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# Reconstruction of Ice Complex Remnants on the Eastern Siberian Arctic Shelf

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## ABSTRACT

Based on the analysis of seafloor topography together with historical, geological and palaeogeographical data obtained from published and archived sources, the position of former Ice Complex (IC) islands has been reconstructed. Within the Laptev Sea shelf and in the western part of the East Siberian Sea shelf, most of these islands have been destroyed by coastal thermal erosion and thermal abrasion during the last thousand years or so. The IC islands were the remnants of the ice-rich syncryogenic freshwater terrestrial deposits (so called IC), which covered most of the arctic coastal plains and the emerged arctic shelf during the Late Pleistocene. At the present time, sandbanks exist at the places of former IC islands. These sandbanks are the subject of intense seafloor thermal abrasion. The approximate rates of seafloor thermal abrasion and the time of complete disappearance of these islands during the last thousand years have been estimated. The rate is different for different islands and for different time intervals. The most common values are between 0.02 and 0.3 m/year. Schematic maps of the former IC islands within the Laptev Sea and western part of the East Siberian Sea shelves have been compiled. Copyright © 2003 John Wiley & Sons, Ltd.

KEY WORDS: Ice Complex; Ice-Complex relict islands; seafloor thermal abrasion; coastal thermal erosion (abrasion); grain-size distribution in seafloor deposits; sandbanks

## INTRODUCTION

During the Late Pleistocene, ice-rich syncryogenic deposits with massive ice wedges, the so-called Ice Complex (IC), developed on the emerged shelf of the eastern Russian Arctic seas and within the coastal lowlands (Romanovskii *et al.*, 1997, 1999) (Figures 1 and 2). The IC in northeastern Siberia is well studied and dated. The fluvial type of IC is predominant in this region (Gravis, 1997). This complex consists mainly of silt deposits, although a significant amount of sand can be also included, especially in the lower parts of the IC geological cross-section. Numerous islands built of IC still can be found within the Laptev and East Siberian Sea shallow waters. These islands can provide important testimony for former prevalence of IC deposits over the Arctic shelf. In this area many of the islands existed in the 18th, 19th, and even in the beginning of the 20th century (Ermolaev, 1932; Khmyznikov, 1937; Grigorov, 1946; Stepanov, 1948a, 1948b; Vize, 1948; Zubov, 1954; *History of the Discovery and Development of the Northern Seaway*, 1954; Gakkel', 1957; Zhigarev and Sovershaev, 1984). By now however, most of the IC islands have been completely destroyed by coastal thermal erosion (abrasion) and replaced by sandbanks with frozen sediments located very close to the seafloor surface.

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Figure 1 One of the Shelonskie Islands composed of IC deposits and being eroded by coastal thermal abrasion (a perspective photo made by V. Tumskoy).

Figure 2 The Bol'shoi Lyakhovskii Island coastal cliff composed of IC and being eroded by thermal abrasion (V. Tumskoy's photo).

The study region covers the Laptev Sea shelf and the western part of the East Siberian Sea shelf (Figure 3). The width of the shelf is 300–400 km in the Laptev Sea and reaches 1000 km in the East Siberian Sea. The IC islands have been studied previously to various extent. Some of them (Vasil'evskii, Semenovskii, Figurin, and Shelonskie islands) were visited and surveyed (Figure 3). The two former islands were visited repeatedly. Mammalian remains (mammoth tusks and musk-ox craniums) were found on Semenovskii Island (Grigorov, 1946), which is indicative of IC presence on the shelf. Other islands (e.g., Diomid Island) were only observed from shipboard. Finally, the existence of Sannikov, Andreev, and Vasema lands is conjectural (Figure 3). Some of the existing islands and peninsulas are on the verge of disappearance, such as Muostakh IC Island (near Tiksi) and the Shelonskie IC Islands (Figures 1 and 3).

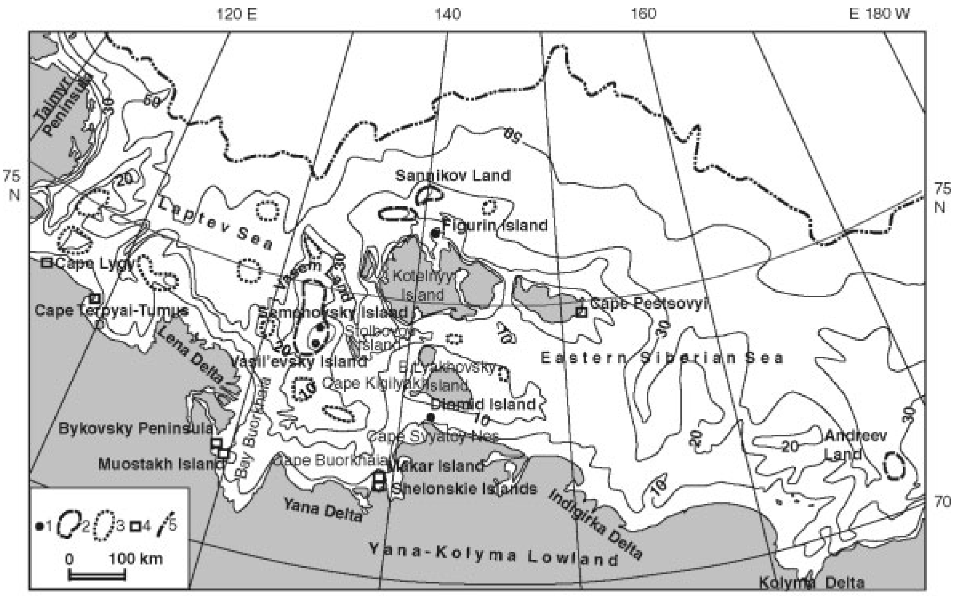


Figure 3 Schematic map of IC islands: (1) IC islands that disappeared according to historical documents in the 18th–20th centuries; (2) IC islands presumably existed (according to historical documents) 100–250 years ago; (3) IC islands, the location of which was reconstructed in this studies based on geocryological data (destroyed by thermal abrasion 300–800 years ago); (4) IC islands, and other islands and peninsulas being eroded by thermal abrasion at the present time; (5) shelf edge.

 

This paper is an attempt to reconstruct the history of IC islands within the Laptev and East Siberian Sea shelves. Existing information on the history of IC islands is widely dispersed among numerous Russian scientific papers, reports and archives. Also, an attempt to estimate the rate of seafloor thermal abrasion was made and a schematic map of former IC islands within the Laptev Sea and western part of the East Siberian Sea shelves has been compiled.

## SUMMARY OF EXISTING DATA ON FORMERLY OBSERVED ISLANDS

The most complete information available is about Vasil'evskii and Semenovskii islands (Figure 3). Being composed of IC sediments, they had high steep cliffs along the shoreline. On Semenovskii Island, the height of its undermined cliffs reached 24 m in 1945, shortly before its complete destruction (Grigorov, 1946). These islands were discovered in 1815 by I. Lyakhov, a Yakutian merchant (*History of the Discovery and Development of the Northern Seaway*, 1954). According to data collected by the P. F. Anzhu expedition, the size of Vasil'evskii Island was 7.4 × 0.4 km in 1823. By 1912, its length had decreased to 4.6 km (Gakkel', 1957), and only a sandbank with depths of 2.5–3.0 m was found in its place in 1936 (Table 1) (Vize, 1948; Stepanov, 1948a).

The size of Semenovskii Island was 14.8 × 4.6 km in 1823, 4.6 × 0.9 km in 1912, 2.0 × 0.5 km in 1936, and 1.6 × 0.2 km in 1945 (Grigorov, 1946). A solitary baydzherakh (residual thermokarst mound)

Table 1 Results of approximate seafloor thermal abrasion rate calculation, m/year.

| Name of the bank | Year of seawater depth measurement | Seawater depth, m | Source of data | Results of approximate seafloor thermal abrasion rate calculations, m/year (years of observations) |
|---|---|---|---|---|
| Semenovskaya | 1950 | 0 | Gakkel' (1957) | 0.02 (1950–1960s years) |
| | 1952 | 0.1 | Gakkel' (1957) | |
| | the early 1960s | 0.2 | Zhigarev and Sovershaev (1984) | |
| | 1965 | 0.8 | Semenov (1971) | 0.05 (1950–1965)<br>0.2 (beginning of 1960s–1965) |
| | the early 1980s | 6.2–6.4 | Zhigarev and Sovershaev (1984) | 0.2 (1950–beginning of 1980s) |
| | 2000 | 10–15 | Dmitrienko *et al.* (2001) | 0.2 (1950–2000)<br>0.27 (1965–2000) |
| Vasil'evskaya | 1936 | 2.5 | Vise (1948) | 0.12–0.2 (1936–2000) |
| | | 3.0 | Stepanov (1948a) | 0.27 (1965–2000) |
| | the early 1960s | 0.6 | Zhigarev and Sovershaev (1984) | |
| | 1965 | 0.8 | Semenov (1971) | |
| | 2000 | 15–10 (?) | Dmitrenko *et al.* (2001) | |
| Diomede | between 1760 and 1810 | 0 | Vise (1948)<br>*History of the Discovery and Development of the Northern Seaway* (1954)<br>Gakkel' (1957)<br>Stepanov (1948b)<br>Ermolaev (1932) | |
| | 1934 | 7.4 | Vise (1948)<br>*History of the Discovery and Development of the Northern Seaway* (1954)<br>Gakkel' (1957)<br>Stepanov (1948)<br>Ermolaev (1932) | 0.05 (from 1760–1810 till to 1934) |

 

and a bar just above the sea surface were found in its place in 1950, and by 1952, there was only a sandbank at an average depth of 10 m (Gakkel', 1957) (Table 1). In the early 1960s, there was a minimum depth of 0.2 m at the Semenovskaya Bank and 0.6 m depth at the Vasil'evskaya Bank (Zhigarev and Sovershaev, 1984). In 1965, these depths increased to 0.8 m (Semenov, 1971). In the maps of the 1960s–1970s, the Vasil'evskaya and Semenovskaya banks were contoured by the 5-m isobath (Holmes and Creager, 1974). In the early 1980s, Zhigarev and Sovershaev (1984) reported depths of 6.2–6.6 m (Table 1). In the present-day bathymetric and geological maps, these banks are delineated by the 5-m isobath (*State Geological Map of Russian Federation*, 1999). For the northern extremity of the Vasil'evskaya Bank, the minimal present depths are about 15 m (Dmitrenko *et al*., 2001). Shallower places (about 10 m depth) also exist in areas of Vasil'evskaya and Semenovskaya banks (Dmitrenko *et al*., 2001).

P. Anzhu, who searched for Sannikov Land, discovered Figurin Island in 1822. At that time, its area was about 8–9 $km^2$, and the height of the undermined shore cliff reached 20 m. This IC island was designated on the maps of 1926 (Ermolaev, 1932), 1941, and 1945 (Stepanov, 1948a). At the very beginning of the 1940s, a hydrographic expedition found that the Figurin Island did not exist anymore (Gakkel', 1957).

Diomede Island (its original name was Saint Diomid Island) was discovered by Dmitrii Laptev in 1739 (*History of the Discovery and Development of the Northern Seaway*, 1954; Stepanov, 1948b). Laptev first believed that he saw two islands (the second was Mercury Island). Later on, he concluded that a single island existed, which was seen from the two different sides. It is believed that seafarers saw Diomede Island for the last time in 1761 (Vize, 1948; *History of the Discovery and Development of the Northern Seaway*, 1954; Gakkel', 1957). However, it could have existed more recently, because Khvoinov, who surveyed Bol'shoi Lyakhovskii Island in 1771, saw a land to the southeast from the Kigilyakh Cape (Ermolaev, 1932). This could have been Diomede Island, an unknown island, or Mercury Island. If the latter was true, Laptev had seen two IC islands rather than one. In the 1810s–1820s, Diomede Island was already not shown on the maps compiled by Gedenshtrom (1811) and Anzhu (1821–1828). A sandbank was found in its place in 1934 during an expedition on the 'Litke' icebreaker (Vize, 1948; *History of the Discovery and Development of the Northern Seaway*, 1954). The sea depth at this bank was 7.4 m.

In conclusion, it should be noted that the discussed banks at the places of former IC islands were underlaid by ice-bonded permafrost (permafrost, in which ice plays a role of bonding material) (Dmitrenko *et al*., 2001). Taking into account that the seafloor in this area is almost entirely occupied by ice-bearing permafrost (permafrost where freshwater ice still exists but a significant amount of unfrozen saline water surrounds the ice crystals and lenses), banks and shoals with ice-bonded permafrost are very specific phenomena.

## PRESUMABLY EXISTED ISLANDS

There is some zonality in the textural composition of seafloor sediments in the eastern Arctic seas. The texture of seafloor sediments becomes finer with distance from the shore and sea depth. Fine clayey silts prevail in the open sea (Kordikov, 1952; Semenov, 1971; Aksenov *et al*., 1987; Pavlidis *et al*., 1998). Therefore, the presence of sand on banks clearly indicates the position of former IC islands. Stepanov (1948b) was the first to note that the abundance of sand among the prevalent clayey seafloor deposits indicates the former presence of IC islands. While it is well known that the silt fraction prevailed in the Late Pleistocene IC sediments, the sandy deposits predominate on the banks. The reason is that waves and streams stir up and remove fine silt particles much easier than sand particles. Coarser and heavier sand particles, on the contrary, remain *in situ*, especially in the lower part of IC deposits.

Among IC islands, whose existence was not confirmed, Sannikov Land is known the best (Obruchev, 1935, 1946; Stepanov, 1948a, 1948b; Grigorov, 1946). It was only seen, but not surveyed and documented. Ya. Sannikov, a manufacturer, was the first to see it in 1810. The polar explorer E. Toll was the last to see this land in 1886 (*History of the Discovery and Development of the Northern Seaway*, 1954; Stepanov, 1948a, 1948b). Numerous efforts to reach Sannikov Land by ice or sea (*History of the Discovery and Development of the Northern Seaway*, 1954), as well as to see it from an airplane in the 1930s (Karelin, 1946) failed. Stepanov (1948a) believed that Sannikov Land gave place to shoals as early as in the late 19$^{th}$–early 20$^{th}$ centuries. In 1901, Toll found shoals 100–150 km to the north from Kotel'nyi Island at depths of 16 m surrounded by 25–30 m depths (the 'Zarya' vessel expedition).

Stepanov (1948a, 1948b) associated Sannikov Land with a place with pure and clayey sands about

100 km to the north from Kotel'nyi Island. Kordikov (1952) found silty sands and sandy silts there with 5–10 and 10–30% of the fraction <0.01 mm, respectively. According to Kosheleva and Yashin (1999), seafloor deposits to the north of Kotel'nyi Island consist of clayey sands with the content of sand particles (0.1–1 mm) above 75%. In Figure 3, Sannikov Land is situated within the above sandy area on the positive elements of the seafloor topography that is delineated by the 20-m isobath. Gravimetric data also provide some evidence for the possible existence of Sannikov Land in the past (Litinskii, 1977).

Two other large islands, namely Vasema and Andreev lands (Figure 3), are much less acknowledged than Sannikov Land. These islands presumably existed in the 17th–18th centuries. It is believed that Semenovskii and Vasil'evskii islands were remainders of Vasema Land (Neupokoev, 1922; Zhigarev and Sovershaev, 1984). Information about an island located 'directly opposite of the Lena River's mouth in two–three days run from it' can be found in *The Map of All Siberian Towns and Lands* compiled by S. Remezov in 1698 (*History of the Discovery and Development of the Northern Seaway*, 1954) and in N. Vitsen's book *Noord en Oost Tattarye* published in 1692 and 1705 (Vize, 1946). Historical analysis of these materials led to a conclusion that the present existing Stolbovoi Island was part of Vasema Land (Vize, 1946; *History of the Discovery and Development of the Northern Seaway*, 1954). As calculated from the data of coastal retreat between 1823 and 1912 in Semenovskii and Vasil'evskii islands, the area of Vasema Land by the end of the 17th century could have been an order of magnitude larger than the present-day size of Stolbovoi Island. Moreover, Vasema Island was closer to the Lena Delta than Stolbovoi Island. As it will be shown below, some other IC islands could have existed near the Lena River delta.

The first information on the existence of an island (later called Andreev Land) in the eastern part of the study region (Figure 3) dates back to the mid-17th century. The search for this vast land to the northeast of the Kolyma River mouth began in 1763–1770. It continued into the 1930s–1940s (Stepanov, 1948b; *History of the Discovery and Development of the Northern Seaway*, 1954; Gakkel', 1957). During the expeditions on the 'Krasin' (1934) and 'Smol'nyi' (1946) icebreakers, a significant amount of sand was found in silty seafloor deposits within the boundaries of the supposed Andreev Land (Stepanov, 1948b). According to the data of Kosheleva and Yashin (1999), sandy silt deposits and sands are widespread in this region. Heavy ice conditions are inherent to the area throughout the year. Therefore, ice scattering is not typical for this region. The contribution of sea ice to the sediment transport is estimated at 0.3% for the entire East Siberian Sea shelf (Pavlidis *et al.*, 1998). However, both Gedenshtrom in 1810 and members of the Arctic Institute expedition on the 'Smol'nyi' icebreaker in 1946 noted a frequent occurrence of piles of sediments on ice floes in this region (Stepanov, 1948b). The sediment composition indicates its relation to IC deposits on the shore. The disappearance of the hypothetical island was facilitated probably not only by thermal abrasion but also the mechanical action of sea ice. The existence of shoals in the region of supposed Andreev Land can be presently confirmed by a large amount of stamukhas (large sea-ice blocks anchored to the bottom).

In accordance with the classification used by Kosheleva and Yashin (1999), banks and shoals in places of former IC islands are composed of sandy and sandy silt deposits. In sandy deposits, the sand (0.1–1 mm) fraction constitutes more than 75%; in sandy silt deposits, the contents of sand and silt (0.01–0.1 mm) fractions varies from 25 to 50% each. These banks are usually surrounded by areas where seafloor sediments are predominantly silty clays (50–75% of the fraction <0.01 mm) and clayey silts (50–75% of the fraction 0.1–0.01 mm). Semenovskaya and Vasil'evskaya banks provide a good example of this type of seafloor sediment distribution (*State Geological Map of Russian Federation*, 1999). Based on geological, historical, and partly on grain-size distribution data, it can be stated that Sannikov, Vasema, and Andreev Lands probably really existed and if so, they were IC islands.

## TECTONICS AND ITS ROLE IN THE CONSERVATION OF IC REMAINDERS ON THE SHELF

The present and past IC islands are mainly confined to tectonically elevated areas. This statement can be illustrated by an example of the Laptev Sea (Figure 4), which was studied better than the East Siberian Sea. In accordance with recent data, shoals in place of the former Figurin Island and the supposed Sannikov Land area correspond to the Kotel'nicheskii horst (Figure 4). The bank in place of Diomede Island also locates within the elevated tectonic block. The elevation of this block is very significant and marked by bedrock outcrops on Svyatoi Nos Cape, Kigilyakh Cape, and Bol'shoi Lyakhovskii Island. The Semenovskaya and Vasil'evskaya banks

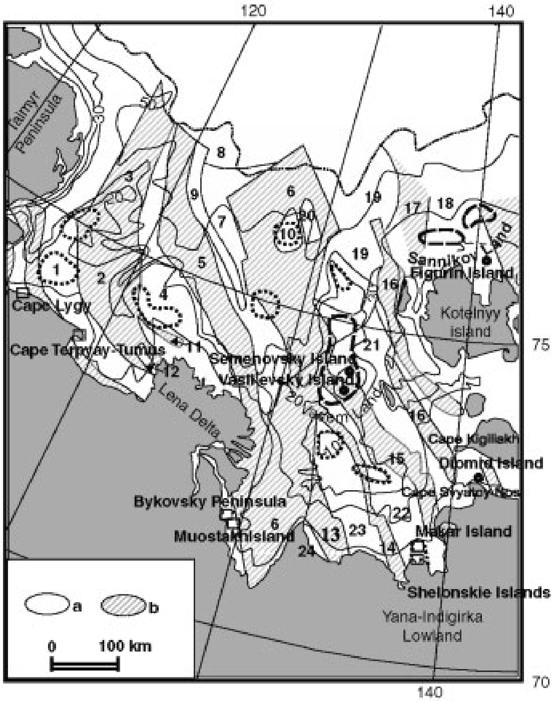


Figure 4 Schematic map relating IC islands with recent tectonic structures: (a) uplifts; (b) subsidence blocks; (1–24) tectonic structures on the shelf (Sekretov, 2001): (1) Lena–Taimyr uplift zone; (2) South Laptev depression; (3) West Laptev depression; (4) Trofimov uplift; (5) Ust'-Lena graben; (6) Omoloi graben; (7) Central Laptev uplift; (8) North Laptev depression; (9) Minin uplift; (10) intensive elevation; (11) Danube trough; (12) West Laptev vault; (13) Ust'-Yana graben; (14) Chondon graben; (15) Shirokostan graben; (16) Bel'kovo–Svyatoi Nos graben; (17) Anisin depression; (18) Kotel'nicheskii horst; (19) East Laptev horst; (20) Omoloi horst; (21) Stolbovoi horst; (22) Berelekh horst; (23) Ust'-Yana horst; (24) Buorkhaya horst. For other notations, see Figure 3.

are within the large East-Laptev tectonic uplift (*Tectonic Map of the Kara and Laptev Seas and Northern Siberia*, 1998; Drachev *et al*., 1995), which is subdivided into smaller elevated and relatively lowered blocks (Sekretov, 2001) (Figure 4).

The predominant confinement of former IC islands to the positive tectonic structures could be expected. During the Late Pleistocene and Holocene, the transgressing sea first covered the negative tectonic structures, which were already occupied by thermokarst lakes (Romanovskii *et al*., 1999, 2000). A system of thermokarst lake basins was developed predominantly in the tectonic depressions where the drainage conditions were least favourable for surface runoff. This ensured advance of the sea along these depressions. It was essentially a transgression into the thermokarst basins accompanied by destruction of bridges between them.

As a result, the sea occupied predominantly negative tectonic structures, whereas the dry land survived within the positive tectonic structures for a longer time. In accordance with delineation of the tectonic structures, the southern region of the Laptev Sea represents a system of bays oriented from the northwest to the southeast (Figure 4). The coastal thermal erosion eventually destroyed the narrowest parts of the peninsulas and gradually transformed them into islands.

## PRESENTLY DISINTEGRATING ISLANDS AND PENINSULAS

A few islands and peninsulas with IC fragments remain presently within the Laptev and East Siberian Sea shelves (Figures 1 and 3). In coastal areas where the base of the Late Pleistocene IC is situated below sea level, the sea intrudes into former thermokarst lake basins (the local name for a thermokarst lake basin is 'alas') after narrow IC land bridges separating alases from the sea have been destroyed. In this way, the Bykovskii Peninsula is presently being transformed into an island (Figure 5) (Romanovskii *et al*., 1999; Tumskoy, 2002). The Kolychev Isthmus that connects the peninsula to the mainland is presently only 1 km wide and is subjected to intensive thermal erosion. Muostakh Island, which in the near past was connected to the Bykovskii Peninsula, is presently at the point of completely vanishing.

A significant advance of the sea along so-called thermokarst lagoons is observed presently in the

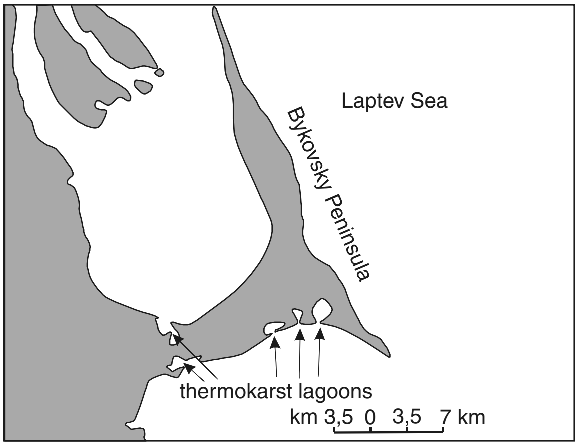


Figure 5 The Bykovskii Peninsula composed of IC is presently being transformed into an island.

Chondon graben (Figure 4) (Romanovskii *et al.*, 2000). Chondon Bay and the Asabyt Gulf are the largest lagoons. On the surrounding land, the surface of alases is only 1 m above sea level and the bottoms of the lake basins are below sea level.

Makar and Shelonskie islands are located within the limits of the Berelekh horst (Figure 4), which is a part of the East-Laptev uplift (*Tectonic Map of the Kara and Laptev Seas and Northern Siberia*, 1998; Drachev *et al.*, 1995). At this site, the basis of IC sediments lies above sea level. These islands are remainders of a formerly vast peninsula, which protruded into the sea for a distance of almost 40 km. Some parts of the islands' area are covered by IC sediments, which are subjected to thermal denudation. The absolute heights of IC islands can reach 40 m, and the shorelines of thermokarst lakes are at an elevation of 1.5 m.

## SEAFLOOR THERMAL ABRASION AND APPROXIMATE ESTIMATION OF ITS RATE

Seafloor thermal abrasion on sandbanks, which remained here after destruction of IC islands, was detected by direct observation (Burenkov *et al.*, 1997; Lisitsin *et al.*, 2000; Dmitrenko *et al.*, 2001). In cross-section through the northern tip of the Vasil'evskaya Bank (Figure 6), this process can be revealed by a maximum of local turbidity accompanied by an abrupt temperature increase in the near-bottom water layer. The fine silt is predominant in the composition of suspended particles. According to Dmitrenko *et al.* (2001), this suspension is a product of destruction of the IC within the Vasil'evskaya Bank. All these observations were made in the summer period, when shoals warmed up and the temperature of their bottom water layer became positive (Dmitrienko *et al.*, 2001). Thus, shallow banks (with a depth of 10–15 m or even more) represent near-bottom seawater temperature anomalies, where more intensive summer thawing of seafloor deposits takes place.

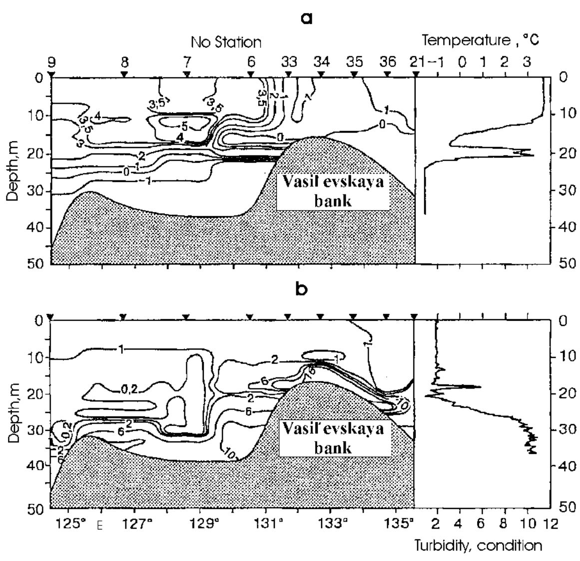


Figure 6 Distribution of (a) water temperature and (b) turbidity in the section along 75 °N through the northern extremity of the Vasil'evskaya Bank in September 2000 (Dmitrenko *et al.*, 2001).

The positive temperature of water during the summer intensifies thermal abrasion of frozen near-seafloor deposits, because their layer-by-layer thawing makes the process of sediment removal much easier. However, seafloor thermal abrasion can also take place under negative (subzero) temperatures because of gradual dissolution of ground ice in salt water ('thermo-chemical' abrasion). This can be proved by intensive intrusion of suspended particles into sea ice observed on a shoal to the north of the New Siberian Islands (Dethleff *et al.*, 1993; Eicken *et al.*, 2000).

To estimate the rate of seafloor thermal abrasion, we used the results of soundings in places of disappeared islands, which were performed over several years (Table 1). As seen from the table, the largest differences in the rates of seafloor abrasion were observed at the Semenovskaya Bank. The highest rate (0.27 m/year) was observed for the period 1965–2000. The lowest rate of bank abrasion (0.02 m/year) was observed during the first 10–15 years right after Semenovskii Island's disappearance.

The lowest rates of seafloor thermal abrasion can be explained by the great volume of material accumulated during the last several years of existence of Semenovskii Island. This material accumulated as a result of active coastal thermal erosion. The removal of this material was hampered by the presence of the island. The data presented in the Table 1 show that in 10 years the material was removed to deeper parts of the sea and the thermal abrasion rate increased. In the first half of the 1960s, it was 0.2 m/year.

The abrasion velocity on the Vasil'evskaya Bank was significant (0.27 m/year) over the entire period of observations (1965–2000) (Table 1). The similarity of the abrasion rates obtained for the Semenovskaya and Vasil'evskaya banks indicate that probably the same type of sediments or, at least, sediments with similar ice content were eroded. If the sediments were similar, most probably they were IC deposits.

The average rate of seafloor abrasion at the place of the former Diomede Island, as calculated from data on sea depth dynamics and on the timing of the island's disappearance, was significantly lower: 0.05 m/year (Table 1). The calculated thickness of scoured deposits was also lower, in spite of the longer duration of thermal abrasion and a strong current in the Dmitrii Laptev Strait. So, only 7.4 m of deposits were eroded from the Diomede Bank during 150–170 years, and 7.5–12 m of deposits were eroded from the Vasil'evskaya Bank within 64 years. It is known that the dense clayey deposits of the Kuchchugui suite with relatively low ice content underlie IC sediments (Romanovskii, 1958; Nikol'skii *et al.*, 1999). Apparently, the deposits of the Kuchchugui suite compose the major part of the Diomede Bank. Therefore, the seafloor abrasion rate significantly depends on the ice content and bulk density of the sediments being eroded.

The obtained rate of seafloor thermal abrasion was also verified by calculations based on other data. The comparison of the sounding results obtained by Edvard Toll in the Sannikov Land region in 1902 with bathymetric maps and recent abrasion data gives a very high value of seafloor thermal abrasion (0.4–0.7 m/year).

In another case, we used Vitsen's data about abundant shoals on the path from the 'ice cape' (according to Vize, 1946, this is the Buorkhaya Cape) to the island that was 'opposite of the Lena mouth' in the 1690s. The depth of seawater at these sites, measured by Russian sailors in the $15^{th}$–$17^{th}$ centuries, was close to 2 m (Vize, 1948; Zubov, 1954; *History of the Discovery and Development of the Northern Seaway*, 1954). Presently, there are no depths of 2 m in the open sea in this area. We consider the banks delineated by the 10-m isobath to the north of the Buorkhaya Cape (Figure 3) as a possible location of the island shown on Remezov's map and described in Vitsen's book (Vize, 1946). At present, the minimal depths on the way to these banks are about 15 m. Using these findings dated back to the 1690s, the abrasion velocity can be estimated at 0.05 m/year.

The obtained rates of seafloor thermal abrasion allow estimation of the time of the supposed islands disappearance. So, Sannikov Land was presumably eroded away about 100 years ago and Andreev Land, 100–250 years ago. It is possible that 300–400 years ago, Vasema Land was only slightly smaller than the present Bol'shoi Lyakhovskii Island.

## RECONSTRUCTION OF THE POSITION OF ISLANDS PRESUMABLY DESTROYED BEFORE THE MID-$17^{TH}$–EARLY $18^{TH}$ CENTURIES

The history of the development of the East Siberian Sea shelf was depicted in documents of the mid-$17^{th}$–early $18^{th}$ centuries. One of the tasks of this study was to locate the islands, which disappeared before that time. The approach to resolve this problem was by delineating the convex forms of seafloor topography composed of sand and intensively abraded.

### Textures of Seafloor Deposits and their Relation to Underwater Topography

The analysis of maps of the seafloor deposits, which were compiled on the basis of both laboratory data and visual estimates (Stepanov, 1948a; Kordikov, 1952; Solov'ev, 1982; Kosheleva and Yashin, 1999; *State Geological Map of Russian Federation*, 1999), made it possible to delineate sandy areas on the bottom of the Laptev and East Siberian seas. In accordance with the latest data of Kosheleva and Yashin (1999), deposits with a sand particle (0.1–1 mm) content equal or higher than the content of finer particles (particle size smaller than 0.1 mm) are shown in Figure 7. These areas mainly correspond to positive forms of seafloor topography. According to results obtained by other authors (Solov'ev, 1982; *State Geological Map of Russian Federation*, 1999), positive forms on the seafloor constructed by sandy deposits are even more widespread than as shown from Kosheleva and Yashin's data.

Data presented in Figure 4 show that positive forms of seafloor topography, which are predominantly composed of sand, are usually confined within positive tectonic structures and vice versa. Thus, it is possible to suggest a correspondence between fine-grained bottom sediments and the most significant negative tectonic structures. In particular, clayey silts containing up to 90–99% of the pelitic fraction, which are usually typical for the outer shelf, were found near the shore in Buorkhaya Bay at the 10-m isobath (Aksenov *et al.*, 1987; Pavlidis *et al.*, 1998). Buorkhaya Bay is located on the Ust'-Lena Rift (Omoloi Rift, by Sekretov), the main structural element of the rift system in the Laptev Sea (Drachev *et al.*, 1995; *Tectonic Map of the Kara and Laptev Seas and Northern Siberia*, 1998).

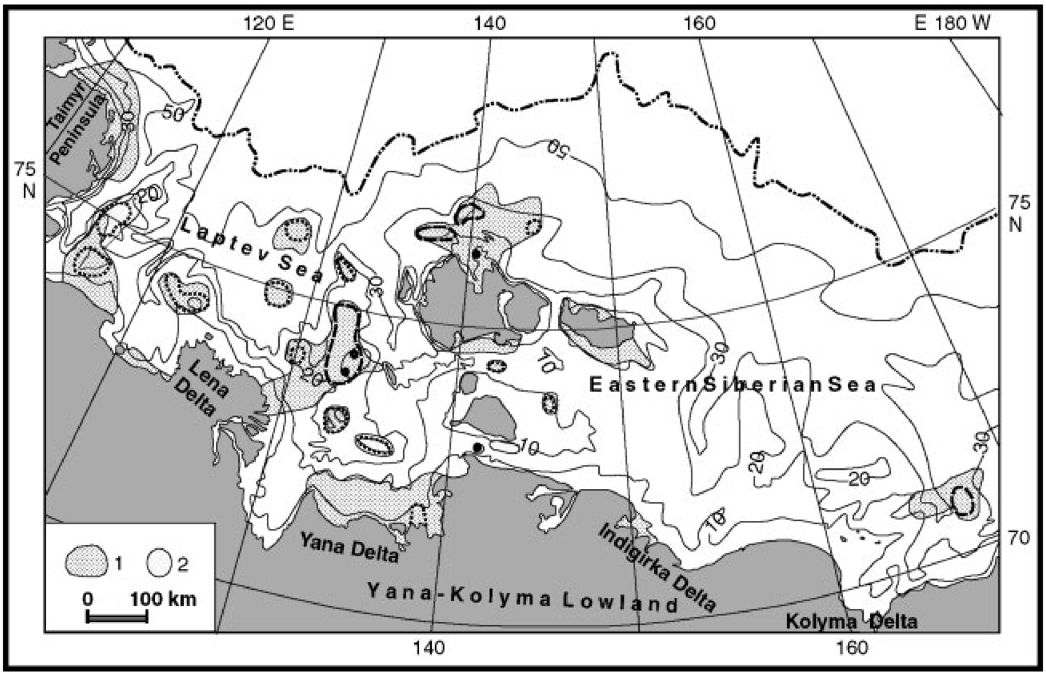


Figure 7 Distribution of predominantly sandy seafloor deposits on the shelf of the Laptev and East Siberian (western part) seas according to the data of (1) Kosheleva and Yashin (1999), and (2) Solov'ev (1982) and *State Geological Map of Russia* (1999). For other notations, see Figure 3.

## Seafloor Abrasion Areas and their Relation with Sandy Shoals and Banks

The seawater mechanical activity on shelves causes sea bottom levelling. Therefore, the positive relief forms are being subjected to seafloor abrasion. As was noted, the removal of fine material from these forms results in the enrichment of their deposits with sand and coarse silt fractions. Based on the data of Semenov and Shkatov (1971), the areas of predominant bottom scouring can be detected by the presence of sand and sandy silt deposits. These deposits are usually developed to seawater depths of 10–30 m in the near-shore zone and to 40 m in open sea. The comparison of the location of the sandy sediments distribution areas and the seafloor abrasion areas determined by the measured seafloor deepening in the Laptev Sea shows good agreement (Figure 8). Positive relief forms composed of sand and intensively abraded at the present time are widespread on the East Siberian Arctic shelf. It is seen in Figure 4 that they predominantly coincide with positive tectonic structures.

We believe that the mentioned seafloor positive relief forms were IC islands in the past. The analysis of available data shows that the depths of seawater within banks and shoals increase with time. A map of the former distribution of IC islands was compiled on the basis of the above materials (Figure 3). This map shows only the islands, the locations of which are best substantiated by available data. Most probably, the actual number of these islands was much larger five–seven centuries ago. Some indication of this could be the existence of numerous small sandy shoals in the Dmitrii Laptev Strait, Yana Gulf, and around the New Siberian Islands.

## Estimation of the Disappearance Time of IC Islands

This estimate was based on calculation of the seafloor abrasion rate. For the abrasion rate of low ice content deposits, which are presumably occurring below the IC base, data on the Diomede Bank (0.02 m/year) were used. The following results were obtained. Islands that existed in place of the recent shoals with seawater depths of 15 m were destroyed probably 300–400 years ago and those on the sites of shoals with 20-m depths, 400–500 years ago. The recent sandy shoals at a seawater depth of 40 m could be the sites of islands eroded away 800–1000 years ago.

 

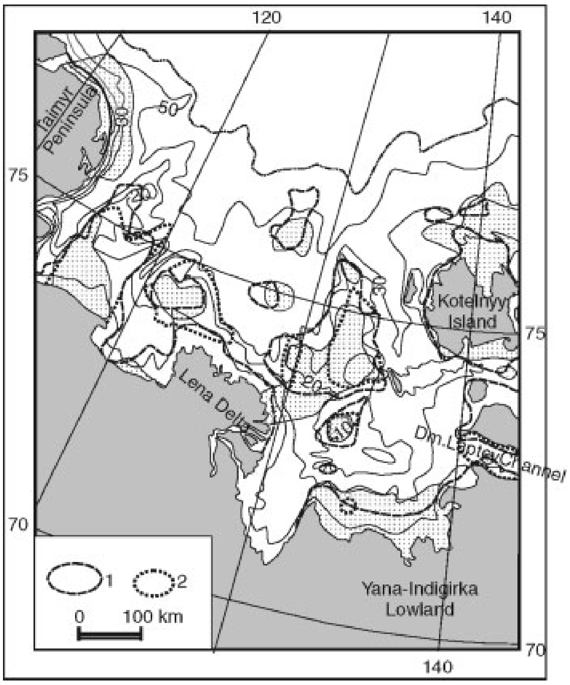


Figure 8 Schematic map of sandy seafloor deposits distribution (Kosheleva and Yashin, 1999) and seafloor abrasion areas (1) Semenov and Shkatov, 1971; (2) Are, 1998; on the Laptev Sea shelf. For other notations, see Figures 3 and 7.

When the IC base locates below sea level, the time of island erosion could be much shorter. If the IC base was 5 m below sea level, the islands on the site of the present banks with 15 m seawater depth could have been destroyed about 200–250 years ago. The complete destruction of islands in place of the present-day 20-m-deep banks (and the IC foot occurring 10 m below sea level) could have happened about 300 years ago. When the IC base occurred 20 m below sea level, islands in the place of the present 40-m-deep shoals could have been destroyed about 500–600 years ago.

The obtained estimates agree with other data. An island marked as 'opposite of the Lena mouth' on Remezov's map and mentioned in Vitsen's book was most probably composed of IC deposits. Researchers who concluded that this was Stolbovoi Island (Vize, 1946; *History of the Discovery and Development of the Northern Seaway*, 1954) ignored the possibility of existence of islands in the late 17$^{th}$ century that were eroded away later on. The secular dynamics of ice conditions were also poorly understood at the time of these publications. The small boats of Russian sailors ('koches') could move only in the zone between the shore and the ice edge (*History of the Discovery and Development of the Northern Seaway*, 1954). In the present conditions, navigation on similar boats from Lena delta to Stolbovoi Island is possible only in warm years. In the late 17$^{th}$ century, the climate and ice conditions in the Arctic were more inclement than they are today. This is attested by data from Iceland coasts (Bergthorsson, 1969). In the second half of the 17$^{th}$ century, the duration of the ice season near the Iceland coast varied from 1 (in the 1660s) to 3–3.5 months (1680s–1690s). At the same time, sea ice did not form at all in this region in the 1930s–1950s. The results of correlation analysis of the present-day ice conditions indicate that the Iceland data can be used for characterization of the secular dynamics of ice conditions in the Laptev Sea (Kotlyakov and Grosval'd, 1987).

The impossibility of sailing in 'koches' to Stolbovoi Island because of heavy ice conditions was also proved by the entire history of development of Lyakhovskii Island, which is located to the south of Stolbovoi Island (Figure 3). Numerous attempts to cross the Dmitrii Laptev Strait in 'koches' in the second half of the 18$^{th}$ century were unsuccessful (*History of the Discovery and Development of the Northern Seaway*, 1954). Therefore, starting from that time to almost the end of the 20$^{th}$ century, Russian explorers and hunters reached the islands by ice during the cold season (*History of the Discovery and Development of the Northern Seaway*, 1954).

The island that was shown on Remezov's map to the south of the present-day Semenovskaya and Vasil'evskaya banks and described in Vitsen's book could be an IC island located at the place of the present-day bank that is delineated by the 10-m isobath (Figure 3). The estimates of the destruction time of such IC islands (about 300 years ago) are in agreement with the possibility of existence of this island near the Lena delta in the late 1690s and the possibility of reaching it in 'koches'.

## CONCLUSIONS

(1) Historical data, archived documents, and information on Quaternary deposits in the region justify the conclusion that present-day sandy banks and shoals represent submarine relics of former IC islands and that the destruction of these islands by coastal thermal erosion and seafloor abrasion proceeded in the time interval from 250 to 50 years ago.
(2) In the more distant past, IC islands on the East Siberian Sea shelf were much more numerous

than it seems from historical data. We reconstructed the locations of IC islands destroyed by thermal abrasion about 300–800 years ago.

(3) The rate of seafloor thermal abrasion was roughly estimated for sandy banks on the site of eroded IC islands. It usually varies from 0.05 to 0.15–0.2 m/year and at some places could be as high as 0.4 to 0.7 m/year.

(4) It was found that relict IC islands are mainly confined to the latest positive tectonic structures. On these sites, the IC was eroded by the transgressing sea more recently than in tectonically depressed blocks. The surfaces of these depressions were significantly lowered under the impact of lake thermokarst, which developed on the shelf before it was submerged under seawater. During historical time, the sea advancing inland along the thermokarst lake basins that dissected elevated IC massifs. Advancing sea also penetrated into the small river valleys, which determined the transformation of the IC massifs into elongated capes and peninsulas and then into relict IC islands.

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