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PROPERTIES OF ICE AND FROZEN GROUND

ICE CONTENT OF CRYOGENIC STRATA (PERMAFROST INTERVAL) IN GAS-BEARING STRUCTURES, NORTHERN YAMAL

Yu.B. Badu

Lomonosov Moscow State University, Department of Geography,
1 Leninskie Gory, Moscow, 119991, Russia; yubadu@mail.ru

The study of ice content of permafrost soils of gas-bearing structures in northern Yamal Peninsula revealed differences in their salinity associated with conditions of the sediment accumulation and freezing in the Late Pleistocene. The pore water salinity at which ice segregation occurred in fine-grained soils has been determined.

Gas-bearing structure, cryogenic strata (permafrost interval), total ice content, degree of salinity, pore water salinity, seawater salinity

INTRODUCTION

Industrial development of the Yamal gas-bearing structures (GBS) is challenged by the continuous permafrost interbedded by ice-rich frozen soils and saline unfrozen soils (with ground temperatures below 0 °C), often containing lenses and layers of cryopegs. The presence of salts in the pore water of soil greatly affects the temperature of freezing and the phase composition of the pore water and, ultimately, mechanical properties of permafrost. Moreover, soil salinity (more specifically, salinity of pore water) influences processes of ice segregation during either epigenetic or syngenetic permafrost aggradation. Data on the degree of sediment and pore water salinities improve our understanding of permafrost characteristics [*Badu and Khariyuzov, 1986; Dubikov et al., 1986; Grigoriev, 1987; Dubikov, 2002; Badu, 2006, 2013; Rivkin et al., 2007*].

SURFICIAL GEOLOGY OF THE STUDY AREA

Kharasavey GBS is located on the northwestern coast of the Yamal Peninsula in the typical subarctic tundra subzone (Fig. 1). The average elevation 10–20 m a.s.l. increases up to 32 m in the northern portion of the GBS. The terrain is mostly flat to hilly dissected by river valleys and gully erosion features. The Late Pleistocene marine terraces (MT) present in the coastal zone include 1st Marine Terrace (8–12 m a.s.l.), 2nd Marine Terrace (12–25 m a.s.l.), and 3rd Marine Terrace (30–32 m a.s.l.) – 1st MT, 2nd MT and 3rd MT, accordingly. The low and high laidas ranging from 20–25 m to 500 m in width fringe the coastline [*Badu, 2006*].

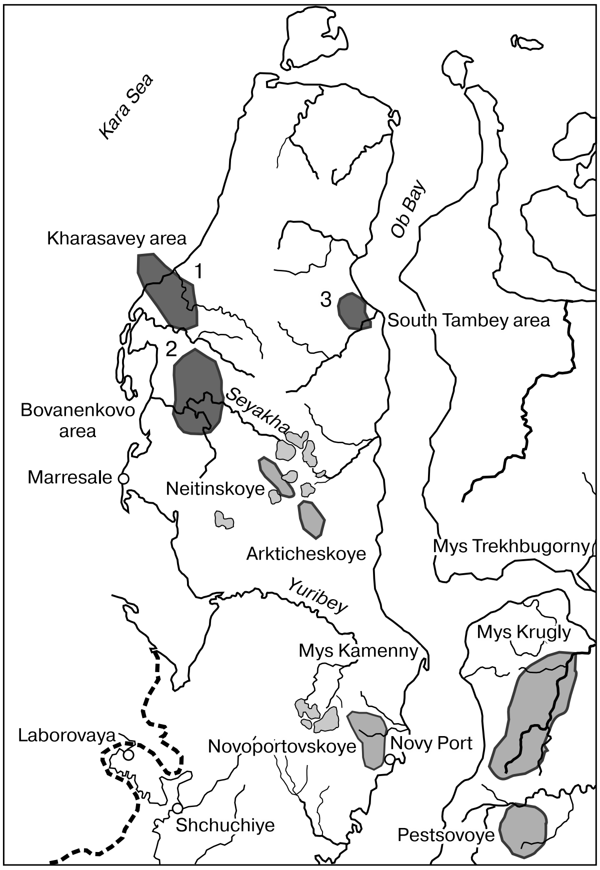
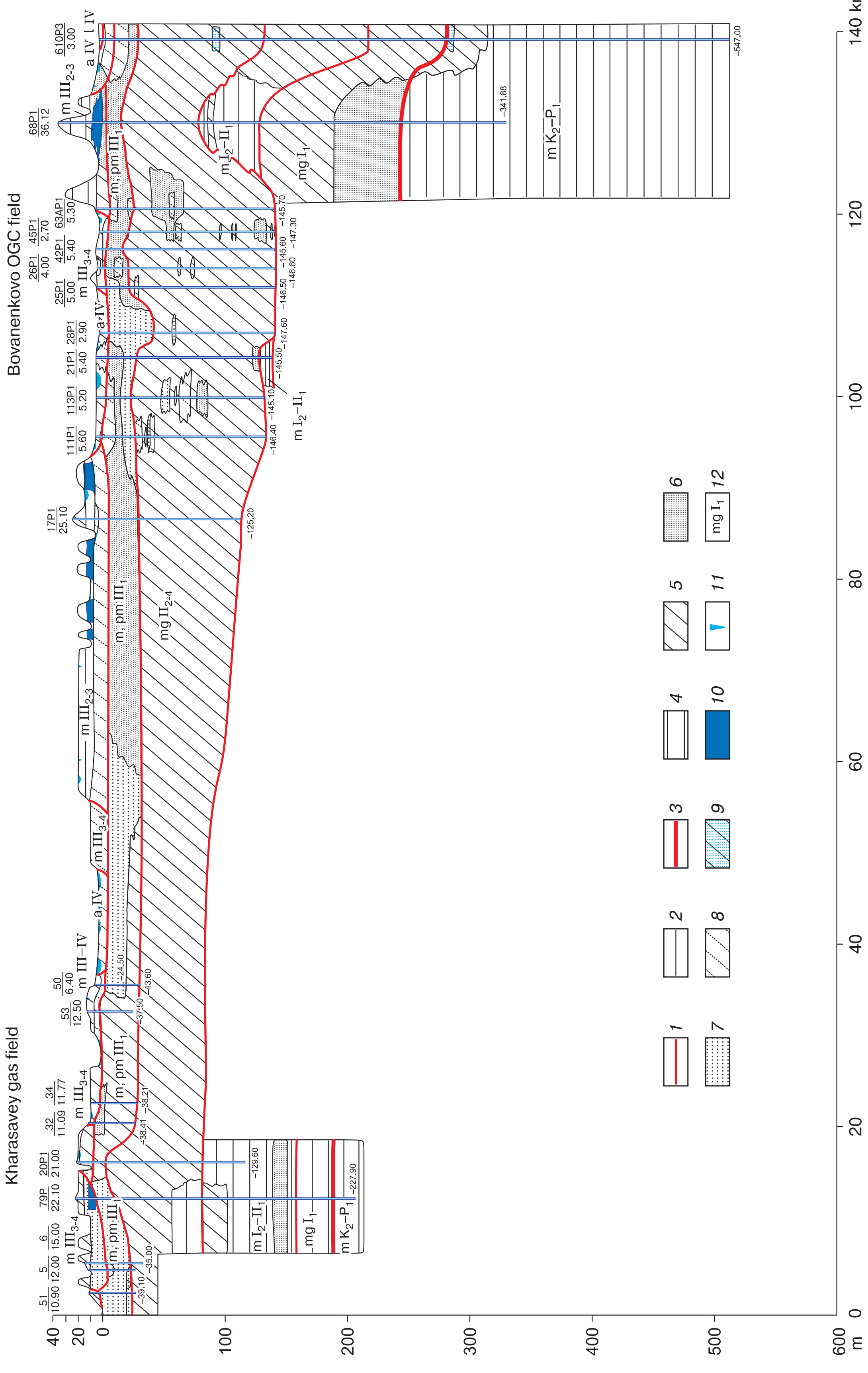


Fig. 1. Schematic map of the study area.

1 – Kharasavey gas-bearing structure; 2 – Bovanenkovo gas-bearing structure; 3 – South Tambey gas-bearing structure.

Bovanenkovo GBS is situated within the flat erosion-accumulative lowland, marshy and lake-studded (Fig. 1). The surface elevations vary from 0.5–

a


Kharasavey gas field
Bovanenkovo OGC field
m III3-4
m, pm III1
m III–IV
a IV
m III2-3
mg II2-4
m I2–II1
mg I1
m K2–P1
0
20
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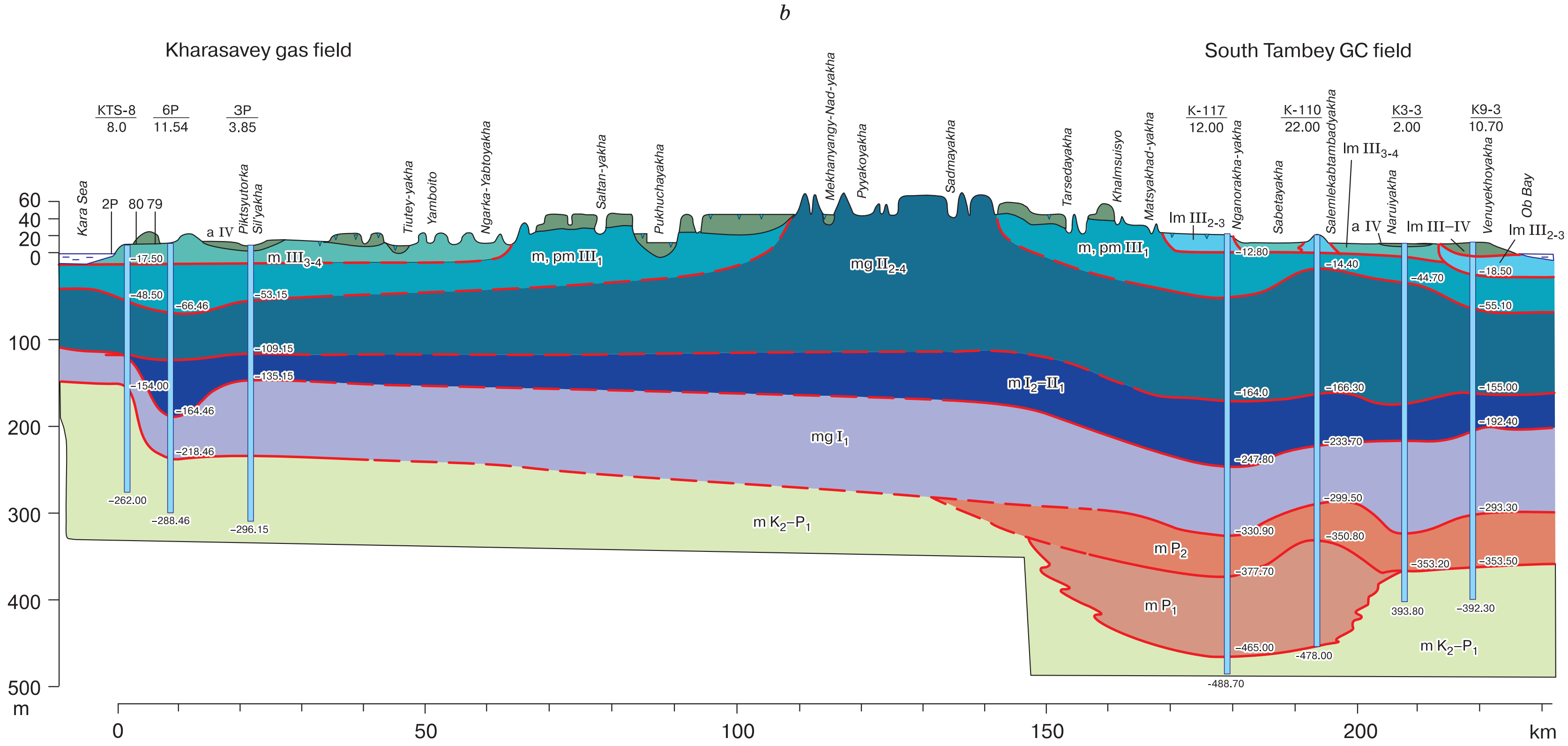


Fig. 2. Geological cross-section of sediments of the Northern Yamal gas-bearing structures [*Badu, 2011, 2013*].

a – Kharasavey GBS and Bovanenkovo GBS; *b* – Kharasavey GBS and South Tambey GBS. Boundaries: *1* – stratigraphic, *2* – lithological, *3* – base of Quaternary deposits. Lithology: *4* – clay, *5* – silty clay, *6* – sandy silt, *7* – fine sand, *8* – sand clay, *9* – silty clay with water-saturated sand. *10* – ice; *11* – ice-wedge polygons. *12* – genesis and age of stratigraphic units.

3.0 m within the low floodplain to 41–45 m within the local watersheds. The lowland comprises large outliers of the Late Pleistocene 3rd MT separated by floodplains of the Naduyyaha, Seyakha, Mordyyaha Rivers which occupy more than half of the area [*Badu and Podbornyi, 2013b*].

South Tambey GBS is located on the north-eastern coast of the Yamal Peninsula (Fig. 1) within the flat accumulative plain dissected by gully erosion, with lower elevation (3–5 m) laidas fringing the coastline. In its coastal area, the following lagoon-marine terraces (LMT) are present: 1st LMT of the Late Pleistocene–Holocene age (up to 12 m a.s.l.), 2nd and 3rd of Late Pleistocene age (20 m and 30–32 m a.s.l., respectively) [*Trofimov et al., 1980*].

Earlier studies [*Badu and Trofimov, 1974; Trofimov et al., 1980, 1986; Badu, 2006, 2011a,b, 2013*] showed that:

– in the study area, Early and Middle Pleistocene sediments accumulated in the open-sea depositional environment, with seawater salinity not greater than the present-day salinity of the Kara Sea;

– the Late Pleistocene relief-forming sediments accumulated in the lithofacies settings of the open sea basin (Kharasavey Cape), of marine bay-lagoon (the lower reaches of the Mordyyaha and Seyakha (Mutnaya) Rivers) and of the mouth of the freshwater Ob Bay;

– the Salekhard Formation sediments, underlying the watershed plain along the centerline of the peninsula, were subject to freezing during the Late Pleistocene, following the long period of diagenetic transformations;

– Late Pleistocene sediments would completely freeze already in the land-partitioned areas of coastal marine, marine-lagoon, and offshore sedimentation in the bay;

– given harsh climatic conditions, freezing of Late Pleistocene sediments occurred simultaneously with their deposition, i.e. syngenetic permafrost formed in the northern Yamal area.

Conditions that controlled ice content in Pleistocene deposits were very heterogeneous in the study area. For their characterization, the data on stratigraphic indices of the deposits, on their genetic types (alluvial, marine, coastal-marine, glacial-marine (Fig. 2)), salinity, total ice content and content of ice formations (e.g., lenses) in frozen soils, and pore water salinity are provided in Table 1.

In the GBS cross-sections, the total ice content of the syngenetic permafrost of Late Pleistocene age was found to be 2–3 times higher than that of the epigenetic permafrost of Middle and Early Pleistocene age. The total ice content varies in the sections (Table 1): for Kharasavey GBS – from 0.10 to 0.15 in the epigenetic portion, and up to 0.20–0.65 in the syngenetic portion; for Bovanenkovo GBS – from 0.15–0.22 to 0.41–0.50; for South Tambey GBS – from 0.18–0.22 to 0.25–0.60.

Table 1. **Ice content, sediment and pore water salinity estimated in fine-grained sediments in the sections of gas-bearing structures**

Indices	Stratigraphic index of genetic types of sediments						
	a IV	m III $_{3-4}$	m III$_{2-3}$	pm III$_1$	mg II$_{2-4}$	m I$_2$–II$_1$	mg I$_1$
				Kharasavey GBS			
I_{tot}	0.56	0.55	–	0.30	0.15	–	0.27
i_i	0.28	0.15	–	0.05	0.03	–	0.02
i_m	0.28	0.40	–	0.25	0.12	–	0.25
D_{sal}, %	–	0.15	–	0.10	0.54	–	0.35
M, g/L	–	5.0	–	7.0	36.0	–	27.0
				Bovanenkovo GBS			
I_{tot}	0.59	0.53	0.50	0.47	0.26	0.19	0.12
i_i	0.30	0.28	0.28	0.06	0.07	0.10	0.05
i_m	0.29	0.25	0.22	0.41	0.19	0.18	0.07
D_{sal}, %	0.25	0.31	0.83	0.17	0.75	0.31	0.28
M, g/L	3.80	8.01	20.7	7.80	37.10	27.70	29.60
				South Tambey GBS			
I_{tot}	–	0.62	0.53	0.40	0.19	0.26	–
i_i	–	0.27	0.20	0.03	0.03	0.02	–
i_m	–	0.35	0.33	0.37	0.16	0.24	–
D_{sal}, %	–	0.48	0.54	0.33	0.80	0.49	0.48
M, g/L	–	20.4	82.4	29.7	124.8	42.5	–

SEDIMENT SALINITY VERSUS PORE WATER SALINITY

Ice content of the marine deposits differs to a certain extent from that of the lagoon-marine deposits composing the GBS. These variations can be explained by formation of the frozen strata under variable conditions of their deposition. In the subaqueous environment, a seabottom sediment accumulates and, gradually, becomes compacted, and the water tends to be bound as the diagenesis proceeds; the ongoing transformations of organic matter and colloidal systems occur due to the chemical reactions. In the deposit formed in such a way, the pore space is filled by seawater with the dissolved salts and gas. In cooling (either by seawater with temperatures around –2 °C, or under adiabatic expansion of gases, as the heat gets absorbed from the overlying soil [*Melnikov and Spesivtsev, 1995; Rokos, 2008*]), wet muddy ground mass begins to freeze, prompting the pore water migration and ice lens inception and growth. At this, salinity of the pore water increases in the soil interlayers, thus lowering their freezing point temperature.

During permafrost aggradation, occurring simultaneously with the accumulation of marine, coastal-marine, and estuary-deltaic sediments, the pore water transforms into segregated ice and pore ice, with its chemical composition remaining practically unchanged [*Badu, 2011a, 2012, 2014*]. A.I. Popov wrote: "Provided that there is no appreciable migration of water, the accumulated sediments are subject to freezing ... in the cases marked by the presence of a frozen substrate at a certain depth in the basal layer of the accumulating sediments. As sediment accumulation proceeds, with the active layer being relatively stable, the permafrost table will rise. Every year, yet another layer, having frozen during the winter at the bottom of the active layer and prevented from thawing in the summer due to sediment accumulation, is added up atop of the permafrost strata. At this, the moisture retained in the newly formed horizon freezes up as a relatively thin horizontal interlayer" [*Popov, 2013, p. 162*].

During the epigenetic permafrost aggradation, with the pore water freezing in the diagenetically transformed soils of Early and Middle Pleistocene age, some changes in the content of soluble salts were recorded, insomuch as certain amount of them might have precipitated during their freezing under harsh climatic conditions of the Late Pleistocene.

These perceptions appear consistent with the ideas expressed by G.I. Dubikov [*Dubikov et al., 1986; Dubikov, 2002*] who suggested that the process of sediment freezing secures both the chemical composition of soil moisture and salinity of the sea basin where these deposits accumulated. N.V. Ivanova [*Rivkin et al., 2007, p. 34–35*] believes that multi-year freezing of the sediments occurred onshore, as the sea retreated in the Pleistocene, whick provided for the preservation of the marine type of the initial salinity and enabled redistribution of salts throughout the stratum, depending on the soil lithology.

There is evidence that pore water salinity values may be indicative of the differences in the facies conditions during the sedimentation and sediment freezing. For instance, for the uppermost 10–15 meters of cross-section of Kharasavey GBS it was found that "...salt composition of the pore water corresponds to the composition of seawater and that of interstitial water in the recent marine organic silty sediments; ...distribution of salts in this cross-section is controlled by soils lithology, their reservoir facies and cryogenic differentiation of salts during the freezing of sediment; ...concentration of salts in clayey soils, which are capable of retaining initial salinity, is 2–8 times higher than the one in sandy soils; ...spatial variability of salinity values for the seabed soils in the near-shore Kara Sea shelf areas is determined ... by facies conditions of the depositional environments, by sediment composition in the near-shore zone, by concentrations of salts in the bottom layer of water, and by specific Pleistocene–Holocene evolution of the shelf..., as well as by differentiation of salts during the sediment freezing in shallow waters; ...salinity of the sea-bottom soils in the near-shore zones of the Kara shelf is different for the offshore area lying to the west of the Yamal Peninsula, and for the Ob Bay, desalinated by the freshwater river influx" [*Rivkin et al., 2007, p. 35–37*].

These aspects have hither not been viewed in the context of conditions forming ice content, simultaneously with the freezing of sediment of different origin. But the author has shown in earlier studies that the freezing of Late Pleistocene sediments within the limits of the GBS occurred simultaneously with sediment accumulation in different lithofacies settings, as the sediment transport approached shallow waters and the accumulating sediment reached the sea level [*Badu, 2006, 2013, 2014*]. These sediments compose a syngenetic unit of the perennially frozen layer of the cryogenic strata (permafrost interval). Ice segregation in this frozen layer occurred in the saturated and soft sediments of the active layer during the freezing event.

The underlying deposits of the Kazantsevskaya and Salekhard Formations (and older) do not form outcrops. These two formations belong to the epigenetic unit of the perennially frozen layer of the cryogenic strata (permafrost interval). As the freezing proceeded, ice segregation occurred in variously dehydrated and consolidated fine-grained soils where migration of water to the freezing front was hindered by low soil moisture content, nearing the lower boundary of the plastic limit. Sparse ice lenses developed only in diagenetic voids and cracks, while ice lens content of the soil was not greater than 0.01–0.03. At moisture content level not exceeding the lower boundary of the plastic limit, well-defined cryostructures (the ice lens content <0.3–0.4) formed in the freezing soils.

DETERMINATION OF PORE SOLUTE MINERALIZATION

When thawed, soil samples are typically tested for dry soil density, natural moisture content (taking into account the amount of unfrozen water) and salinity (D_{sal}), which is determined by the amount of dry residue of salts dissolved in water. So, we can easily calculate the amount of soluble salts contained in the pore water prior to its segregation into ice lenses and freezing in the pores of mineral layers, to become pore ice. The value of pore solute mineralization can be correlated with the salinity of seawater, where the sediment accumulated.

Using the VNIGNI procedure [*Kleimenov et al., 1998*], we made the following calculations relying on the data from the tested silty clay sample: D_{sal} = = 1.12 % (i.e. 1.12 g salt per 100 g of dry sample; dry soil density is 1.85 g/cm^3, humidity is 0.22). The volume of this weighed quantity is equal to 100 g/1.85 g/cm^3 = 54 cm^3 and that of the pore fluid is 54·0.22 = 11.88 cm^3. The volume content of salts dissolved in 1 cm^3 of pore water is 1.12 g/11.88 cm^3 = 0.0942 g/cm^3, which when converted to 1 liter equals 94.2 g/L, i.e. 94.2 ‰.

This method allows to convert the weight of dry salts in dry soil into the volumetric content of salts dissolved in the volume of pore water in soil at the time of complete freezing and transfer into the perennially frozen state, taking into account that the freezing interlayer of clayey soil receives rejected dissolved salts and unfrozen water. The problem thus stated, the calculations do make sense in relation to both syngenetic and epigenetic units of the perennially frozen strata.

VARIABILITY OF ICE CONTENT AND PORE FLUID MINERALIZATION

It was established [*Badu and Podbornyi, 2013a*] that in the Northern Yamal, the pore solute mineralization is markedly different in the depositional complexes of different origin. Table 1 shows the variability of the ice content and the degree of soil salinity in the depositional complexes defined according to the permafrost strata origin (Fig. 3).

Ice content in fine-grained frozen soils of gas-bearing structures. In Kharasavey GBS, the highest ice lens ice content of ice-rich soils with predominantly massive and layered cryostructures is observed only in silty clays and clays in the uppermost section of the 2nd and 3rd MTs. Ice content of the mineral interlayers is almost identical, while the lowest ice content was recorded in layers with the highest D_{sal} value. In Bovanenkovo GBS, the highest ice lens ice content is observed in fine-grained soils of Holocene age. It sharply decreases in the Kazantsevskaya Formation sediments, with ice content of mineral layers reaching its maximum. Total ice content of the syngenetic unit of the perennially frozen strata is 2–3 times higher than that of the underlying Early Pleistocene epigenetic strata.

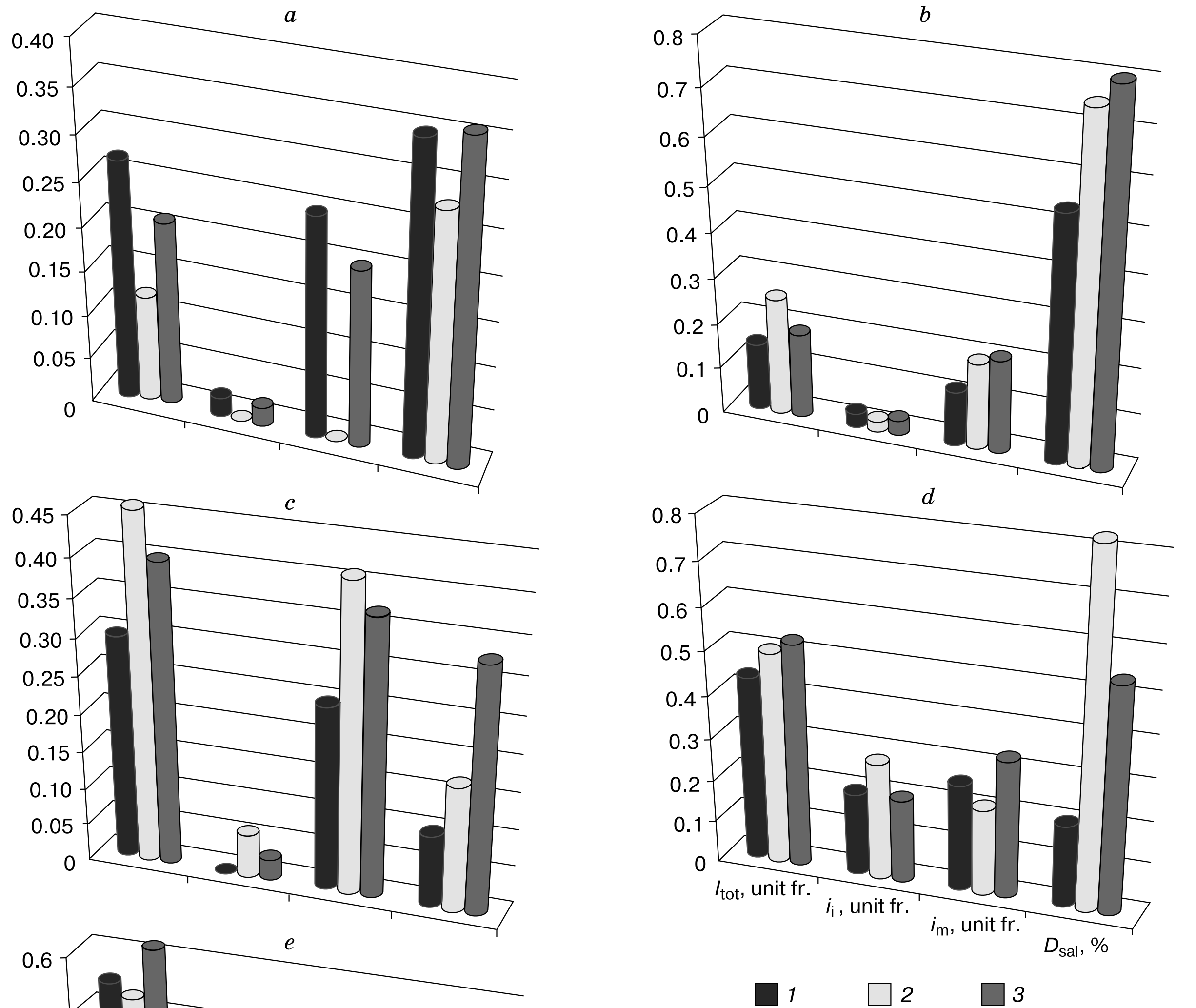
In South Tambey GBS, finely dispersed sediments of the Late Pleistocene age are highly saline, which is confirmed by high values of pore water salinity. Apparently, this substantially reduced the intensity of ice segregation during simultaneous freezing of the accumulating sediment.

Salinity and mineralization of pore fluid in the frozen fine-grained soils. Maximum salt content (on average, not lower than 0.8 %) is characteristic of Middle Pleistocene clayey deposits, while salinity of the shallow-sea coastal Late Pleistocene sediments occasionally grows 1.5–2 times lower.

Mineralization of pore solute tends to decline from its maximum values in clays and silty clay in the Salekhard Formation to its minima in the sediments of Late Pleistocene age. Exceptions are the South-Tambey GBS silty clays and clays emplaced in highly saline marine environment.

The freezing of finely dispersed sediments of the Poluy and Kazym Formations of Early Pleistocene age proceeded with pore water salinity of 27–42 g/L (Table 1) in a wide range of D_{sal} = 0.28–0.49 % and at low rates of ice segregation (ice content at the expense of ice inclusions i_i) (Fig. 3). The salinity of pore water differing greatly, this attests to the substantial variations in seawater salinity in the period of the Poluy and Kazym transgressions. However, the sediments deposited at that time experienced all stages of diagenetic and cryogenic transformations, once they outcropped onto the surface, while the pore water underwent cryogenic metamorphism. It would be reasonable to suggest that, the gap between the end of sedimentation and the onset of freezing accounted for hundreds of thousands of years.

While freezing, finely dispersed sediments of the Middle Pleistocene Salekhard Formation contained pore water with salinity of 36–125 g/L at D_{sal} = 0.50–0.78 % and low ice segregation rates (Fig. 3, *b*). In terms of pore water salinity, the salinity of seawater in the Kharasavey GBS and Bovanenkovo GBS during the maximum of the Middle Pleistocene transgression differed greatly from that of the estuary waters in the South Tambey GBS section (Table 1). Given that the time interval between the end of sedimentation and the beginning of sediment freezing shortened, it probably lasted not longer than a few tens of thousands of years in the areas where the Salekhard Formation deposits are not exposed at the surface.



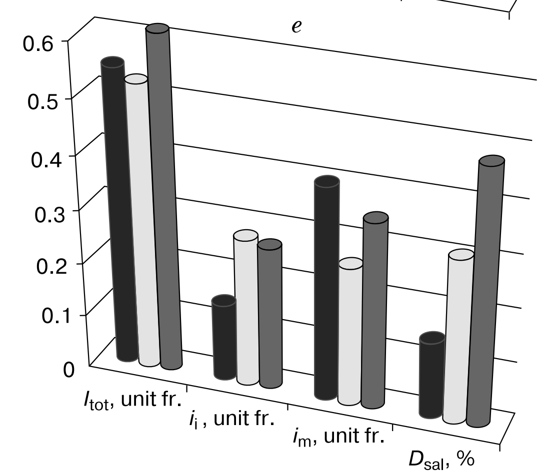


Fig. 3. Total ice content (I_{tot}), ice content of ice inclusions (i_i), ice content of mineral interlayers (i_m), salinity (D_{sal}) of frozen soils in the sections of gas-bearing structures within:

a – Poluy and Kazym Formations; *b* – Salekhard Formation; *c* – Kazantsevo Formation; *d* – 3rd Marine Terrace; *e* – 2nd Marine Terrace. *1* – Kharasavey GBS; *2* – Bovanenkovo GBS; *3* – South Tambey GBS.

As the freezing of the Late Pleistocene Kazantsevo Fm sediments (Fig. 3, *c*) proceeded, pore water salinity varied from 7–8 to 25–30 g/L (Table 1) at D_{sal} = 0.10–0.17 % (up to 0.33 %, in the estuary). These data pinpoint the differences in the salinities of seawater in the open sea basin and in the Pra-Ob bay.

Pore water salinity of the 3rd MT finely dispersed sediments in the Kharasavey area was at 6–10 g/L during their freezing, and that of the 3rd MT sediments in the Bovanenkovo “bay” reached 21–22 g/L, whereas within the coeval LMT in the estuary it was 82 g/L with D_{sal} ranging greately, from 0.18 to 0.80 % (Fig. 3, *d*).

While freezing, finely dispersed alluvial Late Pleistocene–Holocene sediments had pore water with salinity of 4–6 g/L, which did not exceed 10 g/L in the sea bay (lagoon) and averaged at 20–22 g/L in the estuary (their D_{sal} values are 0.12, 0.28, and

0.46 %, respectively). At this, both ice segregation rates and ice content of the mineral interlayers proved to be highest (Fig. 3, *e*), which is characteristic of the syngenetic unit of alluvial deposits and of the Late Pleistocene 2nd and 1st LMTs.

DISCUSSION OF RESULTS

The question, whether mineralization of pore solute of the freezing soils corresponds directly to salinity of the seawater, where the sediment formed, is still open. The values obtained for key geological depositional complexes often turn out to be much lower versus the commonly known level of seawater salinity (35 g/L), whereas measuring salinity in the waters of the Pleistocene transgressions was precluded. In the meantime, the data are available for a variety of seasonal and regional variations in salinity of the Kara Sea waters and those of the Arctic Ocean. For example, A.I. Popov, referring to the data in the famous monograph "Anthropogene of the Northern Part of Western Siberia" by G.I. Lazukov wrote: "...it should be borne in mind that desalination of the seawater body was to some extent greater at that time (in the Upper Pleistocene. – **Yu.B.**), than it is today..." [*Popov, 1991, p. 55*].

The level of pore water salinity changes dramatically in the sediments of Late Pleistocene depositional complexes of different origin, indicating significant differences in the facies conditions of sedimentation and the degree of cryogenic metamorphism of the seawater saturated the freezing sediment.

From the data provided in Table 1 and those shown in Fig. 3 it follows that:

– in the Poluy and Kazym Formations sediments, which accumulation proceeded in the sea basin during the Early Pleistocene transgression, with the pore water salinity in the sediments emplaced above Kharasavey GBS averaging at 27 ‰; at 29.6 ‰ above Bovanenkovo GBS; and at 42.5 ‰ above South Tambey GBS, after the sediment freezing;

– in the finely dispersed sediments of the Salekhard Formation accumulated in the marine basin during the peak of the Middle Pleistocene transgression (and as it waned) pore water salinity after sediment freezing constituted: 36 ‰ above Kharasavey GBS; 37.1 ‰ above Bovanenkovo GBS; 124.8 ‰ above South Tambey GBS;

– in the frozen-through finely dispersed sediments accumulated during the Late Pleistocene Kazantsevskaya transgression, pore water salinity was: 7 ‰ above Kharasavey GBS; < 7.8 ‰ above Bovanenkovo GBS; 29.7 ‰ above South Tambey GBS;

– during the period of accumulation of finely dispersed sediments within the Late Pleistocene 3rd MT and lagoon-marine-terrace (LMT) and their freezing the mineralization of pore water accounted for ca. 5 ‰ above Kharasavey GBS, and for 20.7 ‰ above Bovanenkovo GBS, while it dramatically increased up to 82.4 ‰ above South Tambey GBS;

– in the period of finely dispersed sediments accumulation within the Late Pleistocene 2nd MT and LMT and their subsequent freezing the salinity of pore water in the sediments above Kharasavey GBS accounted for 5 ‰; above Bovanenkovo GBS – for 8.01 ‰, and decreased sharply above South Tambey GBS – down to 20.4 ‰;

– in the period of accumulation of the Late Pleistocene–Holocene coastal-marine and alluvial sediments pore water salinity in the frozen sediments overlying the Kharasavey and Bovanenkovo GBSs did not exceed 3–5 ‰, and 10–15 ‰ atop the South Tambey GSB.

The above data suggest that salinity of seawater, when compared to pore water salinity in the sediments of the open-sea basin of Early and Middle Pleistocene age was close to its modern levels, specifically, in the period of its maximum distribution. The salinity decreased dramatically during the Late Pleistocene, though.

It stands to reason, that the processes of seawater desalination take place in the active layer of the developing syngenetic unit with low-temperature gradients of recurrent freeze-thaw cycles, until the unthawed portion of the active layer completely change into the permafrost state. In the thawed portion of the active layer, sediments will accumulate during the summer in the desalinated seawater, with pore solutes becoming additionally diluted due to the of atmospheric and meltwater input throughout the sediments accumulation, which precedes their cryogenic transformations.

It has been shown by a number of studies [*Badu and Trofimov, 1974; Trofimov et al., 1975, 1980; Badu, 2006, 2013*], that deposition of the marine-lagoon sedimentary complex, overlying the marine deposits of Middle Pleistocene age, occurred in the freshwater estuary of the Ob Bay. The aggradation of the perennially frozen strata there was governed by typical alluvial syngenetic lithogenetic processes inherent in the large river valleys in northern West Siberia.

However, the available data on the cryogenic halocline ingress (from the highly saline seawater at below-zero temperatures) into the mouth of the estuary of the present-day Ob are indicative of the recent sediment accumulation in this cryohalocline-affected water [*Gusev et al., 2001; Rokos, 2008*].

At higher level of pore water salinity, the extensively distributed supercooled soils having below-zero temperatures, experience freezing at lower negative temperatures, once they are emplaced in the shallow-water environment. This was likely to proceed during the Holocene and the Late Pleistocene, since "lithologic affinity of modern and Pleistocene marine sediments... within the bounds of their regional vicinity allows drawing parallels between them in other aspects, too" [*Popov, 1991, p. 55*].

CONCLUSIONS

Given that ice content is a key cryolithological characteristic of permafrost soils, their deposition within the syngenetic perennially frozen layer of the permafrost strata on the Northern Yamal is closely linked to the specific characteristics of the litho-facies conditions of sedimentation in the marine environment. This relationship is revealed in the variations of salinity of pore water saturated fine-grained soil prior to its freezing.

Despite the fact that, in freezing, pore water is redistributed onto ice segregation and pore-ice of mineral layers, and due to the cryogenic transformation of its concentrations and chemical composition, total salinity of pore water in the analyzed bulk soil sample will correspond to the salinity of seawater, where this soil formed.

Fluctuations in the degree of sediment salinity in the sections of Quaternary deposits within the gas bearing structures attest to the variety of the facies conditions at regional scale and their variability in the periods of sedimentation during the entire Pleistocene.

Pore water salinity variations being ubiquitous, this provides evidence for the permafrost strata developing in the lithofacies setting of the open sea basin (Kharasavey area), lagoon-bay (Bovanenkovo area) and the Ob Bay estuary (South Tambey area) in the northern Yamal.

Because of the sedimentation conditions in the sea basin with varying salinity, there was a great probability that sediment freezing proceeded simultaneously with its accumulation. The fact that subaqueous and subaqueous-subaerial types of syncryogenesis and its forms developed in various lithofacies environments [*Badu, 2006, 2013*] is confirmed by the growth of polygonal ice wedges associated with the sedimentation processes taking place within the low and high laidas, and by cryogenic texture of Late Pleistocene deposits and by values of their ice content.

The syngenetic unit of the permafrost strata is composed of clayey and silty sediments of Late Pleistocene age. The sediments, when freezing, were saturated with seawater, which salinity subjected to considerable alteration, as the Kara Sea offshore area grew shallower.

The epigenetic unit of the perennially frozen layer is composed of finely dispersed sediments of the Early and Middle Pleistocene age, which prior to their freezing appear to have been saturated with the seawater with degree of salinity commensurate with the modern Kara Sea salinity.

Based on analysis of pore water salinity variations in the sections of the marine deposits of Pleistocene age overlying the gas-bearing structures, the seawater salinity was assumed to be:

– in the Early Pleistocene Epoch transgression: lower than 27 ‰ above Kharasavey GBS, ca. 30 ‰ above Bovanenkovo GBS, and up to 42 ‰ above South Tambey GBS;

– in the Middle Pleistocene Epoch transgression: 36 ‰ above Kharasavey GBS; 37 ‰ above Bovanenkovo GBS; and 124 ‰ above South Tambey GBS;

– dramatically reduced to 5–8 ‰ above Kharasavey GBS and Bovanenkovo GBS, and to 10–20 ‰ above South Tambey GBS in the epochs of the Late Pleistocene (Zyryan, Kargin and Sartan periods) ingressions.

The thickness of the cryogenic strata in western and eastern parts of the Northern Yamal is directly associated with the marine or marine-lagoonal (estuarine) modes of deposition and, ultimately, with regional variations in degree of soils salinity in some epochs of the Pleistocene and with sediment freezing under the deep-sea and coastal conditions in the regressed sea basin, i.e. shallowing bay-lagoon and estuary, where syn- and epigenetic units of the perennially frozen layer would develop within the cryogenic strata (permafrost interval).

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