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SUBSEA PERMAFROST IN THE OB AND TAZ BAYS, THE KARA SEA

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During the 1995–2013 geotechnical drilling in the Ob Bay and Taz Bay offshore areas (depth interval: from 10–20 m to 50–70 m below seabed) permafrost was exposed in four boreholes. The identified permafrost strata varied considerably in ice content, salinity and temperature. Thus, low-temperature (–4.1...–4.8 °C as minimum), generally highly saline sediments containing no segregated ice lenses were reported from BH-1 and BH-2 in the northern offshore part of the Ob Bay. Whereas BH-3 which is located nearby exposed frozen soils with relatively high temperature (–0.9...–1.2 °C), having low to medium salinity, and rich in ice inclusions. Permafrost deposits exposed by a single borehole drilled in the port of Yamburg are varied in their composition, ice content and salinity. These are ranked as Holocene coastal cryorelics (i.e. relatively young). Formations exposed by BH-3 are referred to the Sartan island-type relic permafrost (rather ancient). Besides, subsea permafrost strata established in the port of Yamburg are found to have submerged as a results of the port water area deepening/widening works. Most of the Ob and Taz Bays offshore area is interpreted as an extensive open talik.

Kara Sea, Ob Bay, Taz Bay, permafrost, ground, salinity, Quaternary deposits

INTRODUCTION

Issues of subsea permafrost aggradation and evolution on the Arctic seas shelf have been amply discussed in [*Are, 1976; Danilov, 1978; Antipina et al., 1979; Neizvestnov, 1981; Zhigarev et al., 1982; Soloviev, 1983; Shpolyanskaya, 2015*]. In the offshore Kara sea, permafrost strata were both hypothetically inferred from shallow seismic profiling [*Rekant and Vasiliev, 2011; Vasiliev et al., 2016*] and exposed by a number of geotechnical boreholes [*Rokos et al., 2009*].

Nevertheless, permafrost conditions of the Ob and Taz Bay remain unclear. On the one hand, the area is likely to have been exposed to deep freezing during the Sartanian regression. On the other hand, this offshore area is largely influenced by the inflowing rivers discharge (the Ob, Taz, Pur and other rivers), whose warming effect by all means cause the intensive thawing and degradation of relict permafrost.

In light of the petroleum resources development in the Ob and Taz Bays the knowledge of and updated data on the geocryological conditions of their offshore areas are of particular importance. This study therefore set out to determine the conditions for the formation, evolution and distribution of subsea permafrost in the region.

RESEARCH METHODS AND MATERIALS

The study is based on the drilling materials obtained in the course of geotechnical studies conducted by AMIGE company (Arctic Marine Engineering Geological Expeditions) in 1995–2013 for structures and facilities of the offshore oil and gas industry. A total of about 150 boreholes (depth range: from 10–20 to 50–70 m from the bottom) were drilled in the waters of the Ob and Taz Bays. The boreholes are distributed unevenly across the offshore area and confined to prospect areas of hydrocarbon fields, as well as to the infrastructure for projected oil and gas production (sub-sea pipelines, shipping terminals, etc.) (Fig. 1).

Drilling of exploratory boreholes (BH) was carried out from a specialized research vessel Kimberlite using the URB-3A-3 drilling unit, with the drill string 132–151 mm in diameter. Ice-bearing soils were sampled with a double core barrel drill (internal diameter: 127–142 mm, length: 4 m). The drilling was done using seawater (temperature up to 4–6 °C) as a drilling fluid.

The physical and mechanical properties of frozen and thawed soils were determined from laboratory analyses conducted in accordance with the current Russian state standards. In the context of this study, soil salinity and temperature appear to be critical indicators. Basically, these are the factors that control conditions of subsea permafrost aggradation and degradation.

Salinity and ion association composition of highly soluble salts were determined according to [*State Standard... 26428-85, 1985*] and [*State Standard... 26423-85, 1985*]. Temperatures of frozen and thawed soils in the Ob and Taz Bays were derived from drill

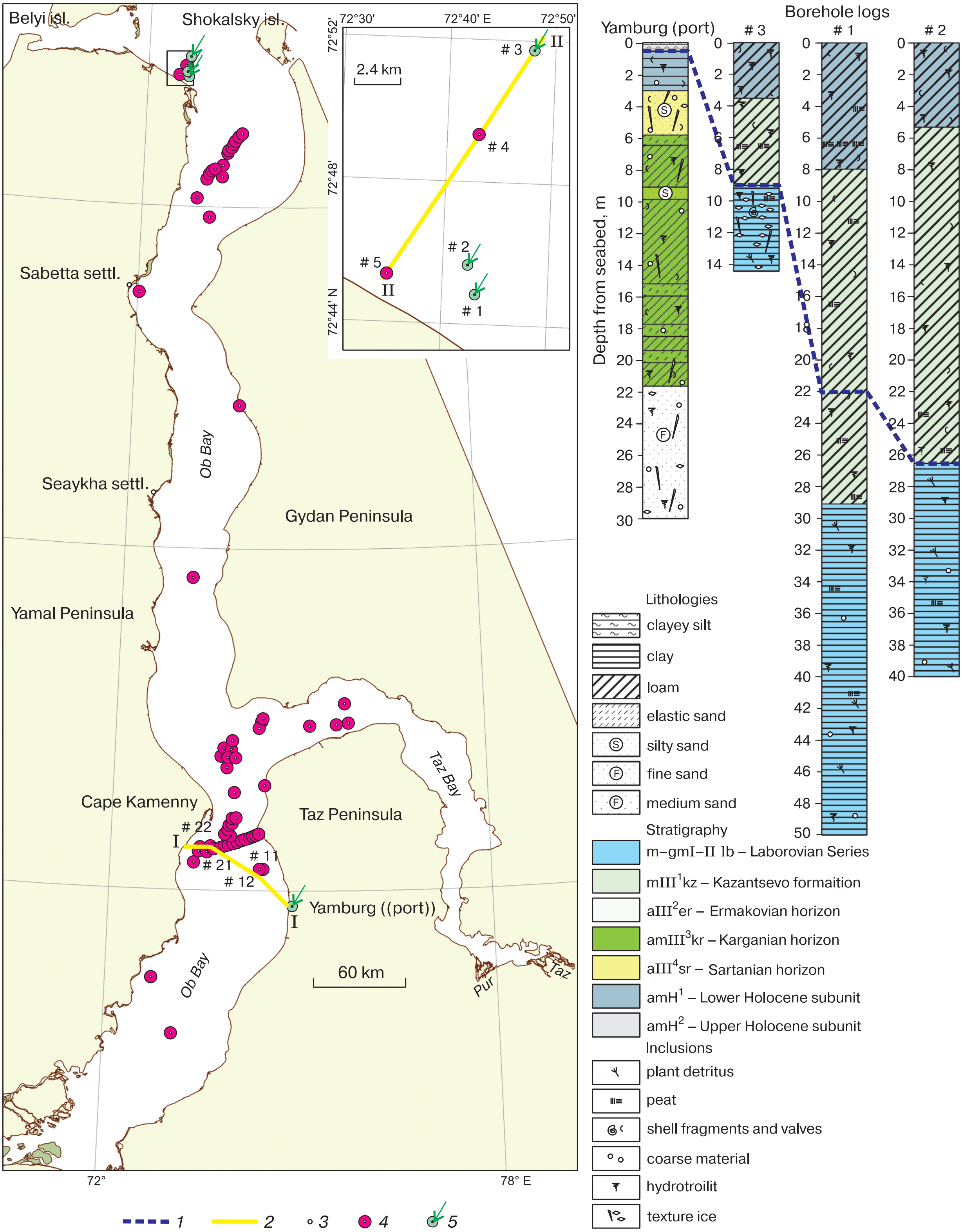

Fig. 1. Locations and well logs of boreholes penetrated permafrost in the offshore area of Ob and Taz Bays.

1 – position of the permafrost table; *2* – shallow cross-section lines; *3* – population centers; *4* – boreholes; *5* – boreholes penetrated permafrost. Stratigraphic division of cross-sections was performed in accordance with [*Volkova and Babushkin, 2000; State... Map..., 2015*].

core measurements using the LTI-M-U2-PO digital thermometer probes (AnalitTeploKontrol company).

Measurements were performed in the core barrel head immediately after its lifting onto the deck, prior to drill cores extraction from the sampler. The boreholes and period the temperature measurements were taken in are specified below: BH-1 (during the period 29–30.08.2005); BH-2 (31.08–01.09.2005); BH-3 (from 30.09 to 03.10.2010); BH in the port of Yamburg (23–24.09.2002).

It stands to reason that measured temperature of drill cores is higher, than that of naturally occurring sediments, inasmuch as core samples are known to receive heat during the coring operation. We assume the difference between *in situ* temperature and temperature of frozen and cooled soil samples to be not more than 0.3 °C. The freezing point was determined in accordance with [*Building Code, 2011*].

GENERAL CHARACTERISTICS OF SUBSEA PERMAFROST STRATA IN THE OB AND TAZ BAYS

The upper part of the section within the studied offshore area is composed of Neopleistocene deposits (Fig. 2). According to [*Volkova and Babushkin, 2000; State... Map..., 2015*], the Neopleistocene sequence comprises a number of stratigraphic units.

The base of the studied section interval is represented by marine Lower-Middle Pleistocene sediments Laborovian series (mI–IIlb), overlain by the Kazantsevo Formation marine dominantly sandy sediments ($mIII^1kz$). These are covered by clayey sequences of alluvial-marine Karganian deposits ($amIII^3kr$), and alluvial sandy horizons dated to Ermakovian ($aIII^2er$) and Sartanian ($aIII^4sr$) time. The section is crowned by the Holocene alluvial-marine sequence (amH), which consists of two units designated as lower (amH^1) and upper (amH^2).

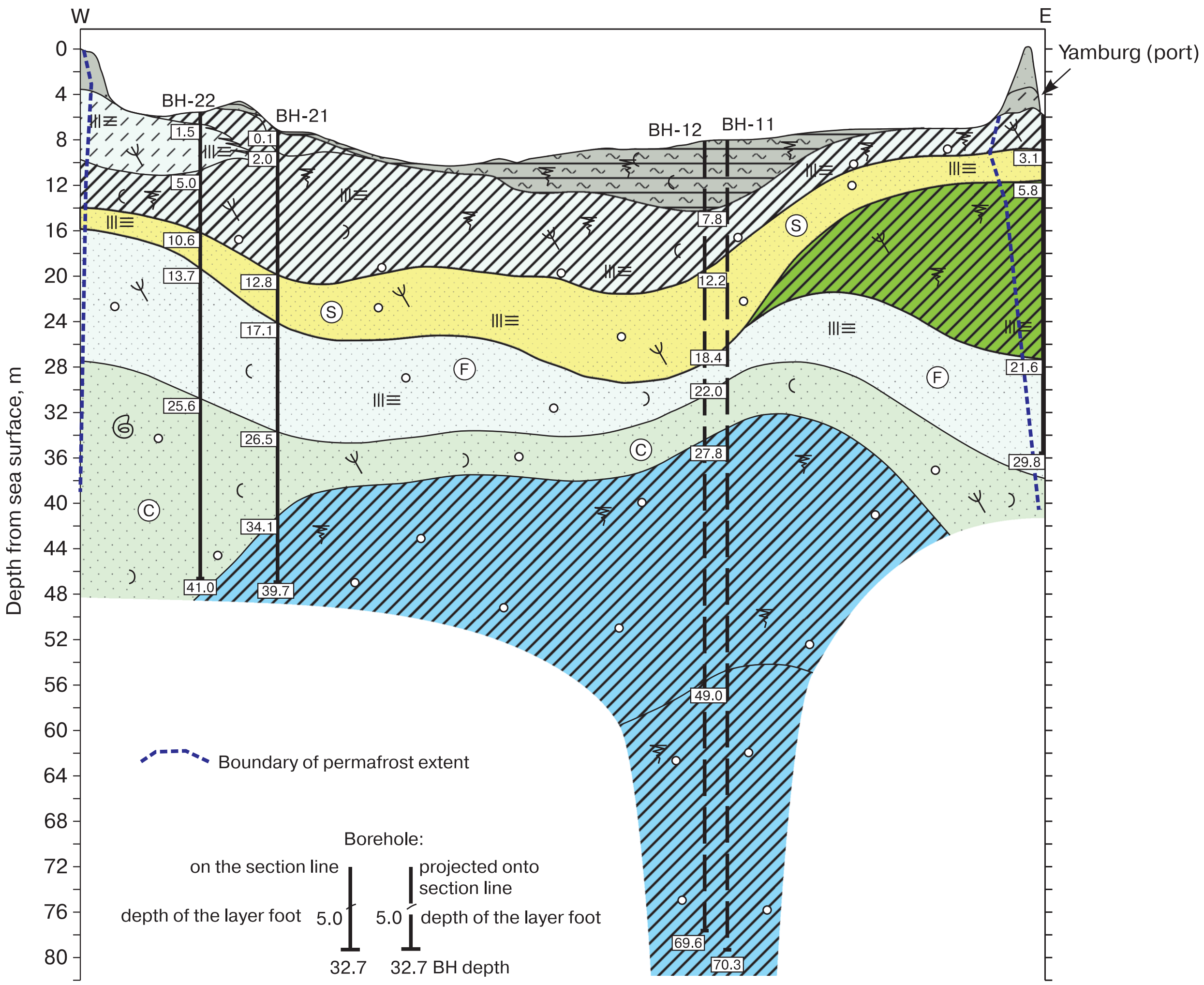

Fig. 2. Shallow structure of sedimentary section of the Ob Bay along line I–I on the geological and geotechnical cross-section with front elevation drawing.

For geographical location and notations see Fig. 1.

Frozen soils were identified in drill cores from four boreholes of which three were located in the northern part of the Ob Bay and one in the waters of the port of Yamburg (Fig. 1). The borehole coordinates are: 67°54′ N, 74°50′ E (Yamburg); 72°45′ N, 72°43′ E (BH-1); 72°46′ N, 72°42′ E (BH-2); 72°52′ N, 72°48′ E (BH-3).

The borehole drilled to a depth of 30 m through soils in the offshore area of the port of Yamburg and located at a distance of 40 m from the shore (sea depth ~8 m) penetrated permafrost at a depth of about 0.5 m below the seabed. The frozen section is represented by Lower Holocene, Sartanian, Karganian and Ermakovian deposits which are rather strongly varied in composition and characterized by heterogeneous properties. The frozen soils included: plastic-frozen clays, hard-frozen sands and loams.

The uppermost layer of the permafrost interval is composed of Lower Holocene plastic-frozen clays hosting horizontal ice schlieren up to 1 cm thick, as well as ice nests and lenses. The underlying Sartanian and Ermakovian sands, along with Karganian loams, are characterized by massive cryotexture, and sporadically occurring inclined ice schlieren. Subhorizontal lenses and nests of segregation ice are also observed in the Ermakovian sands.

BH-1 and BH-2 drilled to a depth of 40 and 50 m from the seabed are located in the northern parts of the Ob Bay adjacent to the coast of Yamal Peninsula at a distance of 2.7 km and 3.8 km from the coastline, respectively (Fig. 1). These boreholes exposed frozen sedimentary formations at a depth of about –22 and –26 m from the seabed at sea depth ~10–11 m. Permafrost soils in drill cores recovered from these boreholes are represented by plastic-frozen fat laminated loams of the Kazantsevo formation and hard-frozen fat to lean clays of the Laborovskaya Series.

The permafrost table is not distinctly expressed here, and the contact between the overlying cooled soils is poorly discernible either. Clays and loams have massive cryotecture, segregation ice is completely missing. The widespread thin layers of hard-frozen sand are intermitted with inclusions of shelly material, peaty lenses and interlayers, wood residues, lenses and nests, saturated with black hydrotroilit.

BH-3 drilled below the seabed to a depth of 14.5 m and located in the northern part of the Ob Bay at a distance of 15.3 km from the coast, tapped plastic-frozen, fat to lean clays (the Laborovskaya series) at –9 m point from the seabed (sea depth ~20 m).

Permafrost deposits (exposed by BH-3) which form a sequence regionally traceable on time sections of the shallow seismic profiles laid across the area, contain numerous ice inclusions. In the upper part, the frozen thickness exhibits subhorizontal, about 20 cm thick ice layers. Deeper down, it is dominated by small ice lenses, nests and inclined schlieren, as well as sub-vertical ice veins.

The thickness of frozen strata both in the port of Yamburg and in the northern offshore portion of the Ob Bay has thus far not been established: the permafrost base occurs probably at levels in excess of the achieved drilling depth.

SOILS SALINITY

Proceeding from [*State Standard... 25100-2011, 2018*], frozen soils of the studied offshore area vary from non-saline to highly saline (degree of salinity D_{sal} = 0.1–1.5 %). Unfrozen sedimentary formations are characterized by medium to high salinity levels.

Upper Pleistocene frozen sediments exposed in the section of boreholes drilled in the port of Yamburg have a predominantly terrestrial type salinity, except the uppermost layer of ancient (Holocene) clays with marine type salinity. The composition of ion associations of highly soluble salts is dominated by anions SO_4^{2-} (> 50 %). Chlorine ion concentration does not exceed 25 % (Fig. 3).

In the northern part of the Ob Bay in the vicinity of boreholes No. 1–3 frozen and thawed soils have exceptionally marine type salinity dominated by Cl^- and $K + Na^+$ ions. In boreholes No. 1 and 2, salinity of subaquatic permafrost soils is generally high and tends to be >1 %, locally reaching 1.4–1.5 %.

The section of BH-3 shows highly to moderately saline soils developed (D_{sal} = 0.37–0.69 %) in the upper part of the exposed permafrost interval, while the lower part is dominated by non-saline and slightly saline sedimentary formations (D_{sal} = 0.08–0.22 %).

SOILS TEMPERATURE

Temperatures measured in frozen drill cores recovered during drilling operations in the waters of the port of Yamburg at the boundary between the near-surface layer of Upper Holocene silts and underlying frozen ancient (Holocene) clays at a depth of about 0.5 m below the seabed, average –0.7 °C (Fig. 4). In the upper part of the Karganian loams and Sartanian sands temperature values vary from –2.2 to –3.7 °C.

The temperature measurements of frozen soils in the boreholes No. 1 and 2 in the northern part of the Ob Bay, yielded fairly low values. The difference between the measured temperatures and the phase transition temperature is found to be >1 °C and generally increasing with depth. The sections of these boreholes are characterized by a pronounced downward (negative) gradient. Temperatures measured in BH-1 vary from –2.1 to –4.8 °C and tend to reduce from top to base of the exposed permafrost interval. In BH-2 ground temperature also drops from –1.8 до –4.1 °C down the section of the permafrost interval.

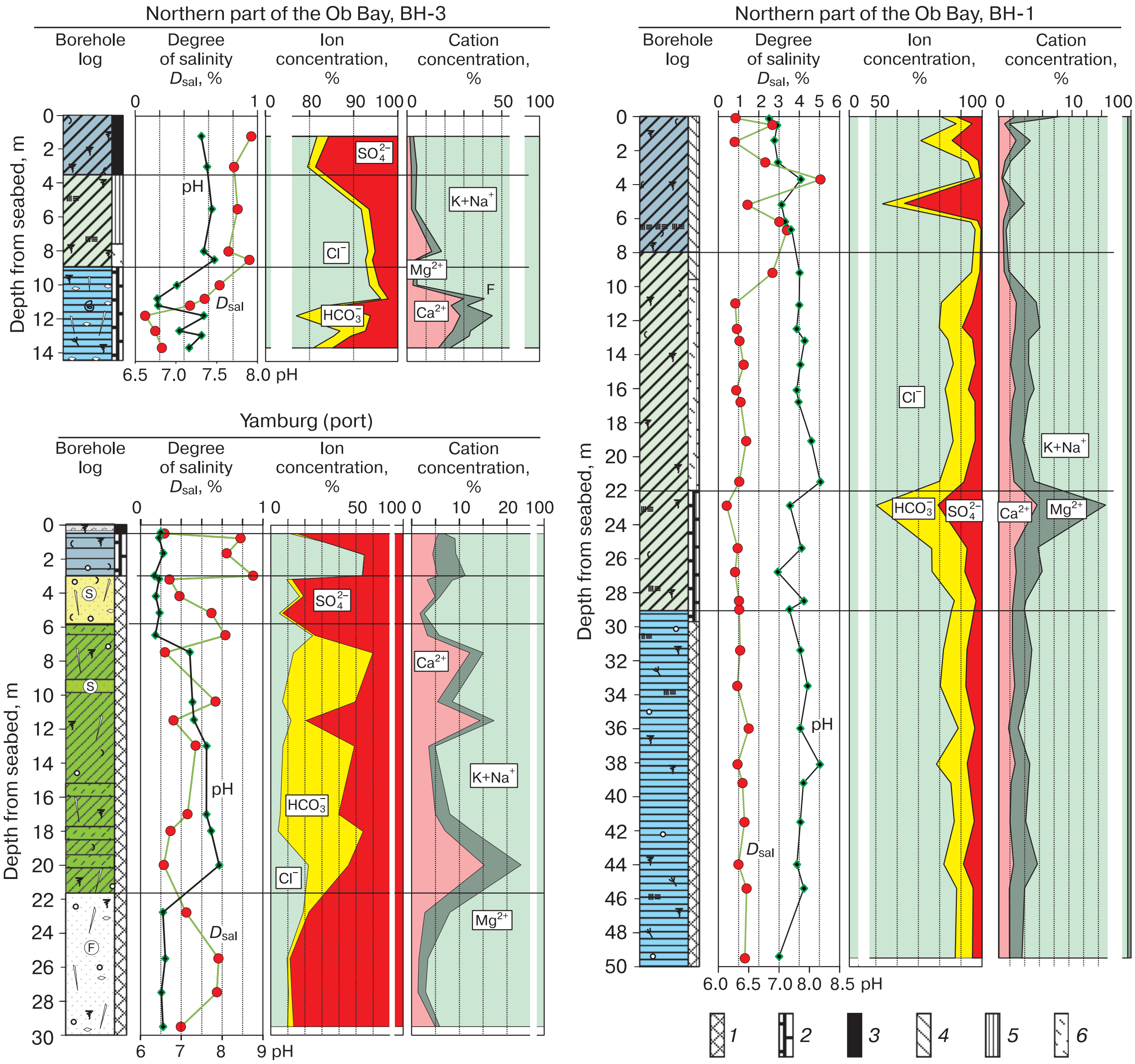

Fig. 3. Permafrost composition, structure and salinity on borehole sections.

1, *2* – state of perennially frozen soils (*1* – hard frozen, *2* – plastic frozen); *3*–*5* – thawing soil consistencies (*3* – very soft, *4* – soft, *5* – stiff); *6* – cooled soils.

Temperatures of frozen drill cores recovered from BH-3 are relatively high and close to phase transition point. The section is generally characterized by a weakly expressed positive gradient. In the upper part of the exposed permafrost interval temperatures are −1.2...−1.1 °C, increasing down the section to −0.7...−0.6 °C.

DISCUSSION OF RESULTS

Onshore permafrost up to 300–500 m in thickness is almost ubiquitously developed within the adjacent Yamal, Gydan, Yavay and Taz peninsulas, along with Beliy and Shokalsky islands, etc. [*Baulin, 1967; Dubikov, 2002*]. Frozen soils in the coastal areas are saline to varying degrees. Their temperature at zero annual amplitudes reaches −6...−8 °C.

At this, permafrost deposits were identified in the offshore area of the Kara sea, where they are interpreted as relic epigenetic formations [*Neizvestnov, 1981; Rokos et al., 2009*] formed about 18 kyr BP during the Sartanian regression, when the sea level lowered down to about −100 m. The investigated sedimentary formations largely degraded during the subsequent transgression of the modern Arctic basin. They have survived as sporadic locally developed patches (relic submarine permafrost).

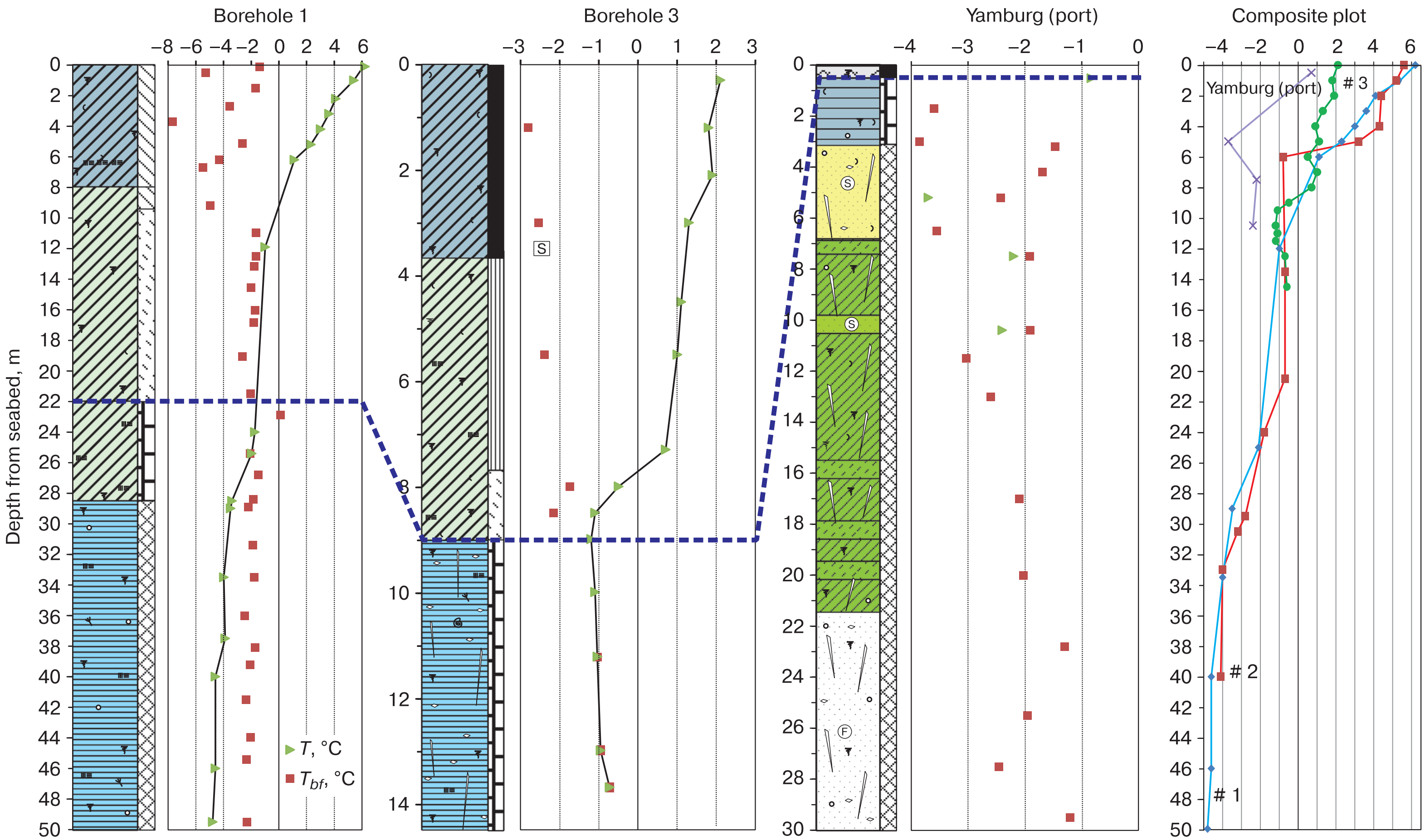

Fig. 4. Measured temperatures of drill cores (T, °C) and freezing points (T_{bf}, °C) in cross-sections of boreholes No. 1, 3, and the one drilled in the port of Yamburg, and composite plot of temperature measurements.

For notations see Figs. 1, 3.

These deposits are characterized by a relatively high temperature approaching phase transition point and a weakly expressed positive (or zero) temperature gradient. The upper intervals of the frozen thicknesses often contain abundant visible ice in amounts tending to decrease with depth (along with total ice content).

In contrast to the onshore frozen soils of the marine origin developed on the coast of Yamal, Gydan and Taz peninsulas, salinity of permafrost deposits in the open sea area within Kara shelf is generally low. These are dominated either by low or non-saline sedimentary formations. The reason for a relatively low salinity of the Sartanian submarine relic permafrost in the offshore area, as compared to the onshore frozen sedimentary formations remains unclear. In some cases, the degree of salinity shows a decreasing trend down the section.

A through talik is found within most of the Ob and Taz offshore area. Its formation is highly probably associated with contributions from warm discharge of the Ob, Taz, Pur, etc. rivers flowing into the Ob and Taz Bays. Besides, the study offshore area is for the most part shallow (sea depths <15 m), which favors the water warming during warm seasons. As a result, relic permafrost thicknesses have degraded here almost completely, except for some small-sized isolated patches.

Closely approaching the onshore permafrost thicknesses on the adjacent coast, hard-and plastic-frozen clays penetrated by boreholes No. 1 and 2 in the northern part of the Ob Bay appear to be related to coastal (longshore) frozen deposits.

There is plenty of proxy data that allow to infer the presence of stretches (bands) of localized permafrost along the Ob and Taz Bays. Thus, in the middle part of the Ob Bay (in the vicinity of Cape Kamenny), the position of the upper limit of hard frozen deposits defined as permafrost passing from the coast into the adjacent offshore area was traced by a geotechnical drilling rig that perform standard penetration test [*Kokin and Tsvetsinsky, 2013*]. The identified upper boundary extends into the offshore area at a distance of 30–40 m from steep coast areas, and up to 300–400 m from flat coast areas. The thawing of the coastal frozen thicknesses occurs probably both from above and from below. This being the case, its configuration in the section is imaged as a visor, whose top gradually subsides in the seaward direction.

Near the eastern coast in the middle the Ob Bay and across the Taz Bay, in the area of the Semakovskoe field, permafrost deposits were also identified according to the electrical prospecting data and interpreted as extending to a distance of less than 1 km from the shore [*Kolesov et al., 2008; Baranov et al., 2014*]. These thicknesses are characterized by enhanced electrical resistivity (up to 400–1000 Ohm·m) and reduced polarizability, which is accounted for the presence of ice in the sedimentary formation. It was noted that the hypothetically ice-bearing thickness soon pinches out in the seaward direction.

The continuous distribution of the longshore relic permafrost zones can be disturbed by taliks that formed in localities across from the mouths of both modern and ancient (Sartanian and Early Holocene) rivers which (used to) flow into the Ob and Taz Bays. Assumingly, permafrost completely pinches out in the apex parts of the Ob and Taz Bays under warming effect of the discharge from the Ob, Pur and Taz rivers. Whereas in the northern part of the Ob Bay, the width of permafrost bands may increase due to generally increasing climate severity and decreasing influence of warm river flows.

Frozen thicknesses exposed by nearshore boreholes No. 1 and 2 are expressly differentiated by high salinity and totally missing segregation ice, against submarine relic permafrost in the open offshore area of the Kara Sea.

The temperatures of frozen soils measured from drill cores recovered from these boreholes can also be considered as abnormally low with respect to temperatures of the Sartanian cryorelics in the open sea shelf. Actually, the Sartanian cryorelicts temperature in the Kara Sea is commonly −0.8...−2.5 °C [*Rokos et al., 2009*], while the temperature minima reported from boreholes No. 1 and 2 reach −4.1...−4.8 °C (Fig. 4). Rather, these values are closer to the permafrost temperature of the adjacent coast.

Apparently, the abnormally low temperature of the inshore frozen sedimentary formations of the Ob and Taz Bays is explained by the fact that the studied permafrost is significantly younger, than the frozen relic formations of the Kara sea shelf formed in the Sartanian cryochron. Due to this fact, the former experienced warming to a much lesser extent, than permafrost thicknesses of the open sea shelf, which were continuously overlain throughout the post-Sartanian time by the water column with a temperature exceeding the melting point.

In this respect, it can be assumed that the freezing of the studied sedimentary formations took place in the Holocene. This event is likely to be dated as the Younger Dryas ~9 kyr BP or even later, which in the authors' opinion was marked by lowering sea level to about −15 m. As a result, a vast offshore area was drained, which triggered a rather deep freezing of the soils masses uncovered by the water column removal.

The Holocene regression is evidenced here by the boundary of erosion-produced inconformity between the strata of the Lower and Upper Holocene subunits. This boundary is distinctly expressed on the drilling and shallow seismic profiles (Fig. 2), accentuated by sandy interlayers in thin layers of very soft clays, and accumulations of peat and coarse-grained material. The lower Holocene sediments un-

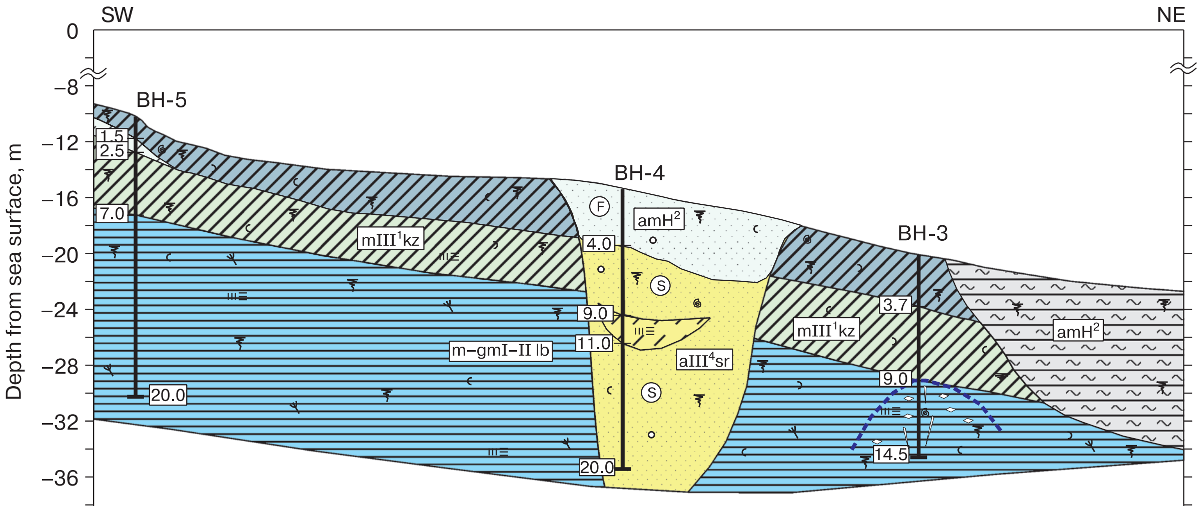

Fig. 5. Geological and geotechnical cross-section along line II–II connecting heads of BH-5 and BH-3.
For geographical location see Fig. 1; for notations see Figs. 1, 2.

derlying this boundary are characterized by traces of ancient cryoturbations, over-compacted intervals and other signatures which attest to a break in sedimentation and deposition of Lower Holocene sediments in subaerical conditions.

Permafrost soils documented in profiles of BH-3 by their salinity, temperature and ice-content pattern are identical to the Sartanian cryorelics of the open Kara offshore area.

However, it appears all but impossible to attribute these sediments to the Holocene coastal cryorelict, given that this borehole is located at a considerable distance from the shore, and the permafrost table is exposed therein at higher levels than in the boreholes 1 and 2 located much closer to the coastline (Fig. 1). Besides, frozen soils were not detected in the nearby boreholes No. 4 and 5 drilled to a depth of 20 m from the bottom and located on the profile line between the wellhead point of BH-3 and Yamal coast (Fig. 5).

Permafrost interval penetrated by BH-3 is generally considered to be the Sartanian cryo-relic massive-sland formations, in nature similar to the coeval frozen outliers of the open offshore area of the Kara sea shelf, suggesting that such formations are encountered only within the deep-sea northern part of the Ob Bay, where the bottom waters temperature is low enough, and the warming effect of the river discharge is minimal.

The frozen deposits penetrated by a borehole drilled in waters of the port of Yamburg (Fig. 1), are in a sense unique. The borehole was drilled in September 2002 after the port expansion and dredging operations had been completed about a year earlier. In fact, the borehole is located on a site, which previously was on the day surface and only recently was covered by water. Previously, permafrost sediments here formed and evolved as part of the onshore cryolithozone of the Taz Peninsula coast until the moment they were encroached upon by water column as a result of earthworks.

Trapped under the water, the frozen soil massed began to rapidly degrade, once they absorbing heat from sea water and warmer discharge from rivers flowing into waters of the Nyudyamontapoepoko-Yakha R. port. The thawing depth at the time of drilling (about a year after completion of earthworks) was about 0.5 m. It's undeniable that the degradation of ice-bearing sediments occurring under waters of the port of Yamburg will show further progress and intensify.

CONCLUSIONS

1. A large, most likely, through talik has developed in most of the offshore area of the Ob and Taz Bays. Permafrost deposits are developed in narrow coastal strips and locally widespread as massive islands in the northern part of the Ob Bay, as borehole as under the bottom of artificially intruded offshore areas.

2. Highly saline low-temperature permafrost dominantly clayey deposits of Holocene cryo-relics, exposed by BH-1 and BH-2, belong to the inshore permafrost developed along the coast.

3. Weakly to moderately saline permafrost (clayey soils with ice inclusions) having a relatively high temperature exposed by BH-3 are interpreted as subaqueous relic permafrost which experienced freezing in the Sartanian time and in their nature similar to the frozen outliers of the open offshore area of the Kara Sea. As such, frozen thicknesses can be found only in the deep-sea northern part of the Ob Bay, where bottom waters have negative temperature.

4. Permafrost thicknesses varied in composition and heterogeneous in salinity, exposed by a borehole drilled in the port of Yamburg, passed into a subaqual state a year before the drilling of this borehole as a result of earthworks intended to deepen and expand the water area of the port. This permafrost is currently experiencing intense surface thawing under the influence of warm discharge from the inflowing rivers.

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