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CRYOGENIC PHENOMENA IN SEAS AND OCEANS

FROZEN AND CRYOTIC SOILS IN THE BAYDARATA BAY AREA

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The purpose of this study is to establish the genesis and conditions of formation of different types of sediments in the permafrost area of Baydarata Bay. Perennially and seasonally frozen and perennially and seasonally cryotic sediments have been identified on the basis of temperature measurements in core samples obtained during geotechnical drilling and temperature cone penetration tests along the profile crossing the bay. We suppose that permafrost was formed in this area in the course of epigenetic freezing during the Sartan regression. Seasonally frozen soil of the seafloor is subdivided into two types. The first type is characteristic of coastal shallows, where landfast ice contacts the seafloor. The second type is formed in the seaward part of the water area during the cold season, when the temperature of near-bottom seawater drops to values below the freezing point. Perennially cryotic (but unfrozen) soil is formed below the depth of the 0° isotherm traced during the warm season. Seasonally cryotic soil above this isotherm has above-zero temperatures in the warm season. In the winter season, under the impact of subzero temperatures of seafloor water, it is transformed into the cryotic or seasonally frozen state.

Keywords: *the Kara Sea, the Baydarata Bay, permafrost, frozen soil, cryotic soil, seasonally frozen soil, subsea permafrost, soil temperature, melting point temperature, temperature cone penetration test, Quaternary sediments.*

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INTRODUCTION

The geocryological conditions in the southwestern part of the Kara shelf and the adjacent coast of the Yamal Peninsula have been described in a number of works [*Grigoriev, 1987; Baulin et al., 2003; Vasil'chuk et al., 2006; Rokos et al., 2009; Dubrovin et al., 2015; Shpolyanskaya, 2015; Vasiliev et al., 2016; Badu, 2018*]. Permafrost in the Baydarata Bay is considered in detail in [*Dubikov, Ivanova, 1996; The Environmental..., 1997*]. It was shown that both permafrost and thawed soil, as well as seasonally freezing and cryotic soils are present in this area. As published data on soil temperature in the studied water area are very few, the temperature characterization of the shelf zone remains incomplete and rather schematic. At the same time, for the Baydarata Bay, there is a rather large volume of temperature records and drilling data obtained in 1994–2006. However, these data and their interpretation have not been published. The aim of this study is to identify, localize, and typify frozen and cryotic soils in the Baidarata Bay on the basis of earlier obtained drilling and thermometric data.

MATERIALS AND METHODS

This study is based on the materials of engineering-geological surveys carried out by the Arctic Marine Engineering Geological Expeditions (AMIGE) in 1988–2006 for the construction of the Yamal–Center gas pipeline crossing the Baydarata Bay (four strings in a corridor with a total length of about 70 km and a width of about 500–700 m). Data on drilling, temperature measurements by temperature cone penetration tests, core thermometry, and laboratory determinations of the composition and properties of seafloor soil have been obtained during the survey.

In the summer-autumn navigation season, drilling was carried out from specialized vessels "*Bavenit*" and "*Kimberlit*" in the seaward part of the water area with sea depths of more than 5–7 m. In the coastal shallows, boreholes were drilled in the cold winter–spring season from landfast ice.

A total of 639 boreholes with depths ranging from 7–10 to 20–40 m from the seafloor were drilled in the aquatic part of the pipeline route (Fig. 1). One borehole (no. 01) was drilled to a depth of 115 m in the central part of the survey route. The sampling was carried out by double and single core barrels, as well as by hydroimpact, vibration, and pressure samplers.

Table 1 demonstrates the data on the boreholes that revealed frozen soil in the bay.

Frozen soil in core samples was visually and tactilely identified by the presence of ice inclusions and pore ice-cement.

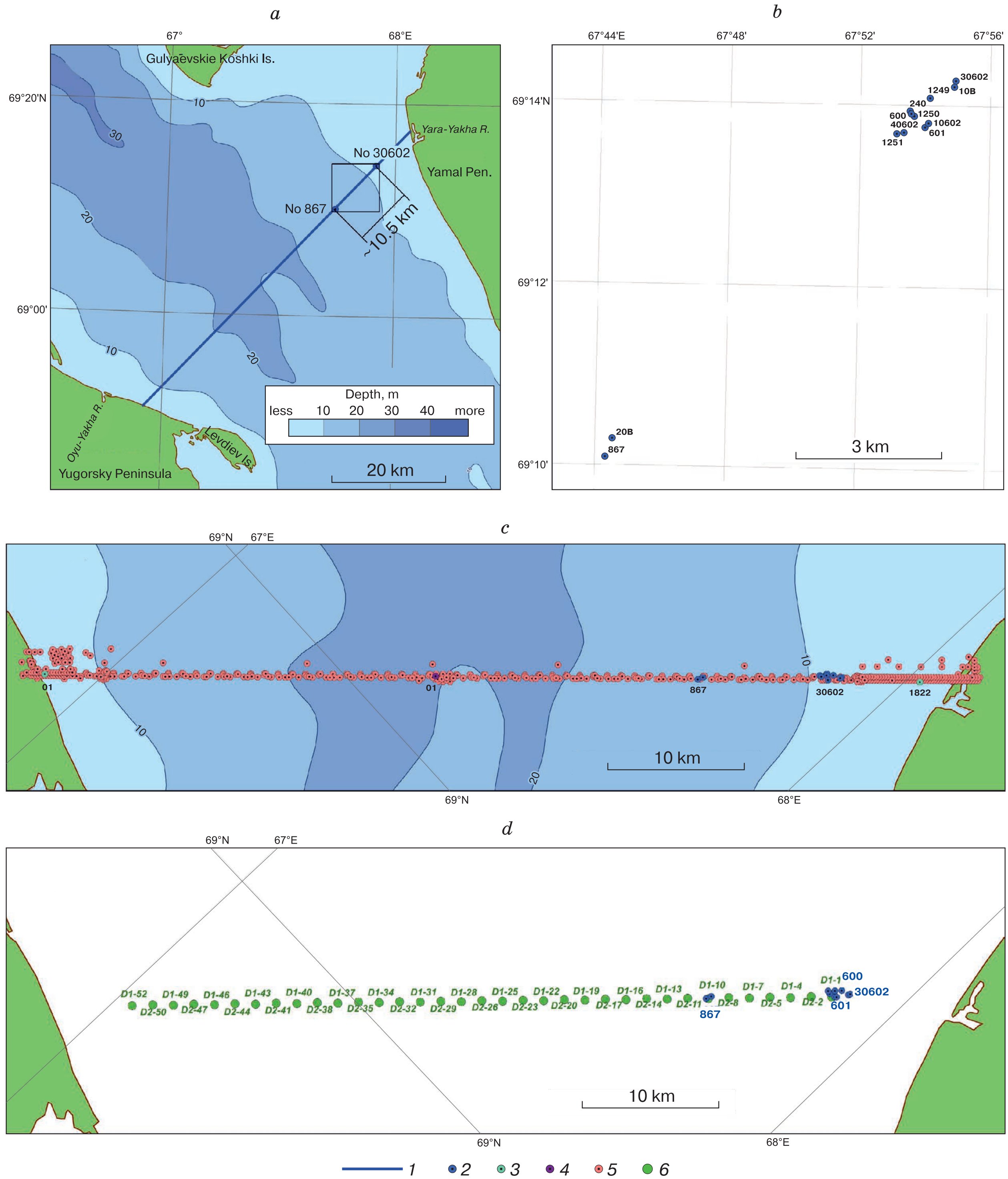

Fig. 1. Location of the survey route, engineering-geologic boreholes, and points of the thermostatic cone penetration tests.

a – survey route and permafrost occurrences between boreholes nos. 867 and 30602; *b* – boreholes that exposed local permafrost; *c* – engineering-geological boreholes; *d* – thermostatic cone penetration test points. *1* – pipeline route, *2* – engineering-geological boreholes that exposed permafrost, *3* – engineering-geological boreholes that exposed seasonally frozen sediments, *4* – 115-m-deep (from the seafloor) engineering-geological borehole, *5* – engineering-geological boreholes of more than 10 m deep from the seafloor, *6* – thermostatic cone penetration test points.

Table 1. **Coordinates and the sea depth at the points of boreholes, in which permafrost was identified in the seaward part of the water area**

Borehole no.	Coordinates (WGS-84)		Sea depth, m	Date of drilling	Depth of drilling from the seafloor, m	Depth of the permafrost table from the seafloor, m
	N	E				
867	69.1674550	67.7404280	17.5	16.09.88	30.0	28.8
600	69.2311615	67.8949207	13.6	15.09.94	33.4	18.0
601	69.2287213	67.9022537	13.4	16.09.94	33.5	15.2
240	69.2316465	67.8944893	12.8	17.09.91	42.0	15.7
10B	69.2361840	67.9168456	12.5	09.09.95	30.0	13.0
20B	69.1708220	67.7440327	16.9	27.08.95	39.0	18.6
10602	69.2302524	67.90225595	13.5	31.07.06	20.0	12.8
30602	69.2380446	67.91582619	12.3	29.07.06	20.0	12.2
40602	69.2286056	67.88918972	13.8	28.07.06	20.0	18.8
1251	69.2283158	67.8858501	12.8	17.04.89	22.5	18.4
1250	69.2315677	67.8945328	13.5	13.04.89	21.5	16.3
1249	69.2349333	67.9027684	13.6	26.04.89	21.0	13.2
112	68.8556010	66.9277430	5.5	12.05.88	11.5	3.5
1822	69.2732580	68.0207630	6.8	28.05.88	19.5	0.0

Note: The table does not include boreholes with permafrost drilled in the shallow coastal area with sea depths less than 2.5 meters.

Thermostatic cone penetration tests were performed in September 1994 at 40 points on two strings of the survey route. Estimates of the soil temperature obtained by this method appear to be the closest to the true values. Thermostatic cone penetration tests to a depth of up to 11 m from the seafloor were carried out with a Wheeldrive-type seafloor unit (Fugro Engineers B.V.) using the continuous probe indentation. In addition, these studies were carried out in the boreholes with step-by-step drilling of the penetrated intervals. The pressure force was up to 200 kN in both cases. Temperature was measured with an F7.5 Sket/V-a probe (Fugro Engineers B.V.). An accuracy of temperature measurements was ±0.05°C. The penetration depth varied from 4 to 21 m below the seafloor. The method of the performed thermostatic cone penetration test generally corresponds to state standards [*GOST R 58961-2020, 2020*].

Comark C9001 thermometers (Comark Instruments) with sensors in a thin metal rod were used for **core thermometry**. Measurements were taken at a hole bottom immediately after lifting the core sampler before the extraction of the core.

The temperatures measured in the cores were highly variable because of differences in the drilling conditions. The cores were affected by the intensive thermal influence during drilling due to operation of rock-destroying tools and circulation of drilling fluid in the bottom part of the borehole and along the walls of the sampler. Seawater used as a drilling fluid was taken from the upper horizons of the water column, where, in the warm season of the year, it warmed up to +5...+10°C, which significantly exceeded the temperature of the soil (both permafrost and thawed soil). In addition, differences in drilling methods and modes, as well as variability in the composition and properties of sediments affected the degree and intensity of the core heating.

It is obvious that these operational changes in the temperature of core samples relative to the true soil temperature can only result in the temperature rise. At the same time, the core temperatures can in any case be considered as the upper limit of the true temperatures in situ.

Another limit, which allows us to verify the obtained data, is the temperature of the beginning of soil thawing or freezing (T_{bf}) for frozen or thawed soil, respectively. Obviously, the temperature of frozen soil cannot be higher than T_{bf}, and the temperature of thawed soil cannot be lower. The values of T_{bf} given in this paper were calculated on the basis of the concentrations of pore solution in accordance with Appendix B of Design and Construction Rules for Bases and Foundations on Permafrost Soils [*SP 25.13330.2012, 2011*].

Salinity and composition of the ionic complex of soluble salts were determined according to GOST 26428-85 [*1985*] and GOST 26423-85 [*1985*].

Characteristics and classification of frozen and thawed soils in this work are given in accordance with GOST 25100-2020 [*2020*].

Geological structure of the upper part of the section

According to the materials of engineering-geological drilling and shallow seismic and in accordance with [*Volkova, Babushkin, 2000*], the authors distinguish the following stratigraphic-genetic units in the structure of sediments in the upper part of the section to the depth of 30–50 m (from bottom to top) (Fig. 2):

– Marine and glaciomarine sediments of the Kazantsevian horizon $m, gmIII^{1}kz$;

– Alluvial sediments of the Yermakovian horizon $aII^{2}er$;

– Marine and alluvial-marine sediments of the Karginian horizon $m, amIII^{3}kr$;

– Lacustrine-alluvial sediments of the Sartanian horizon $laIII^{4}sr$;

– Holocene marine sediments *mH*.

A unit of the Holocene lacustrine-palustrine sediments (*lpH*) is also distinguished on the Yugorsky coast.

Permafrost soils

Permafrost soils are widely developed on the coasts of the Yamal and Yugorsky peninsulas adjacent to the Baydarata Bay. Generally, permafrost is continuous. A thick (over 50 m) layer of frozen sediments occurs on a terrace with a height of about 5 m asl on the western Yugorsky coast in the vicinity of the pipeline route. This sediment sequence with massive

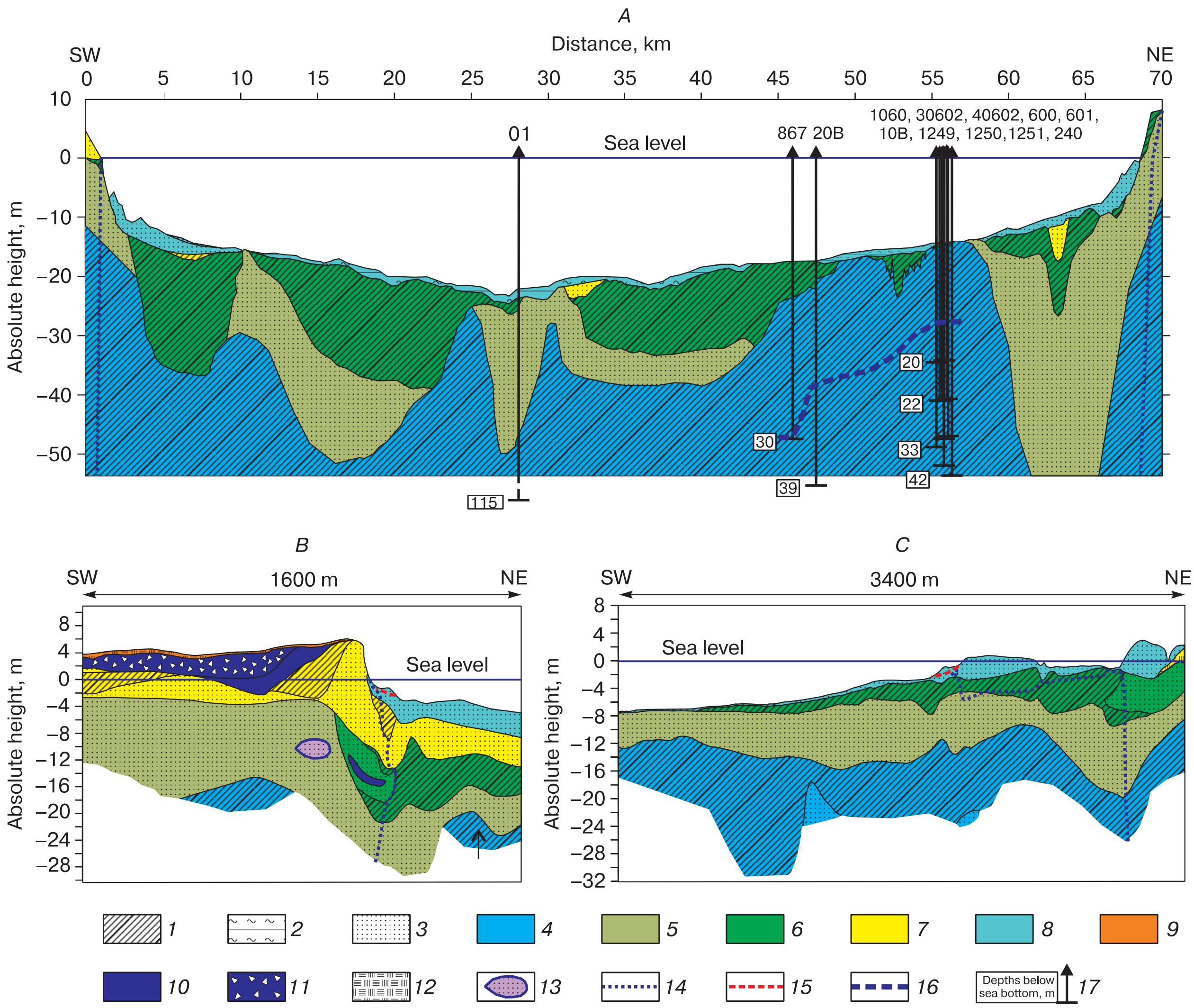

Fig. 2. Engineering-geological sections through the water area of the Baydarata Bay and adjacent coastal areas.

A – Baydarata Bay, *B* – western coast, *C* – eastern coast. *1* – loams, *2* – clays and loams, *3* – fine-grained and silty sands, *4* –marine and glaciomarine sediments of the Kazantsevian horizon ($m,gmIII^{1}kz$), *5* – alluvial sediments of the Yermakovian horizon ($aII^{2}er$), *6* – marine and alluvial-marine sediments of the Karginian horizon ($m,amIII^{3}kr$), *7* – lacustrine-alluvial sediments of the Sartanian horizon ($laIII^{4}sr$), *8* – Holocene marine sediments (*mH*), *9* – Holocene lacustrine-palustrine sediments (*lpH*), *10* – beds of massive ice, *11* – ice-rich soils with massive-agglomerate cryostructure, *12* – peat and peaty soils, *13* – cryopegs, *14* – boundaries of onshore permafrost, *15* – lower boundary of seasonally frozen layer, *16* – presumed table of local subsea permafrost, *17* – engineering-geological boreholes and their depths (m).

icy beds and cryopegs is abruptly interrupted at the very water line (Fig. 2).

The eastern Yamal coast in the vicinity of the pipeline route is represented by a low accumulative layda composed of the Holocene sediments. It is likely that the layda was formed in the Late Holocene and was repeatedly flooded by the sea and the Yara-Yakha River waters. Therefore, a thickness of the frozen sequence here is low (up to 6 m). The outer boundary of the thick (more than 30 m) subaerial frozen sediments is located at a distance of about 700 m from the coast.

In the water area, the local occurrence of frozen soil was revealed along about 10.5-km-long strip in the eastern part of the survey route section between boreholes nos. 867 and 30602 at water depths from 9.0 to 17.5 m (Figs. 1*a*, 1*b*; Fig. 2).

According to drilling, the permafrost table occurs at a depth of 12.2 to 28.8 m below the seafloor (Table 1, Fig. 2). The thickness of frozen sediments varies from less than 1 m to 15 m and more. This formation is separated from the permafrost of the nearest Yamal coast by a wide talik (the term "talik" is used hereinafter in accordance with [*Romanovsky, 1972*]). The length of the talik along the survey route is about 8.6 km. Table 1 demonstrates data on the boreholes, where the presence of permafrost was identified.

The described formations are represented by loams and clays of the Kazantsevian horizon. Two varieties are distinguished in their composition. The first of them is represented by plastic frozen loams with a low to medium ice content, less often by clays with inclined ice lenses (probably, fragments of the reticulate cryostructure). Soils salinity varies from low to medium; the salinity type is marine chloride and sulfate–chloride.

The second type is represented by ice-rich loams. In some intervals, there are pure transparent glassy fresh ice (beds of massive ice?). According to a single determination, the ice mineralization is 0.36 g/L. The total thicknesses of ice-rich sediments and ice beds in the borehole sections is up to 10 m. Ice-rich loams are generally characterized by the massive-agglomerate (ataxic) cryostructures.

In addition, frozen soil was also uncovered by the boreholes drilled in the cold winter–spring season from landfast ice. It was represented by silty fine-grained sands near the seafloor surface. In terms of the occurrence and distribution, two types of the considered frozen soil can be distinguished.

The first type of subsurface frozen sediments is revealed in some parts of the offshore zone at sea depths up to 2.5 m and a distance from the water line no more than 200 m. Here, the frozen soil is traced in the form of thin "caps" the lateral base of which is conjugated with the coastal frozen massifs and thins out seaward (Fig. 2). The thickness of these frozen soil formations does not exceed 2.5 m, their top lies at a depth of 1–2 m from the seafloor surface and in some cases coincides with it.

Another type of subsurface frozen sediments is developed relatively seaward. These formations were penetrated by boreholes no. 112 (drilled on May 12, 1988) in the interval of 3.5–3.8 m from the seafloor and no. 1822 (May 21, 1988) in the interval from the seafloor surface to a depth of 1 m (Fig. 1*c*). These sediments are represented by silty and fine-grained sands. In the area of borehole no. 112 (425 m from the Yugorsky coastline), the depth of the sea is 5.5 m. In the area of borehole no. 1822, the depth of the sea is 6.8 m, and the distance from the Yamal coastline is 2200 meters. No similar frozen formations were found in the core samples from the neighboring boreholes. This fact suggests that the frozen sediments are characterized by the discontinuous distribution and occur in the form of thin lenses.

Results of temperature measurements in frozen sediments

Soil temperatures within the Baydarata Bay obtained by different methods vary from about +5.0...+10.0°C to −1.6...−1.0°C.

The vertical distribution of temperatures measured in core samples shows a negative gradient in the sections of thawed soils in the interval from the seafloor to the top of frozen formations (Fig. 3). In this interval, the soil temperature decreases from positive values near the seafloor to negative values at the bottom of the thawed intervals.

The frozen intervals also show a decrease in core temperatures from the top to the middle and lower parts of the sections. In the top of the frozen section, the temperature of frozen sediments is not higher than −1.1...−0.9°C; at the bottom, it is no lower than −1.6...−1.4°C. In borehole no. 10B, in the lower interval of plastic frozen loam underlying ice-rich soil, the temperature comes to the minimum values (−1.6°C) and does not change with depth (according to three measurements).

Only the upper intervals of the frozen sediment sequence composed of plastic frozen loam were subjected to thermostatic cone penetration tests. It was not possible to make the measurements in the ice-rich sediments using this method, because the pressure force turned out to be insufficient for penetration of the measuring cone.

The temperature of the section composed of both frozen and thawed sediments in borehole no. 600 was measured to a depth of 21 m from the seafloor at the point near the borehole head. At the transition from the cryotic (but unfrozen) sediments to frozen sediments, the temperature abruptly dropped from −0.3 to −0.9°C at a depth of 18 m from the seafloor (Fig. 3). In the uppermost interval of plastic frozen loams, it varied from −1.0 to −0.9°C (three measurements). It

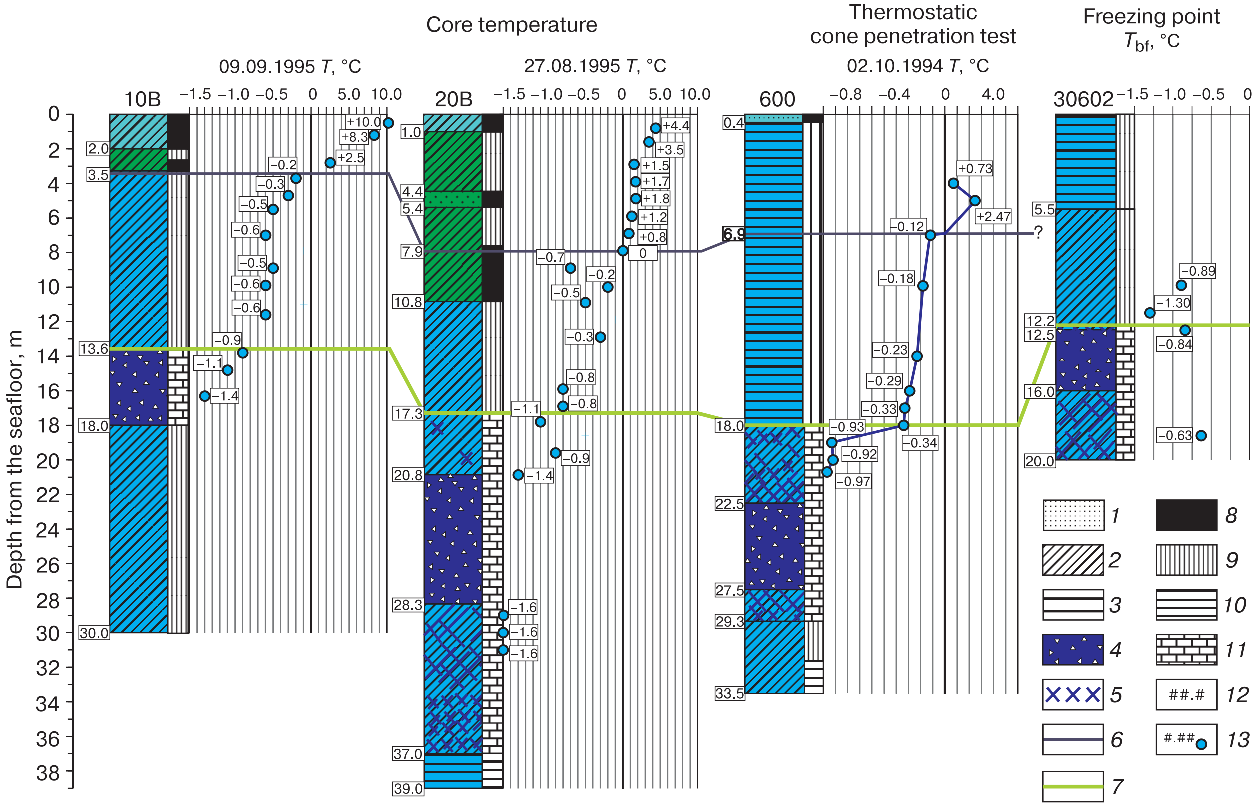

Fig. 3. Vertical temperature profiles according to temperature measurements of core samples from boreholes nos. 10B and 20B, the results of thermostatic cone penetration tests of borehole no. 600, and the distribution of freezing point temperatures in sediments sampled from borehole no. 30602.

1 – sands, *2* – loams, *3* – clays, *4* – ice-rich clays and loams with massive-agglomerate cryostructure and beds of massive ice, *5* – ice lenses, *6* – upper boundary of cryotic sediments, *7* – permafrost table, *8–11* – state of sediments (*8* – liquid for clays and loams, water-saturated for sands, *9* – tight-plastic, *10* – solid–semisolid, *11* – frozen), *12* – depths from the seafloor surface, m (to the left of the borehole columns), *13* – points of temperature measurements and recorded temperature, °C. The stratigraphy is given in Fig. 2. Location of boreholes is shown in Fig. 1*b*.

was impossible to determine the presence of the temperature gradient from these data because of the small penetration depth of the measuring cone and the insufficient number of measurements.

It was not possible to impress the measuring cone into the frozen sediment to a sufficient depth at the testing point near the mouth of borehole no. 601; presumably, the cone could not penetrate a thick ice layer in the uppermost part of the frozen section. Therefore. it was impossible to reliably measure the temperature of frozen sediments using this method.

In general, the temperatures of frozen soil obtained by both thermostatic cone penetration test and core thermometry were lower than the thawing point temperatures within the corresponding intervals (relative to the top of the frozen soil) in the neighboring borehole no. 30602, which testifies in favor of their reliability.

Identification and localization of cryotic sediments

Cryotic (cooled) sediments were distinguished on the basis of data obtained by the subsurface thermostatic cone penetration test carried out to depths up to 7–11 m from the seafloor in 38 points. These points were evenly distributed along the entire 51-km-long survey route (Fig. 1*c*, Fig. 4). The sea depth within the studied route section varied from about 10.0 to 22.5 m.

Correlation of the temperature plots of the subsurface thermostatic cone penetration test shows a well-defined negative gradient in the interval from the seafloor surface to the depths, where the temperature was close to 0°C. Deeper, the temperatures were within a relatively narrow subzero range (from –0.8 to 0°C) without any distinct gradient. Saline sediments with subzero temperatures and containing no ice °are considered as cooled soils (or cryotic se-

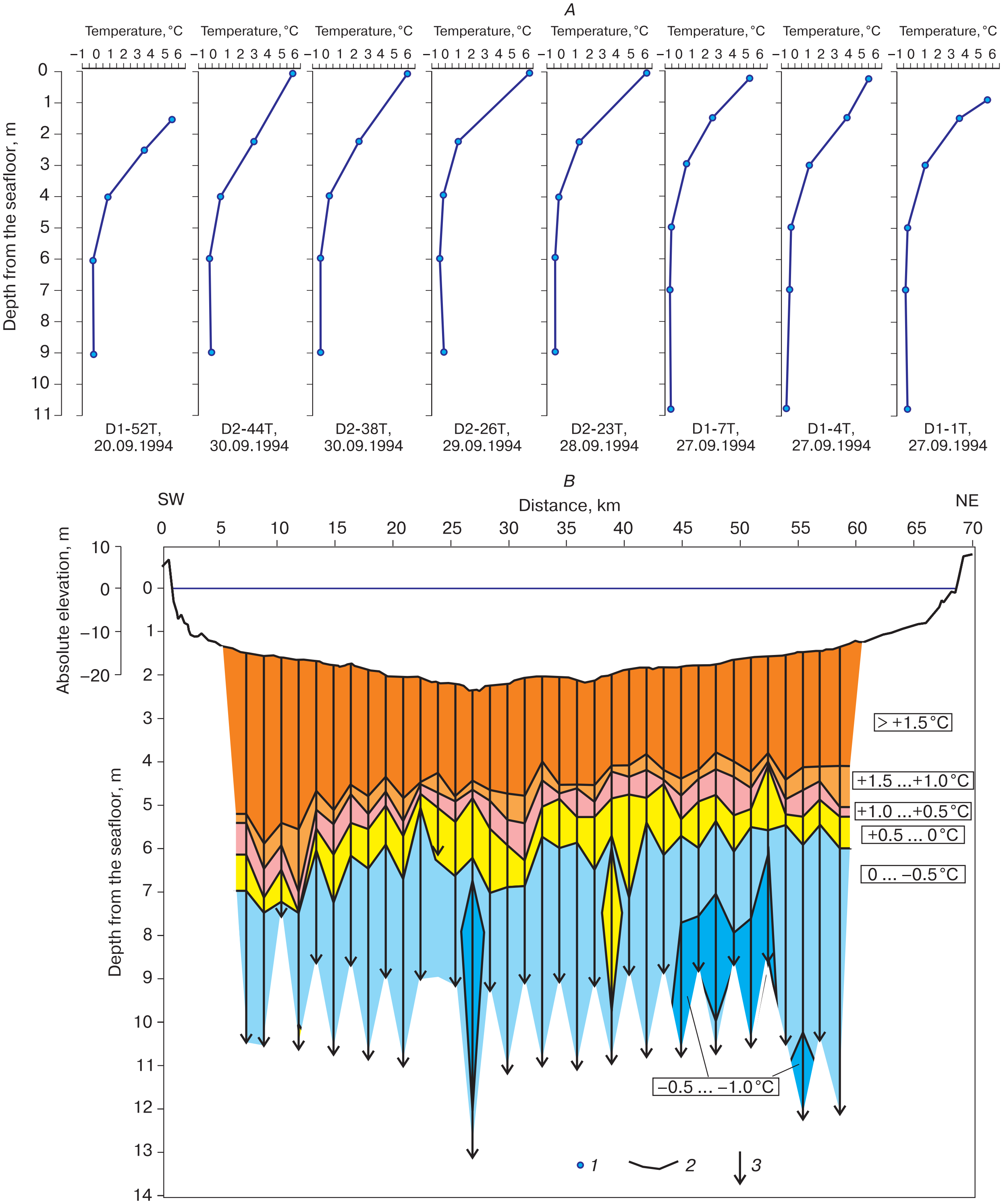

Fig. 4. Correlation of the plots of thermostatic cone penetration test (*A*) and geothermal section through the Baydarata Bay (*B*).

On the geothermal section, the position of the land surface and the seafloor is given relative to sea level. The distribution of temperatures in the sediments is is given relative to the depth from the seafloor. *1* – temperature measurement points, *2* – land and seafloor surface, *3* – thermostatic cone penetration test points (see Fig. 1*d* for their location).

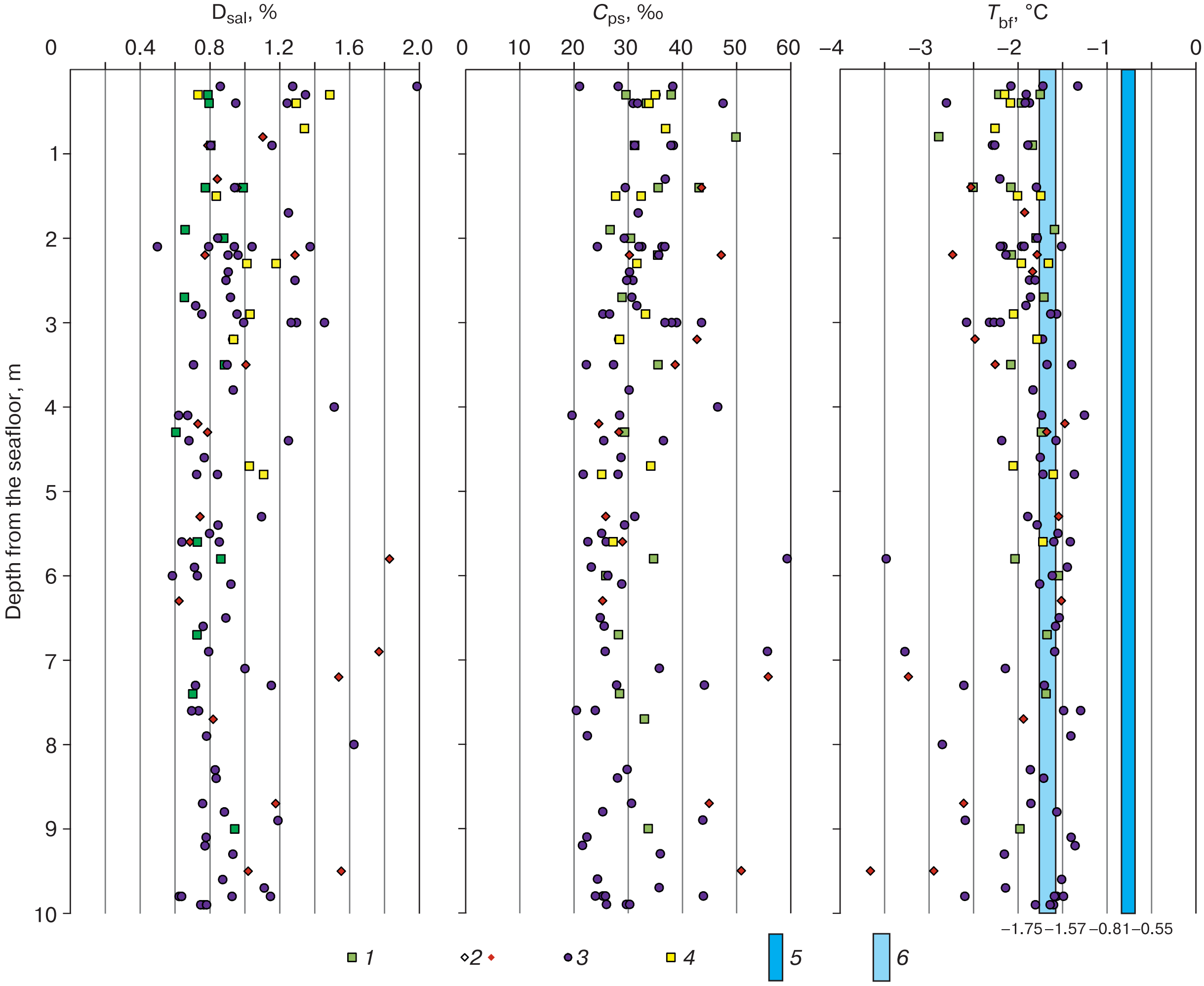

Fig. 5. Summary plots of vertical variability of the salinity degree (D_{sal}), the pore solution concentration (C_{ps}) and the soil freezing point temperature (T_{bf}) in the interval from the seafloor surface to a depth of 10 m.

1 – sand, *2* – loamy sand, *3* – loam, *4* – clay, *5* – range of the mean annual values of the seafloor water temperature, *6* – range of the minimum values of the seafloor water temperature.

diments) in accordance with GOST 25100-2020 [*2020*].

During the observation period September 20 to September 30, 1994, the depth of the 0°C isotherm corresponding to the top of the cryotic sediment sequence ranged from 3.0 to 8.4 meters (from the seafloor) with minimum values in the eastern and central parts of the route and maximum valuer near the western coast.

According to their salinity (D_{sal}) and in accordance with GOST 25100-2020, cryotic sediments in the subsurface layers belong to low-saline sediments (Fig. 5). The salinity of the pore solution (C_{ps}) in these sediments varies from 20 to 40‰. In some cases, it can be up to 50‰ and more.

DISCUSSION

Permafrost in the relatively deep-water part of the bay (sea depths >9 m) is developed in route section between boreholes nos. 867 and 30602 (Figs. 1*a*, 1*c*; Fig. 2) and, apparently, belongs to relict formations. Such formations are quite widely developed on the shallow Arctic shelf. They were formed under the subaerial conditions during the last Late Pleistocene regression, when the sea level dropped to about 100 m b.s.l. [*Osterkamp, 2001; Angelopoulos et al., 2020*]. On the Kara Sea shelf, this regression occurred during the Sartanian, when deep epigenetic freezing of the sedimentary sequence occurred under the conditions of cold Arctic climate [*Rokos et al., 2009*]. It is important to note that at the sea depths substantially greater than 100 m, frozen soils containing ice have not been found.

The subsequent transgression of the modern Arctic basin resulted in the significant degradation of permafrost under the impact of abrasion and the heat action from the seafloor water layer with temperatures exceeding the phase transition temperature. Sediments with the low ice content and high salinity were thawed first of all. Low-saline and nonsaline sediments with the high ice content and with beds of massive ice were thawed last.

At present, frozen sediments containing ice are preserved as local massifs (cryogenic relicts) separated by extensive taliks (permafrost distribution in the form of isolated patches). At present, these cryogenic relicts are affected by slow thawing from the bottom under the action of the deep heat flow. Their temperature is mostly negative and close to the temperature of the phase transition.

Frozen sediments in the eastern deep-water part of the Baydarata Bay between boreholes nos. 876 and 30602 are considered by the authors as such cryogenic relicts. In terms of their distribution pattern, as well as salinity, state, and temperature conditions, these sediments are similar to the relict permafrost formations in other regions of the Arctic shelf, including the Kara and Pechora seas [*Rokos et al., 2009*].

It should be mentioned that there are alternative hypotheses on the genesis of subsea permafrost. According to them, permafrost can be formed under the influence of the negative temperatures of seafloor waters and/or under the cooling associated with adiabatic expansion of gas contained in subsurface sediments [*Shpolyanskaya, 2015; Badu, 2018*]. To date, these assumptions have not been clearly and unambiguously confirmed by the available factual material.

The temperature of plastic frozen soil varieties of the described cryogenic relict is –0.9 to –1.6°C. Such values are generally typical for the plastic frozen clayey sediments with the low to moderate salinity and low to moderate ice content. These values are close to the temperature of soil thawing point (T_{bf}); the difference usually does not exceed 0.5°C. In the intervals of the section composed of ice-rich sediments (including beds of massive ice), the difference between the soil temperature and the temperature of soil thawing point is significantly higher than in the plastic frozen clayey sediments with a low to moderate ice content. This is due to the fact that fresh ice with a thawing temperature of about 0°C predominates in the composition of the above varieties.

Frozen sediments developed near the seafloor surface (at a depth of up to 5 m), are considered by the authors as seasonal formations. This is confirmed by the fact that no signs of ice were found in cores from the boreholes drilled during the warm period in the areas, where the described sequences were uncovered during drilling in the cold months of the year.

The authors divide seasonally frozen sediments into two genetic types differing from one another in terms of their distribution patterns. Coastal seasonally frozen sediments, which occur in the form of "caps" thinning out seaward at an insignificant distance from the shoreline, are referred to the first type. The second type is represented by thin subsurface frozen lenses revealed in the more seaward and deep-water parts of the water area.

It is assumed that sediment sequences of the first type are formed in the coastal areas with sea depths of less than 2.5 m, where landfast ice contacts the seafloor (Fig. 1*c*, Fig. 2). Ice acts as a "thermal bridge" between cold atmospheric air and the seafloor surface due to its high thermal conductivity, which is much higher than that of seawater. This contributes to intensive cooling of seafloor sediments and to the formation of a seasonally frozen layer. This layer is likely affected by rapid thawing after the breakup and/or destruction of landfast ice.

A similar process of the formation of subsea seasonally frozen sediments in the sublittoral part of the Kharasavey field area and other coastal areas of the Yamal Peninsula was previously described in [*Grigoriev, 1987; Baulin et al., 2003; Vasil'chuk et al., 2006; Shpolyanskaya, 2015*].

We attribute the second type of the subsurface frozen sediments uncovered by boreholes nos. 112 and 1822 (Fig. 1*c*) and developed in relatively more seaward and deep-water areas to seasonal freezing as a result of heat exchange between the upper layers of the sedimentary sequence and the layer of seafloor water during the cold winter–spring period of the year.

According to the data [*The Environmental..., 1997*], the mean annual temperature of seafloor waters of the Baydarata Bay near the Yugrorsky and Yamal coasts at sea depths from 3 to 13 m is about –0.5 and –0.8°C, respectively. In the near-axis deep-water part of the bay with sea depths of more than 13 m, it is –0.8°C. In the coldest month (May), the water temperature near the seafloor drops to –1.6°C near the Yamal coast and to –1.8°C in the deep-water part of the bay. In the warmest season (August–September), the seafloor water temperature in these areas is above 0°C.

Comparison of these values with the freezing point temperature of sediments in the route section with sea depths of more than 5 m shows that the upper part of sediments (to a depth of about 10 m from the seafloor) may transit into the frozen state during the coldest months of the year (Fig. 5). At the same time, the depth of possible freezing remains unknown.

Seasonally frozen soils of this type have been revealed by only two boreholes, in areas near the coasts. However, the authors assume that the considered formations are much more widely developed within the water area. Probably, if the number of boreholes is increased, and drilling operations are expanded to the entire bay during the cold season, the number of findings of seasonally frozen formations of this type will increase significantly.

In addition, it should be noted that the mean annual temperatures of the seafloor water layer are much higher than the temperatures of the sediment freezing point. Obviously, this does not allow permafrost to be formed here.

The authors consider the **cryotic sediments** in the section deeper than the 0°C isotherm (Fig. 4) as the thawed permafrost. After ice melting in these formations, the temperature of the upper part of sediment sequences increased, but remained in the field of subzero values. At the same time, these values exceed the freezing point of the sediments due to their relatively high salinity.

The 0°C isotherm drops along the section as a result of heat exchange with the seafloor water horizon and the near-surface sediment layer in the warm season of the year, when water near the seafloor warms up. At this time, the seafloor sediments above the 0°C isotherm are subjected to thawing and acquire a positive temperature. During the cold season, the seafloor waters are cooled to subzero temperatures, and this cold is transited to the seafloor sediments. This leads to a decrease in the temperature of the subsurface sediment layer (thawed in the warm season) to subzero values.

Therefore, the authors subdivide the cryotic sediments of the Baydarata Bay into perennial and seasonal varieties. Position of the 0°C isotherm in the section (Fig. 4) is given according to the data obtained during the period close to the peak of the warmest season. Therefore, it can be assumed that it cannot go much deeper. Accordingly, the cryotic formations occurring lower than the 0°C isotherm keep the negative temperature throughout the year. This allows us to consider them as perennial, and the isotherm itself as the top of the perennially cryotic sediments.

Sediments above the 0°C isotherm had a positive temperature at the time of the measurements. It is assumed that during the periods, when the temperature of seafloor water becomes negative, these formations mostly transit to the seasonally cryotic state (seasonal freezing is also possible).

It should be noted that climate warming observed in the recent decades intensifies permafrost thawing in the coastal areas of the Kara Sea [*Vasil'chuk et al., 2006; Vasiliev et al., 2016*]. Therefore, it can be supposed that the current position of the 0°C isotherm is somewhat lower than its position recorded in 1994. However, no repeated measurements have been made to such an extent in subsequent years, and it is impossible to estimate the absolute values of the probable change in the depth of the 0°C isotherm.

CONCLUSIONS

1. Subsea permafrost in the Baydarata Bay represents a local cryogenic relict massif formed during the Sartanian regression. It is composed of plastic frozen loams and clays with the low to moderate salinity and low ice content, as well as of ice-rich clayey sediments with the massive-agglomerate cryostructure and ice beds. The mean annual temperature of frozen sediments varies from −1.0 to −0.9°C in the upper part of the section and to −1.6°C in the lower part.

2. Seasonally frozen sediments are divided into two types according to their origin and distribution pattern. The first of them is confined to the coastal shallows, where the seasonally frozen sediments compose relatively thin "caps" thinning out seaward. They are formed in cold periods of the year in the areas, where landfast ice touches the seafloor. The second type of seasonally frozen sediments is represented by local thin lenses. Their formation is associated with the heat exchange between the seawater near the seafloor with temperatures below the freezing point of the sediments in the cold season and subsurface seafloor sediments.

3. Cryotic sediments were distinguished from the data obtained by the temperature cone penetration tests in the seaward deep-water part of the bay. Here, the position of the 0°C isotherm was traced at depths from 3.0 to 8.4 m below the seafloor over the route about 51 km long using the data obtained during the warmest season of the year. The sediments at depths below this isotherm keep subzero temperature throughout the year and are classified as the perennially cryotic sediments.

4. Sediments above the 0°C isotherm had a positive temperature at the time of measurements. In cold season, as a result of the heat exchange with the lower layer of seawater with subzero, they probably transit into the seasonally cryotic or, in some places, into the seasonally frozen state.

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