
Abrasive-denudation	6,2	12,3	
Abrasive	9,6	17,3	
Abrasive fossil	–	4,9	
Thermo-abrasive	12,7	11,2	
Abrasive-accumulative	11,5	–	
Accumulative beaches	–	4,9	
Lagoon	49,2	49,4	
Setup (foreshore)	10,8	–	
Delta	–	–	

Alekseevsky (2007)

5. Schmidt region (between Capes Vankarem and Yakan), which is characterized by thick accumulative bodies, including the remains of bedrock. There are no lagoons of this size in the other regions of the Chukchi Sea.

The *Dezhnev coastal region* includes adjacent abrasion shore regions, in addition to the Uelen and Inchoun lagoons (Fig. 2.24). The lagoons are located in the lowlands, which join together and form a vast coastal plane. The height of individual hills reaches 100 m. They are confined to the mountainous regions (the Dezhnev massif, the Inchoun mountain massif, etc.) Basement rocks pierced by quartz veins form the foundation of the hills (chloritic and clayey schists). They are covered by a layer of loose Quaternary deposits, which include marine blue clays and loams. Sands, loams, clays, pebbles, and boulders of glacial and water-glacial origin form the upper part. Several rivers cross the coastal plane. They meander wildly and split into a multitude of creeks. They also flow into the lagoons, therefore only slightly influencing the dynamics of the sea shore. Numerous lakes are spread widely across the lowlands.

The Uelen and Inchoun Lagoons have many common morphological features. They combine the properties of lagoons and firths. The configurations of the Inchoun Lagoon are simpler. Their formation is related to the flooding of the estuary-valley of the Inchoun River during the Holocene transgression of the sea. The firth that appeared here is separated from the sea by a bay-bar. The Uelen Lagoon consists of two heterogeneous regions: its southwestern part is a firth and the region stretched along the sea coast is a classical example of a lagoon.

The bay-bar of the Inchoun Lagoon is a thick accumulative structure. This bay-bar not only crosses the entrance part of the lagoon but continues along the low shore as a coastal bar. In some places, this bar is adjacent to the land, and in other places, a series of shallow-water lagoons remain after the bar. It is likely that the bay-bar in this region gradually displaced the coastal plane. A series of lagoons is a relict

structure of a large lagoon similar to the Uelen Lagoon. Some indicators provide evidence of the displacement of the bay-bar of the Inchoun Lagoon in the direction of the land: it is eroded from the sea side, and at the same time, its rear part displaces in the direction of the secondary accumulative bodies of the Azov spit type.

The bay-bar of the Uelen Lagoon has no indicators of displacement. This bay-bar consists of two thick coastal bars. Its structure resembles the accumulative bodies, which V.P. Zenkovich called double bars. The first one (from the sea side) has a significant height and occupies almost the entire bay-bar along its width. The second bar of smaller height is located parallel to the first. It is likely that it was formed by the waves inside the lagoon. A series of secondary lagoons exists between the bars. Creeks connect it with the main lagoon basin.

The petrographic composition of the pebble forming these bay-bars points to the main source: the transport of sediments from the underwater slope. Here, we find syenite pebbles as well as pebbles of various erupted rocks, although the neighboring abrasion regions are formed of schists. Pebbles cannot be transported along the coast from distant regions, owing to the existence of the capes protruding into the sea. It is likely that the Quaternary water-glacier columns forming the coastal valley and the bottom were the source of such material. During the transgression of the sea, these sediments formed a large bar, which gradually displaced the coast and became the basis of the modern bay – bars.

Sediments are transported in the lagoons along bedrock coasts and the rear parts of the bay-bars. The shores of their basins change as a result of the formation of double crescent bars, accumulative ledges, and other accumulative bodies. Owing to these processes, the coastlines of the lagoons dismember first and then later align, while the lagoons are divided into a number of basins of the oval form.

The *region of Cape Serdtse-Kamen* is the result of the development of Paleozoic rocks that form the mountainous coastal ridge. The youngest set of rocks, which is represented



Fig. 2.24 The Inghoun (upper left) and Uelen (middle) Lagoons and the Dezhnev Cape (Modified from Kosyan 2013)

by sandstone and schists of the Middle and Upper Carboniferous, is located close to the sea. The rocks forming the coast are strongly dislocated and separated by the intrusions of granitoids. Numerous tectonic cracks predetermined the formation of erosion intrusions, talus troughs, and surge niches.

The mountains at the shore form steep coastal cliffs almost everywhere, the sole exception being the bays in the region of the Serdtse-Kamen massif. The mean heights of the coastal ridge in this region are 400–600 m. Most of the rivers cross the slopes of the ridge through narrow, poorly developed valleys and fall into the sea through hanging mouths. In general, the coastline is aligned, with only the granite intrusion massifs Inkigur and Serdtse-Kamen protruding far into

the sea. There are not many accumulative structures above water in this region. Even a river as large as the Chegytun has a comparatively small lagoon separated by a bay-bar from the sea. This lagoon is only a widening of the river valley when it debouches into the sea. The bay-bar near the mouth of the river is formed as a result of the accumulation of the material transported along the coast.

In the *Genretlen coastal region*, the shore becomes low west of the Serdtse-Kamen massif. The mountains retreat far to the south, and only near Cape Genretlen does a spur of the mountainous ridge protrude into the sea. The Genretlen massif and Ildidlya Island are the only outcrops of the bedrocks in the region of the shore. The remainder of the shore is formed of a loose sand column, sandy loam, and loams with

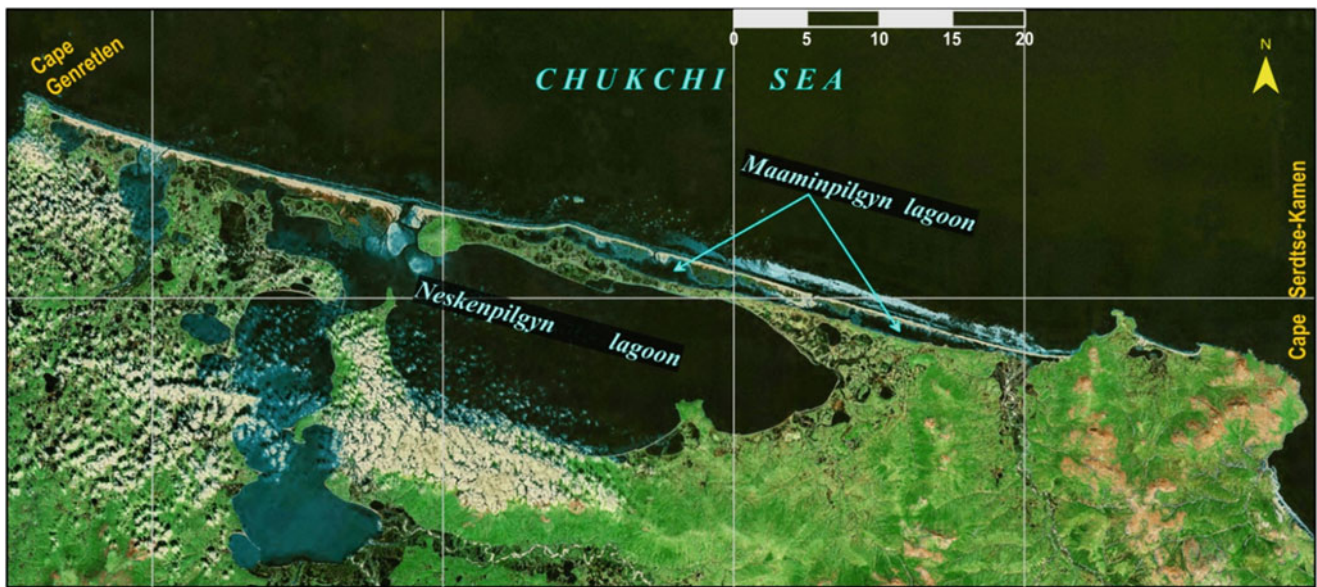


Fig. 2.25 Large Neskenpilgyn Lagoon is not a classical lagoon but a sea gulf (Modified from Kosyan 2013)

layers of peat. The plain approaches the sea only in the region from Cape Genretlen to the Belyaka Spit. The rest of the shore is rich in the lagoons separating the coastal plane from the sea. These lagoons are very specific, both in morphology and in their origin.

The Neskenpilgyn is not a classical lagoon. This is a large marine gulf with a narrow and shallow entrance. It is separated from the sea, and from the real Maaminpilgyn Lagoon (Fig. 2.25), by narrow bands of low tundra, which resemble the usual bay-bars of lagoons. The coasts of the gulf are abrasive.

The Maaminpilgyn Lagoon is very specific in its morphological peculiarities. It extends along the shore over double digit kilometers as a narrow band (Fig. 2.25). The bay-bar of this lagoon has a complex structure. The coastline of the sea side is aligned, while on the lagoon side, it is strongly dismembered. In some places, the bay-bar widens and protrudes into the lagoon basin over hundreds of meters, while in other places, it narrows to roughly 20–30 m. Peat formations outcropping on the cliffs of bedrock remain included in the bay-bar of the Maaminpilgyn Lagoon. These layers alternate with sand layers 5–8 cm thick. A low ridge of dunes is located above these deposits along the sea shore. After the dunes, the bar bay surface becomes lower closer to the lagoon where there is further outcropping of peat formations. It is likely that the layered deposits on the sea side appeared due to the long-term transport of sand from the bottom to the shore. Ridges of dunes were formed from this sand. Intervals in the sand supply occurred in certain periods, possibly related to the increase in the ice cover of the sea, during which the dunes were partly eroded by the wind and partly covered with vegetation. Thus, their surface became covered

with peat. A new ridge of dunes was formed on the surface of the peat structures and the process was repeated many times.

Several lagoon-lakes are located between the Neskenpilgyn Gulf and Cape Genretlen, among low tundra. These lakes are confined to the mouths of the river valleys. The valleys of the rivers are wide; therefore, the lagoons that appear when the valleys are flooded are wide and shallow. The Einenekvyn Lagoon has a different form, which extends along the valley in the estuary of the river with the same name. It is separated from the sea by a bay-bar, which includes the bedrock remains of the land.

A thick accumulative structure (the Belyaka Spit) is located in the western part of the region (Fig. 2.26). It consists of two branches, between which there is a lagoon of the same name. The research in this region shows that the branch of the spit separating the Belyaka Lagoon from Kolyuchinskaya Guba is not an accumulative structure, but rather a low peninsula formed by loose clayey and sandy-loam deposits whose column outcrops at the northern coast of Kolyuchinskaya Guba. Thus, the southern part of the Belyaka Spit, similarly to the bay-bar of the Neskenpilgyn Lagoon, is a part of the coastal valley. The northern part of the Belyaka Spit is an accumulative structure of a free type. Its distal end is wide and turned to the southwest, while the base part consists of one narrow sand bar, over which the waves gush in stormy weather. The width of the wide end of the spit reaches a few kilometers. Ancient shore bars covered with vegetation, whose direction coincides with the configuration of the coastline, are seen on its surface. Small lagoons are located between the bars.



Fig. 2.26 The Belyaka Spit (*right*) and Yuzhny Island (the Islands of Serykh Gusey) (Modified from Kosyan 2013)

Vankarem Coastal Region The mountains closely approach the coastline here. In the region of Cape Onmai, their ridge protrudes into the sea. A loose Quaternary column forming the coastal lowland plane consists of peat, sands, and clays, with inclusions of vein ice. Significant regions of the coastal lowland plane are formed of loams, also with inclusions of vein ice. The coastal cliffs formed by a loose column break intensely under the influence of sub-aerial processes. During storms, the waves erode and transport material away from the coastal cliffs, cutting their basements, which facilitates the activation of slope processes and hinders stabilization of the equilibrium on the slopes.

The majority of accumulative structures of the Vankarem coastal region are represented by bay-bars and spits separating the lagoons of different size from the sea. A number of lagoons separated from the sea by spits, which appeared as a result of the accumulation of sediments from the abrasion shores, are found in the region from Cape Onman to the Vankarem Lagoon. The Eikuy Lagoon, itself separated from the sea by two small spits, is an example of these.

The Islands of Serykh Gusey are a peculiar accumulative structure (Fig. 2.26). This series of islands resembles a spit in its morphological structure. It has grown due to the accumulation of sediments transported along the coast from north to

south and then separated by the straits into individual parts. However, it is possible that this spit has never been a single accumulative body. Setup-setdown currents at the entrance to Kolyuchinskaya Bay prevented this. It has an extremely narrow entrance, which is frequently blocked by ice. During setdowns, the pressure of water collected from the vast basin of the guba (bay) can be extremely high. Owing to this, the islands did not unite into one accumulative body but formed a bar torn into individual parts. It is possible that if the northern (accumulative) part of the Belyaka Spit had not been protected by the bedrock Belyaka Peninsula, a single accumulative body could not have been formed here.

The bay-bar of the Vankarem Lagoon (Figs. 2.7 and 2.27) is an interesting accumulative structure. It is located at the mouth of the river with the same name; therefore, it has a configuration characteristic of the firths. The lagoon is separated from the sea by two spits: a smaller one in the southeast and a longer one in the northwest.

The *Schmidt coastal region* includes the shore from Cape Vankarem to Cape Yakan. The bay-bars extend across the region, excluding Cape Schmidt. They separate a series of vast lagoons from the sea. A coastal plane with hills occupies a wide band between the lagoons and the marine mountain ridge. The elevation marks of this plane do not exceed



Fig. 2.27 The lagoon coast of the Chukchi Sea between Cape Schmidt and Cape Onmyn (Modified from Kosyan 2013)

20–30 m. Numerous lakes are located between the hills. The marine mountain ridge that extends over a large distance removed from the coast closely approaches the sea near Cape Schmidt and then recedes again, only veering back near Cape Yakan, where it breaks to the sea in the form of steep rocks.

In general, the coast of the region considered here is of the lagoon type. The Nutauge and Tynkurginpilgyn Lagoons are the largest on the coast of the Chukchi Sea (Fig. 2.27). The majority of the lagoons are connected by the channels, forming a single series with a total length of more than 100 km. The Kuvetlilchin Lagoon extends along the coast as a narrow band. Its length exceeds 50 km. All the lagoons of the region are shallow.

Lagoons and bay-bars of different morphology in the Schmidt coastal region have developed in approximately equal conditions under the influence of the same shore-forming factors. Over the entire length of the coast, the resultant wave vector is directed from northwest to southeast. In this relation, the debris material also has a tendency to be transported in the same direction. The configuration of shore bars on the bay-bars of the lagoons and the outlines of the secondary accumulative structures in their basins provides evidence that this is true. It is likely that at present, when the coastline is aligned and almost no abrasion regions are left on the shore, only the bottom gravel-pebble material participates in the motion of sediments. There are no other sources of sediment supply, because the rivers debouche into lagoons, in which the terrigenous material transported by them is accumulated.

Significant alongshore displacements of sediments also occur from the rear side of the bay-bars. The accumulative

structures that are formed in the lagoon basins are related to the Azov type of spit. The abundance of such spits in the lagoons of the Chukchi Sea corresponds to the hypothesis of V.P. Zenkovich, according to which their basins tend to take on an oval shape in the process of their development and frequently divide into individual round parts owing to the opposite growth of accumulative capes at the opposite coasts. Hence, the narrower the lagoon and the stronger it is extended along the shore, the greater number of accumulative structures that are formed on its shores, which tend to divide the basin.

Each of the lagoons in the region considered here has its own peculiarities and differs from those that neighbor it (Fig. 2.28). For example, the Amguema Lagoon and certain other smaller lagoons can be considered typical firths, formed during flooding of the estuarine parts of the river valleys and separated from the sea by bay-bars. The Ekiatap, Tenkergynpilgin, and Kuvetpilchin Lagoons were also formed as a result of the flooding of negative topographic forms, but these depressions were not developed by the river valleys. Therefore, the outlines of the lagoons are various and complex. The narrow Kinminyakily Lagoon, the creek between the Ekiatap and Tenkergynpilgin Lagoons, and certain regions of the other lagoons appeared at the basements of ledges eroded by rivers or sea due to the separation of narrow basins from the sea by a bar. Depending on the formation process, we distinguish long and narrow (cord-shaped) lagoons (R'ypil'gyn, Er'okynmanky lagoons), bay-lagoons (Kanygtokynmangky lagoon), and firth lagoons (western R'ypil'gyn lagoon) (Alekseevsky 2007; Kaplin et al. 1991).



Fig. 2.28 The western part of the Chukchi Sea coast is characterized by the abundance of accumulative bodies and lagoons of different type (Modified from Kosyan (2013))

2.5 Conclusion

The majority of the lagoons of the Russian Arctic coast are formed by accumulative bodies: bars, bay-bars, and spits. The influence of the changes in the external conditions on the accumulative coastal bodies is different depending on their type of feeding and formation.

Accumulative bodies of longitudinal motion of sediments are usually formed through the drift of material from breaking bedrock shores or through transport by rivers. The transport of solids in rivers within the Arctic coast is insignificant (related to the transport of sediments by the wave field). Therefore, abrasion material is the main source for the formation of accumulative structures. If there is a region of abrasion shore that supplies beach-forming material to the coastal zone and under the conditions for the formation of alongshore transport of sediments, wide beaches or bay-bars are formed at the adjacent concave regions of the coast; spits are formed at the convex regions of the shore. The increase in sea level usually causes more rapid destruction of abrasion shores; therefore, it can lead to an increase in the rates of growth of associated accumulative bodies. An increase in the depths in the coastal region can induce the intensification of wave impact on accumulative bodies and lead to their transformation or destruction.

The increase in wave impact under the condition of an increasing ice-free period and length of the wave fetch cause intensification of the rate of abrasive coastal destruction; therefore, it can lead to the growth of the associated accumulative structures.

A change in the dominating wave direction can significantly change the configuration of similar accumulative bodies. An increase in the transversal to the shore wave component can lead to a decrease in the amounts of along-

shore transport of sediments, which inevitably will lead to the degradation of accumulative structures. In this case, conditions can be formed in the erosion region of the bedrock shore for the accumulation of sediments. An increase in the alongshore component will lead to an increase in the growth of the distal end of the accumulative structure and local erosions along the accumulative body.

The main sources of sediments for an accumulative body of transversal sediment motion can be either the abrasion material from the neighboring parts of the shore or debris from the underwater slope. Relative sea level rise (resulting from tectonic motions of the Earth's surface and a global rise in the ocean level) can lead to the reconstruction of these accumulative bodies (their displacement in the direction of the land). If the amount of sediment is insufficient, some regions can be flooded. In general, taking into account the small values of sea level rise (compared with the amplitude of tides, setup-set-down fluctuations of the level, and similar short-period processes), nothing threatens the integrity of the majority of them.

An increase in wave impact related to the changes in the synoptic situation, an increase in the duration of the ice-free period, or changes in the wave fetch can cause intensification of the displacement of such accumulative structures in the direction of the land. A strong storm at the Uelen bay-bar and near the settlement of the same name, as shown in Fig. 2.29, which continued for 93 h in October 1969, caused a displacement of the bar in the direction of the land by 5 m (Alekseevsky 2007). The composition of beach sediments can also change. If the intensity of wave impact increases, sediments of larger size would be required for beach formation. If they are lacking, the sediments would be transported to deep places, causing gradual degradation of the accumulative structure, eventually resulting in its complete destruction.



Fig. 2.29 The Uelen settlement is located on the spit (bay-bar) of the same name (the Chukchi Sea)

Simultaneously, the increase in the height and length of the waves would facilitate further transport of sediments from the underwater slope if they are still deposited there.

The most threatening factor for the stability of bars and bay-bars formed out of the material from the underwater slope would be an increase in the sea level with a simultaneous increase in wave forcing. At a specific moment in time, the wave forcing would no longer be compensated by the increase in the height of the bar and it will be flooded. Correspondingly, the hydrological regime of the lagoon would be distorted up to its complete merging with the sea.

A change in the direction of the dominating waves can lead to an increase in the amounts of alongshore sediment transport, which will lead to redistribution of the material between different parts of the accumulative structure. Conditions can be formed in some regions for the complete degradation of the accumulative body.

The slopes of underwater topography are very small in many coastal regions of the Arctic Seas, and no transport of sediments from underwater slopes occurs. Beach-forming sediments are only supplied from the erosion of bedrock shore or with river outflow. An elongated accumulative structure (beach-barrier) is formed along the entire shore if the amount of sediment is sufficient (Fig. 2.30). According to their structure and evolution, these bodies are closest to bay-bars, which means that the transversal motions of sediments and Aeolian processes play a great role in their dynamics (Sivintsev et al. 2005). If the positive balance of sediments remains, small fluctuations in the sea level would not lead to significant changes in such accumulative bodies. Aeolian bodies develop intensely if the sea level remains constant. If the sea level rises, accumulative bodies gradually displace towards the land. In this case, the transversal structure almost remains the same. The situation is different if wave forcing increases or wave parameters change. If the intensity of wave forcing increases, larger grain size sediments would be needed for beach formation. If they are lacking, the sediments will be transported to the deeper water regions and degradation of the accumulative body would gradually occur up to its complete destruction. Variations in the direction of dominating waves can lead to an increase in the volumes of alongshore transport, which would inevitably lead to the redistribution of the sediments between different regions of the accumulative body. Erosion of the accumulative body would be observed in some regions of the body, while in the other regions, intense accumulation of sediments would occur.

Shores of a special type are formed under the conditions of low wave forcing (most frequently in deep bays or in regions with long ice-covered periods) in the regions of gently sloping coastal topography (usually in the zones of the modern tectonic subsidence of the Earth's crust) with a lack of beach-forming sediments. In such regions of shores simi-

lar to the one shown in Figs. 2.4, 2.5, and 2.21, the tundra zone and the sea basin are usually separated by a zone of tidal or set-down foreshore, which is sometimes a few kilometers wide. Several levels are frequently distinguished in the morphology of such zones (ru.wikipedia.org). Both sea level rise and changes in the synoptic characteristics (increase in wave height or setup levels) are hazardous for such shores. An increase in sea level leads to the flooding of new land regions (which can be catastrophic during setups). The development of abrasive or accumulative processes can be observed in some regions. The volume of sediments participating in these processes are small and do not have any significant influence on the evolution of the shore.

Lithologic structure, coastal topography and, most of all, natural peculiarities facilitate the appearance of an intriguing situation. Many settlements, industrial, and transport objects on the coasts of the Russian Arctic Seas are located at the most dynamic part of the sea shore: accumulative coastal bodies (spits, bay-bars, and bars) (Fig. 2.31). Therefore, human industrial activity has a permanent place in the influence zone of hazardous natural processes and simultaneously impacts the ecosystems of the sea and lagoons.

How strongly does anthropogenic activity influence the state and dynamics of the Arctic lagoon shores? In general, the technogenic factor only slightly influences the coastal development of the Russian Arctic Seas. To a greater degree, this depends on the low industrial and economic importance of the regional shores, which, in its turn, is influenced by difficult natural conditions. The existing and future technological transformation of the shores of the Arctic Seas are actually limited by the following:

1. Construction of hydro-technical structures and military ports. The majority of such constructions has been built or is planned for closed bays or gulfs and do not have a significant impact on the lithodynamic conditions of the adjacent coastal regions. The negative influence of such constructions is limited by the immediate zone of their location and the zone of the actual or potential (in the case of accidents) pollution of the neighboring shores. An opposite situation appears when attempts are made to interfere with the lithodynamic links. Distortions of alongshore fluxes of sediments (during the construction of protection for the ports) can lead to changes in or even the destruction of the accumulative bodies and lagoon formations over a significant extension of the shore.
2. Construction of pipelines (including underwater pipelines). Currently, construction and projection of long pipelines for oil and gas transport is being carried out in the region. They are designed to transport hydrocarbons to processing locations, for consumption or for reload onto sea tankers. Usually, the impact of such objects on coastal ecosystems is limited by the width of the corridor

Fig. 2.30 If the amount of sediments is sufficient, the accumulative body separates the low-land tundra and the sea basin. The development regime of the accumulative body is determined by the configuration of the shore. The Pechora Sea is shown on the *left* and the Laptev Sea is on the *right* (Modified from Kosyan 2013)



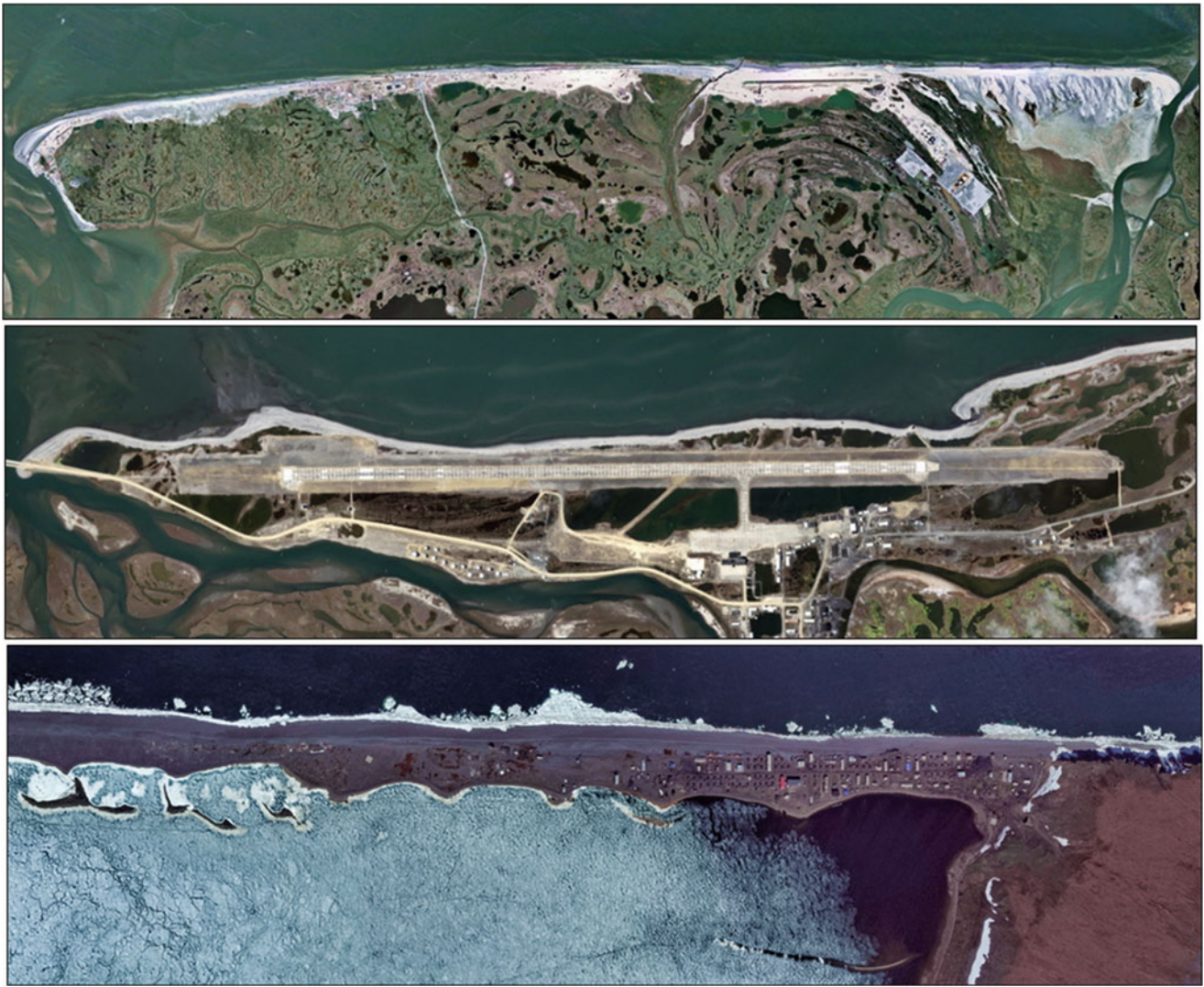


Fig. 2.31 Many settlements, industrial, and transport objects on the coasts are located on accumulative coastal bodies (spits, bay-bars, and bars). From top to bottom: Varandey (Barents Sea), Pevek (East Siberian Sea); Uelen (Chukchi Sea) (Modified from Kosyan (2013))

for this construction or by the width of the zone of negative consequences of possible accidents. Pipeline construction under permafrost conditions can provoke intensification of thermal erosion and thermal abrasion, which inevitably will result in the evolution of the adjacent part of the shore. The existence and motion of large ice masses is another factor, as it influences the bottom up to sufficient depths. Construction of underwater pipelines should provide for their reliable protection from ice forcing. Usually, underwater pipelines do not prevent the alongshore transport of sediments; therefore, there is no hazard to the stability of accumulative bodies.

3. Construction of roads for automobiles under permafrost conditions. This can provoke intensification of thermal erosion and thermal abrasion. Frequently, roads for auto-

mobiles are constructed immediately on the surface of the accumulative bodies. Under such conditions, the road can play the role of a wave rake, which would lead to the erosion of beaches and the loss of beach-forming material. In addition, construction of roads for automobiles can induce distortions in the evolution of Aeolian processes, which would also decrease the stability of accumulative bodies.

4. Construction of power stations (thermal, tidal, hydroelectric plants). While designing such objects, it is necessary to take into account their significant influence on the hydrological and microclimatic conditions of vast regions. Variations in the hydrothermal regime would inevitably influence the ice and (indirectly) the wave regimes of the adjacent basins and can strongly change the evolution of

lithodynamic processes. It is especially important to take into account the direct and indirect influence of power stations on the hydrothermal regime of lagoons, which is extremely important for the hydrochemical and biological processes that develop there.

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