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ICE AND FROZEN GROUND PROPERTIES

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THE COMPOSITION, STRUCTURE AND PROPERTIES OF FROZEN AND THAWED DEPOSITS ON THE BAYDARATSKAYA BAY COAST, KARA SEA

D.M. Aleksyutina, R.G. Motenko

Lomonosov Moscow State University, Department of Geology,
1, Leninskie Gory, Moscow, 119991, Russia; aleksyutina@gmail.com, rmotenko@mail.ru

Field and laboratory studies of the composition, structure and properties of frozen and thawed soils have been carried out on the western coast of Baydaratskaya Bay. The freezing point of the ground, the unfrozen water content, the thermal and mechanical properties of soils with different grain-size distribution have been analyzed depending on the water content, density, salinity, organic content and temperature of the soil. The results of comparing the soil parameters obtained from the boreholes depth-wise have been summarized.

Dispersive frozen soils, thermal and mechanical properties of deposits, unfrozen water

INTRODUCTION

The Arctic offshore regions contain a large amount of yet unused energy resources; therefore, their exploration requires that variability of the environment caused both by natural factors and by the anthropogenic impact should be strictly considered. It is impossible to simulate the natural phenomena and to forecast cryogenic processes without knowing the characteristics of near-surface loose deposits.

The coast of Baydaratskaya Bay is composed of dispersive frozen soils, which are sensitive to the external variations of the environment; therefore, the geocryological characteristic of these deposits is a rather essentail task. Regular observation was conducted on the coast of Baydaratskaya Bay over erosion of the shore composed of permafrost soils [*Geoecology of the North, 1992; Kamalov et al., 2006; Belova, 2014*], which is related to active growth of the oil and gas industry in the region, as well as to construction of a pipe reducer Bovanenkovo–Ukhta at the bay bottom. Investigation of the composition, structure and properties of the soils was conducted in the framework of the engineering and geological survey; however, there are practically no published data relating to the characteristics of the soils or in most cases only their physical properties of the deposits have been studied. The data on the mechanical and thermal physical properties of soils in the upper part of the section are scanty, whereas it is these soils that become revealed on the shore terraces and become destroyed due to thermal abrasion and thermal denudation.

In this paper, the results of studying the characteristics of near-surface frozen and thawed deposits, reflecting the natural variability of their composition, structure and properties, are discussed.

THE AREA OF INVESTIGATION

The investigation was conducted on the western coast of Baydaratskaya Bay of the Kara Sea. The area under study 3.6 km long is located 4 km southeast of the mouth of the River Oyu-Yakha between the islands of Levdiyev and Torasayey (Fig. 1).

The geological structure of the area consists in the following: the Mesozoic-Cenozoic soils are overlaid by Quaternary deposits up to 50 m thick [*Geomorphological Map..., 1999*]. The area refers to the soil permafrost zone; in the transverse section, frozen soils alternate with cooled soils, and thawed deposits are found near the mouths of large watercourses and thermokarst lakes. Earlier observations [*Dubikov, 1991; The engineering and geological... conditions..., 1995; Baulin et al., 1997*], which were conducted during engineering survey in the area, showed the depth of annual temperature fluctuations to be 12–15 m, with the average annual temperatures of the soils at the depths of zero annual ranges varying from –4 to –8 °C.

In accordance with the results of the state geomorphological survey, along the coastline of Baydaratskaya Bay [*Ivanova and Voitsekhovsky, 1959; Geomorphological Map..., 1999*] accumulative and pedimented coastal-marine and littoral-fluvial forms of

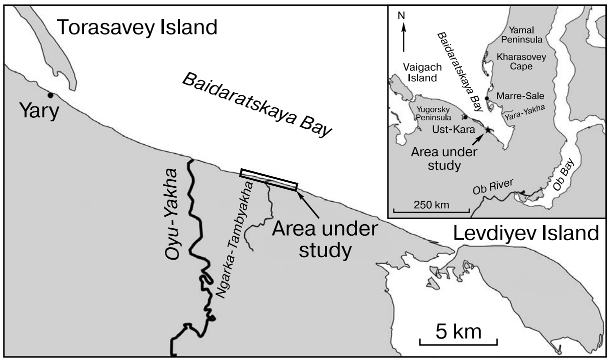

Fig. 1. The studied territory.

the relief with different actual elevations can be seen, within the limits of which the first and the second sea and river terraces, a layda, a flood plain and a beach are identified. The elevations and actual elevations of laydas and flood plains reach 3 m, those of the first sea terraces reach 4.5 m, those of river terraces reach 5–8 m, and those of the second sea and river terraces reach 12–15 m. Thus, division of the terraces into sea and river terraces only based on their hypsometric levels does not seem to be possible.

In conducting field works in the region under study, two observation sites were selected (I, II), divided by the flood plain of the Ngarka-Tambyakha River, which is flooded during the autumn wind-induced surges (Fig. 2). The sites differed for the height of the escarp over the middle level of the bay (*hereinafter the heights are cited in relation to the level of the bay different from the Baltic system of elevations by −0.5 m*) and for the composition of the deposits: site I, located in the southeastern part, was established on a terrace with the elevations of 4–6 m (named 'low' in the paper); site II in the northwestern part of the territory under study was established on a terrace with elevations reaching 16 m (named 'high' in the paper). To characterize the deposits constituting the coastal escarps, six boreholes were drilled (3.5–6.5 m deep), later equipped for making temperature observations. The annual temperature in the bottom hole varied from −4.0 to −4.5 °C.

The deposits in the area under study are characterized by variety in the lithological composition (Fig. 3)*.

In the southeastern part of the low terrace, there are disperse deposits with low ice content, represented by sandy clays, sands and their alternation. In the northwestern part of the low terrace, fine variations contain more ice and are alternations of loams and sandy clays (borehole 4), which comprise a large number of ice veins, the edge of which was opened up by borehole 3.

The deposits of the flood plain (layda) are presented by sandy clays and sands, overlaid from the surface by a layer of peat.

In the bank cliffs of the high terrace, sandy deposits with a high content of ice prevail. The only deep borehole (borehole 5, up to 5 m deep) on this

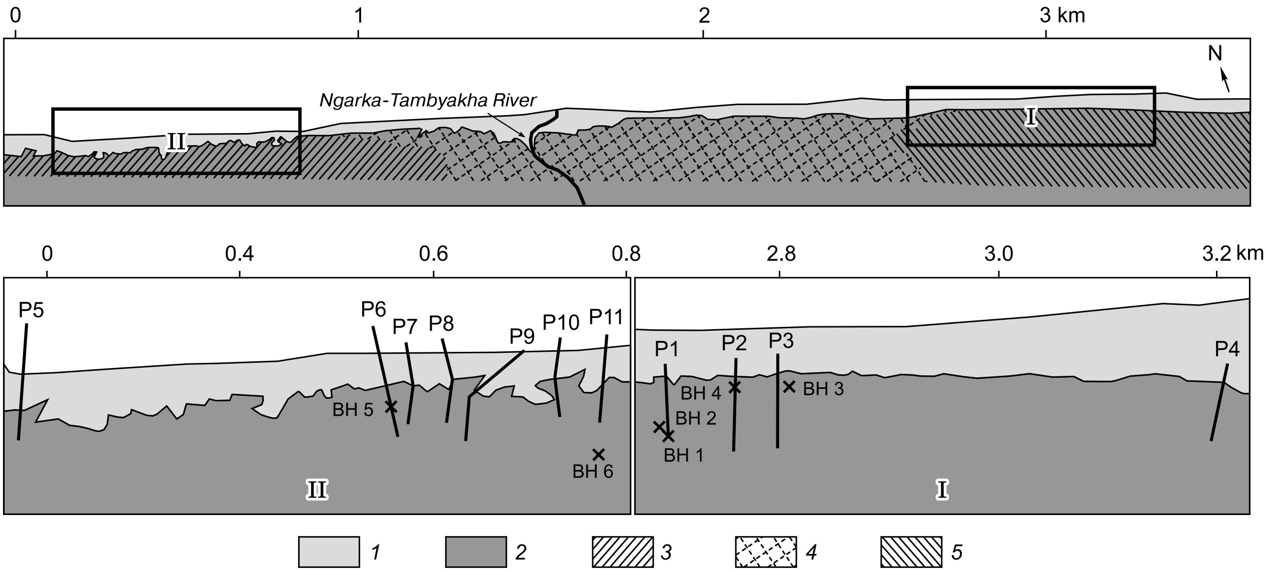

Fig. 2. Locations of the observation sites (I, II) on the studied area of the coast, profiles (P) and boreholes (BH).

1 – sand beach; *2* – shore; *3* – higher terrace; *4* – flooded valley (layda); *5* – lower terrace.

* The deposits of the flood plain and of the high terrace were assessed on the basis of visual field observations with literrary data added [*Baulin et al., 1997; Belova, 2014*].

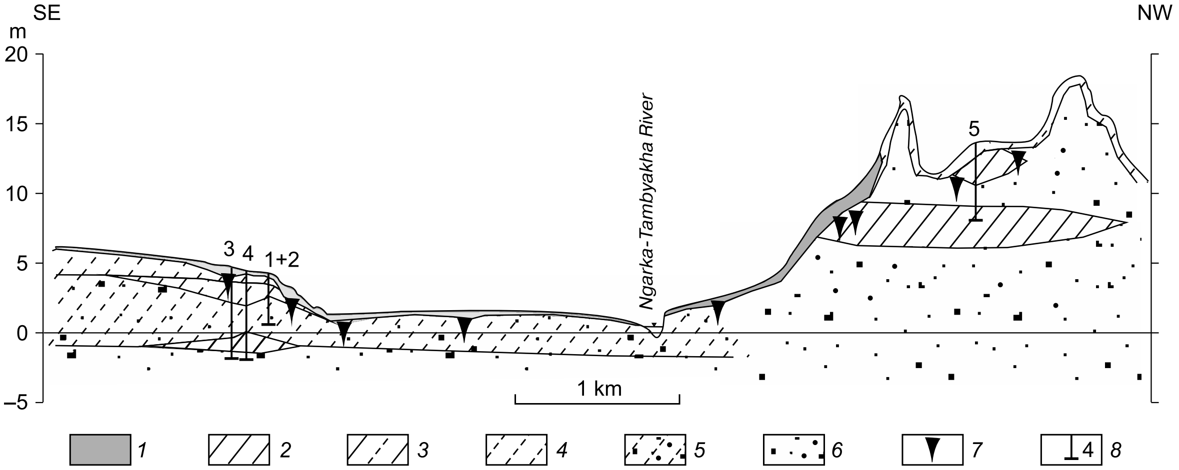

Fig. 3. Schematic transverse section of the studied territory:

1 – peat; *2* – loam; *3* – alternating loamy sands and loams; *4* – loamy sands; *5* – loamy sands with interlayers of sand; *6* – sand; *7* – ice veins; *8* – borehole and number.

site was drilled at the place of a drained thermokarst lake and cannot be most representative.

THE METHODOLOGY OF SAMPLING AND LABORATORY STUDIES

The boreholes were drilled manually with a portable motor-driver auger without washing and blowing, in order to preserve the cryogenic structure of the drill core. In case of difficult passage through some rock horizon (for example, given an interlayer of semigravel frozen sand), drilling was continued with a conveyer screw until the deposits became more passable. To sample core, metal spoons were used with the diameter of 4 and 7 cm. Out of all the boreholes and from the terrace slope, 86 monolith samples and samples of disturbed structure were collected. The total number of property measurements on the collected samples constituted over 1000.

For all the collected samples, the laboratory studies determined the following characteristics: *dispersion ability, moisture content, plasticity, density, the degree of salinity and the relative content of organic matter*. The main characteristics of the soils were investigated with a series of standard methods [*GOST 5180-84, 1984; GOST 27753.2-88, 1988; GOST 26213-91, 1992; GOST 12536-2014, 2015*]. In addition, determined were *the thermal physical characteristics of soils in the thawed and frozen states, the temperature of the beginning of freezing, and physical and mechanical properties of the unfrozen water of the frozen soils.*

The thermal physical characteristics of thawed and frozen soils were characterized by investigating three parameters: heat capacity, thermal conductivity and thermal diffusivity. Under field conditions, the thermal conductivity of soils in a solid mass was determined using a probe method with a MIT-1 measuring device (the relative measurement error was ±7 %). Under laboratory conditions, the thermal physical characteristics were determined using the method of a first-order regular mode [*Methods..., 2004*] and a measuring device KD2 Pro, the measuring error of which was ±5–7 %. The freezing point was found using a cryoscopic method with the accuracy of ±0.03 °C. The unfrozen water content in frozen grounds was determined using a combination of two methods (the cryoscopic and contact method), developed at the department of geocryology of the Moscow State University [*Yershov et al., 1991; Motenko and Komarov, 1996; Motenko, 1997; Methods..., 2004*]. The studies were conducted with double repetition, with the measurement error being ±3–5 %.

The studies of the physico-mechanical properties (equivalent cohesion, compressibility and precipitation during thawing) included testing frozen grounds using the ball stamp method and the compression method for settlement during thawing [*GOST 12248-2010, 2011*]. The physico-mechanical characteristics of the deposits sampled from borehole 4 were investigated under the guidance of M.N. Tsarapov.

THE RESULTS OF INVESTIGATING THE COMPOSITION, STRUCTURE AND PROPERTIES OF THE DEPOSITS

The variations in the characteristics of the samples under study are shown in Table 1.

Grain-size distribution. The studies of the grain-size distribution showed the prevalence of loamy sands in the sections, with the total variability of the deposits being from heavy silty loams to sands of the middle degree of the grain size (Fig. 4). The domineering content of large silty particles was characteristic of all the samples (except fine sands).

Table 1. **Variations in the physical and thermal properties of deposits**

Deposit	W_{tot}, %	ρ, g/cm^3	D_{sal}, %	I_r, %	λ_f	λ_{th}	C_f	C_{th}	$a_f \cdot 10^6$	$a_{th} \cdot 10^6$
					W/(m·K)		J/(kg·K)		m/s^2	
Sands	5–89	1.5–2.0	0.08–0.58	2.8–11.2	0.24–2.10	0.24 –1.91	770 –1500	770 –2400	0.19 –1.19	0.19 –0.96
Loamy sands	9–162	1.2–2.1	0.01–0.71	3.6–14.4	0.22–1.65	0.22 –1.81	770 –1650	770 –2900	0.16 –1.59	0.16 –0.74
Loams	19–205	1.1–1.7	0.04–0.99	4.9–25.3	0.18–1.55	0.18 –1.53	840 –1770	840 –3150	0.15 –1.44	0.15 –0.58
Peats	114–955	0.9–1.2	–	62.1–88.3	0.82 –1.30	0.38 –0.59	1980 –2260	3020 –4200	0.41 –0.61	0.12–0.16

Note. W_{tot} – moisture; ρ – density; D_{sal} – salinity; I_r – organic matter content; λ_f, λ_{th} – thermal conductivity of frozen and thawed deposits; C_f, C_{th} – specific thermal capacity of frozen and thawed deposits; a_f, a_{th} – thermal diffusivity of frozen and thawed deposits, respectively.

In the fine sands of the lower and higher terraces, the fine fraction of the sand particles prevails (Fig. 4, *a*). In the silty sands of the lower terrace, the shares of the fine fraction of the sand particles and of the large fraction of the silty particles are roughly the same, domineering over the other fractions; in the silty sands of the higher terrace there is a maximum amount of the fine fraction of the sand grains (Fig. 4, *b*). The sandy loamy sands of the lower terrace are divided into two types: in one type the fine fraction of the sand grains prevails, in the other type fractions of fine silty and large silty grains are domineering (Fig. 4, *c*). The sandy loamy sands of the higher terrace are characterized by a large amount of the three indicated fractions, whereas the silty loamy sands are represented by the fine fraction of the sand grains and by the fraction of large-grain silt. In the silty sandy clays of the lower terrace, the fractions of

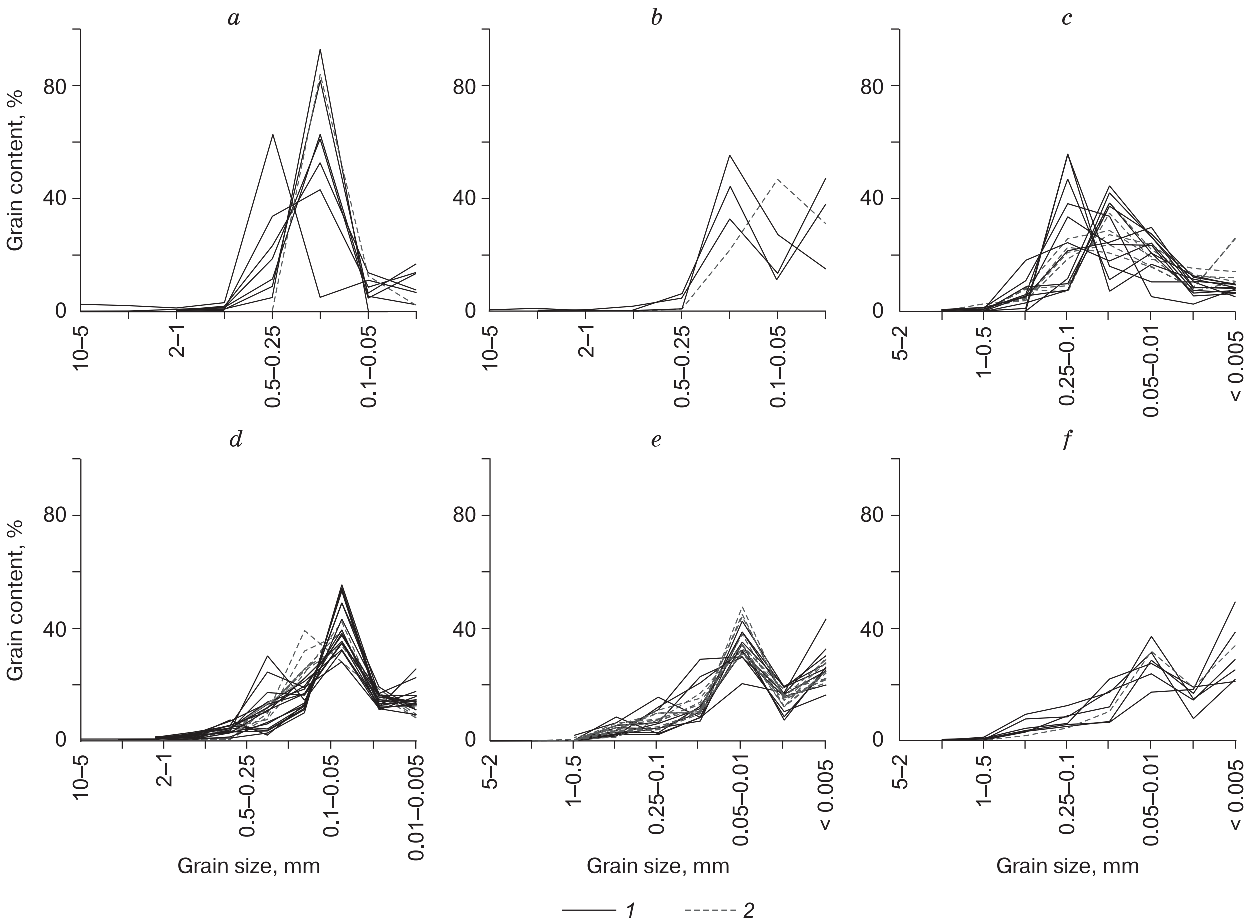

Fig. 4. Differential curves of the grain-size distribution of deposits of the lower (*1*) and higher (*2*) terraces.

a – fine sands and medium-grain sands; *b* – silty sands; *c* – sandy loamy sands; *d* – silty loamy sands; *e* – light silty and sandy loams; *f* – heavy silty loams.

large-grain silt and of medium-size sand grains prevail (Fig. 4, *d*). The sandy clays of the higher terrace are characterized by a high content of large-grain silt and of loamy particles, and in the lower terrace sand grans are added to the above mentioned fractions (Fig. 4, *e, f*).

The cryogenic structure. In the sands, massive and thin lens-shaped cryogenic structures prevailed, in sandy loamy sands the prevailing structure was lens-shaped and porphyritic, rarer massive. In sandy clays, the highest variety of cryo textures observed: the lens-shaped texture prevails, but also massive, flaky and ataxite textures occurred, normally found in the upper parts of the lower terrace section.

The total ice content (i_{tot}) varied considerably to increase in fine-grained and peated deposits. The maximum total ice content varies in organic variations (peats) from 59 to 96 %. The maximum values of i_{tot} for mineral and organomineral deposits reached 85 %, while the minimal values were to be found for sands, 7 %, loamy sands, 11 % and loams, 26 %.

The natural moisture content (W_{tot}) of the deposits is related to differences in the cryogenic state of the deposit components. In sands, the average values of W_{tot} were 19 % (within the range of natural variability W_{tot} from 5 to 89 %), in loamy sands they were 30 % (within the range of natural variability W_{tot} from 9 to 162 %), in loams, 42 % (within the range of natural variability W_{tot} from 19 to 112 %). The natural moisture content of the peats varied from 80 to 955 %.

Plasticity. The liquid limit (W_L) in loamy sands varied from 14 to 32 %, in loams, from 26 to 42 %. The plasticity limit (W_p) in loamy sands varied from 12 to 26 %, in loams, from 17 to 31 %. The plasticity index (I_p) varied in a wide range: in loamy sands, from 2 to 6.9 %, in loams, from 7 to 16 %.

The density (ρ) of the deposits varied from 0.9 to 2.1 g/cm^3, minimal values were characteristic of peats, while the maximum ones were typical of sands. The density of the matrix (ρ_d) varied in sands from 0.82 to 1.68 g/cm^3, in loamy sands, from 0.46 to 1.76 g/cm^3, in loams, from 0.38 to 1.62 g/cm^3 and in peats, from 0.09 to 0.81 g/cm^3.

The content of organic matter (I_r) in clay and sand deposits varied from 0 to 25 %, and in peats, from 62 to 83 %.

Salinity. The study of the soil salinity (D_{sal}) revealed prevalence of the chlorine, sodium and potassium ions in the soils with a marine type of salinization. The variation range D_{sal} for all the samples under study was equal to 0–1 %. Analysis of the degree of salinization of the soils of the first marine terrace showed loams to be the most saline deposits (0.04–0.99 %), while sands proved to be the least saline (0.08–0.58 %).

Equivalent cohesion. In the frozen soil samples, equivalent cohesion (C_{qt}) varied in a wide range, depending on the temperature and the dispersion ability. The highest values were observed in sands, while the lowest values were found in loams. In loamy sands, at the temperature of –3 °C the value of C_{qt} varied from 0.063 to 0.131 MPa and increased to 0.26 MPa when the temperature decreased to –8 °C.

Absorbing when thawing. The studies showed that the values of absorbing when thawing (A) in loams (from 0.225 to 0.268 units with the moisture values varying in the range of 59–112 %) were higher than in loamy sands (A = 0.052 with W = 48%).

Compressibility (m). For sandy clay-loam deposits, the compressibility values were close and varied from 0.19 to 0.25 MPa^{-1}.

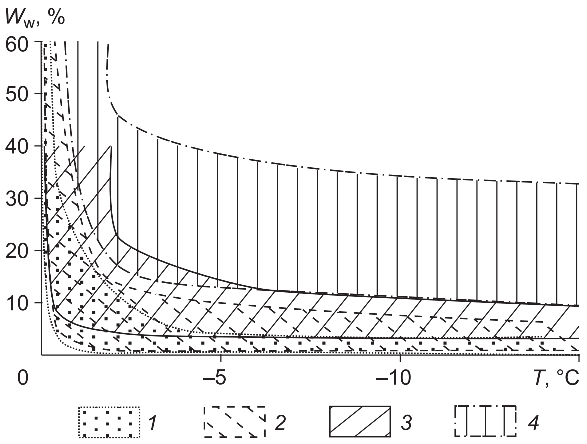

Fig. 5. Dependence of the unfrozen water content W_w on temperature T for the studied frozen deposits:

1 – sands; *2* – loamy sands; *3* – loams; *4* – peats.

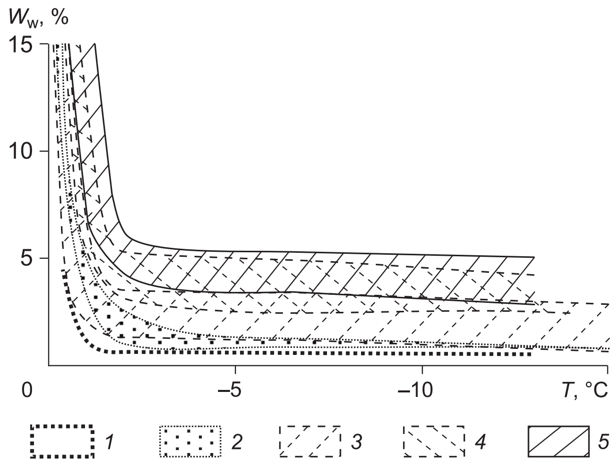

Fig. 6. Dependences of the unfrozen water content W_w on temperature T of frozen deposits of different grain-size distribution:

1 – fine sand; *2* – silty sands; *3* – sandy loamy sands; *4* – silty loamy sands; *5* – loams.

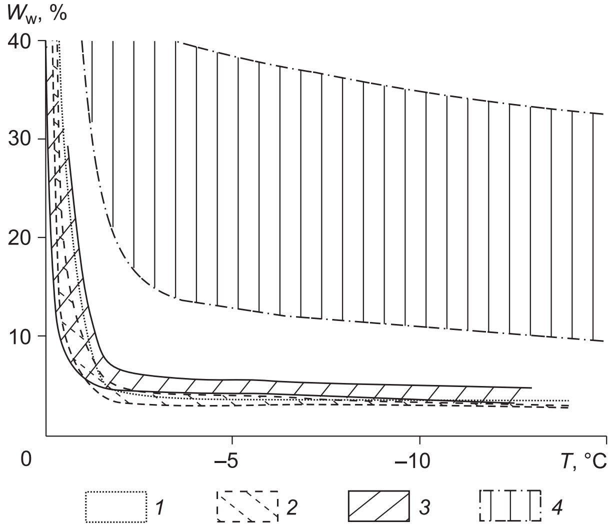

Fig. 7. Dependences of the unfrozen water content W_w on temperature T of frozen peated deposits:

1 – sands; *2* – loamy sands; *3* – loams; *4* – peats.

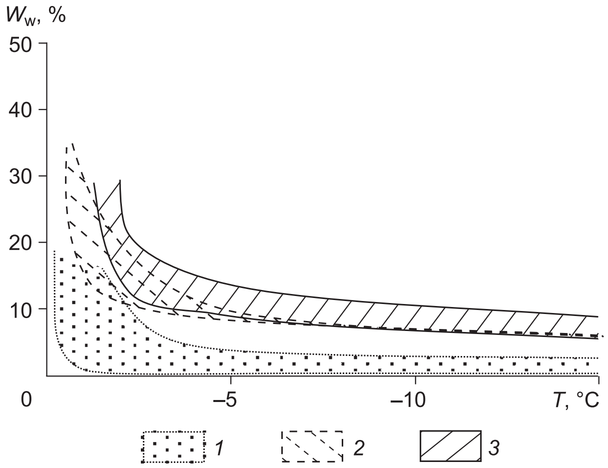

Fig. 8. Dependences of the unfrozen water content W_w on temperature T of frozen salinized deposits:

1 – sands; *2* – loamy sands; *3* – loams.

The unfrozen water content (W_w). The main factors which influence on the unfrozen water content in frozen soils are the temperature, grain-size distribution, salinity, peat content, etc. [*The phase composition..., 1979; Cheverev, 2004*].

Shown in Fig. 5 is dependence of moisture due to unfrozen water (W_w – weight) on temperature for all the deposits under study.

The range of variation in the content of unfrozen water in the frozen samples is very wide, for example, at the temperature –1 °C, W_w varied from zero (in sands) to hundreds of per cent (in peats), and at the temperature of –15 °C, from 0 to 33 %.

The impact of the grain-size distribution of the deposits on the unfrozen water content in them is shown in Fig. 6. With the temperature of soils being –4 °C in fine sand W_w = 0.6 %, in silty sands it varied from 0.8 to 1.5 %, in sandy loamy sands – from 1.1 to 3.4 %, in silty loamy sands – от 2.5 до 4.8 %, while the largest amount of unfrozen water was observed in loams (4.0–5.3 %).

The impact of the content of organic matter is shown for organomineral and organic variations (Fig. 7). The highest values are characteristic of well-decomposed peats of the reddish color, while the lowest values were revealed for dark-brown peats. With the mean annual temperature of the soils being –4 °C, W_w in frozen peats varied from 13 to 40 %. In peated sand, W_w = 3.6 %, in loamy sands with I_r = 6–14 % the content of unfrozen water varied insignificantly – from 3.2 to 5.0 %, in frozen loams at I_r = 5–25 % it varied from 4.4 to 5.6 %.

The impact of salinity. The largest amount of unfrozen water was observed in medium- and strongly salinated loams (Fig. 8), W_w and varied from 9.6 to 15.2 % at the temperature of –4 °C. The content of unfrozen water in salinated loamy sands varied from 8.6 to 11.5 %, and, as the temperature values W_w decreased to 6 % at the temperature of –14 °C, which is related to the natural variety of the samples under study. The content of unfrozen water in weakly salinated sands varied from 0.4 to 2.4 %, in strongly salinated sands, from 1.6 to 4.6 %.

The results of laboratory studies of the hase composition of the moisture contained in the frozen saline soils were compared to the results of the summary obtained previously for this region [*Baulin et al., 1997*]. In saline sands, the results practically coincided, and for loamy sands and loams, the revealed ranges of changes in W_w insignificantly differed due to the smaller number of the samples we investigated.

The frezing point of the ground (t_{bf}) depends on the same factors which affect the content of unfrozen water. In the investigated nonsaline nonpeated soils, one can clearly see the impact of dispersity and natural moisture of the deposits on t_{bf}. In sands, t_{bf} varied from –0.14 to –0.5 °C (W_{tot} = 4–19 %), in loamy sands, from 0 до –0.3 °C (W_{tot} = 6–150 %) and in loams, from –0.05 to –0.2 °C (W_{tot} = 27–108 %).

In peated samples an in peats, the temperature of the beginning of freezing is close to zero due to a high content of moisture in them. In peats t_{bf} varies from 0 to –0.2 °C at the moisture content from 114 to 954 %, in peated loamy sands and in sands it is –0.1 °C at W_{tot} = 90–107 %, in loams, from 0 to –0.25 °C at the moisture content from 30 to 230 %.

The impact of the salinity of the soils of different granulometric composition on the temperature of the beginning of their freezing is shown as dependence of t_{bf} on the concentration of the pore solution (C_p).

To allow evaluation of the results obtained, in Fig. 9 a dashed line shows the temperature of the beginning of freezing of sea salt solution [*World ocean, 2015*]. It can be seen from Fig. 9 that the dependence is practically linear for all the samples under study.

The thermal conductivity of the ground (λ). The natural values of the moisture content and density of the samples under study vary in a wide range. It is possible, for example, to analyze the results obtained depending on the volume water content (W_ρ) as a generalized indicator considering the water content and the density of the matrix.

Shown in Fig. 10 are dependences of the thermal conductivity for all the samples studied on the volume water content for the frozen (λ_f) and thawed (λ_{th}) states.

As the water content increases from the dry state to complete moisture saturation, the thermal conductivity of the deposits of different grain-size distribution grows. As the water content increases further, the variation rate λ in the frozen state slows down, and in the thawed state the values of λ_{th} decrease in loamy sands and in loams. The maximum values of the thermal conductivity are characteristic of sands, the minimum values refer to peats. The variation of λ is related to the natural variety of the deposits, therefore, it si necessary to analyze the results obtained depending on different factors.

The impact of the organic matter content in the deposits studied on their thermal conductivity is related to the lesser ability of the peat particles to conduct heat, to the greater content of unfrozen water in the frozen samples, etc. As the content of organic matter in the deposits grows, the thermal conductivity decreases in the series "mineral grounds–grounds with admixture of peat–grounds with low content of peat–peats". The decrease if λ in organomineral and organic grounds was recorded both in frozen and thawed samples.

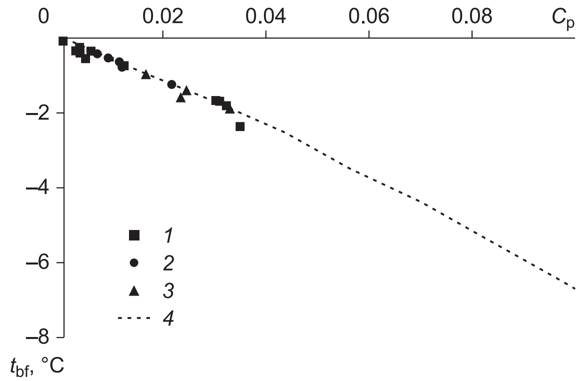

Fig. 9. Dependence of the freezing point t_{bf} on concentration of the pore water C_p of salinized deposits:

1 – sands, *2* – loamy sands, *3* – loams; *4* – saline solution (sea salt).

The impact of salinity on the thermal conductivity is more manifested in the frozen state and is practically not observed for the thawed state, resulting in the decrease of the heat conductivity coefficient in frozen sands and in loams by approximately 20 % and more [*Aleksyutina and Motenko, 2016*].

Heat capacity of soils (C). The results of studying the specific heat capacity of the samples within the range of the volume water content variation are shown in Fig. 11. The highest values of the specific heat capacity are characteristic of peats: for the thawed state they reach 3950 kJ/(kg·K), for the frozen state they are 2350 kJ/(kg·K). The values of the heat capacity of loamy sands and loams are very close, but even for the peated variations they are lower than for peats.

The thermal diffusivity of soils (a). Shown in Fig. 12, *a*, *b* are dependences of the thermal diffusivity

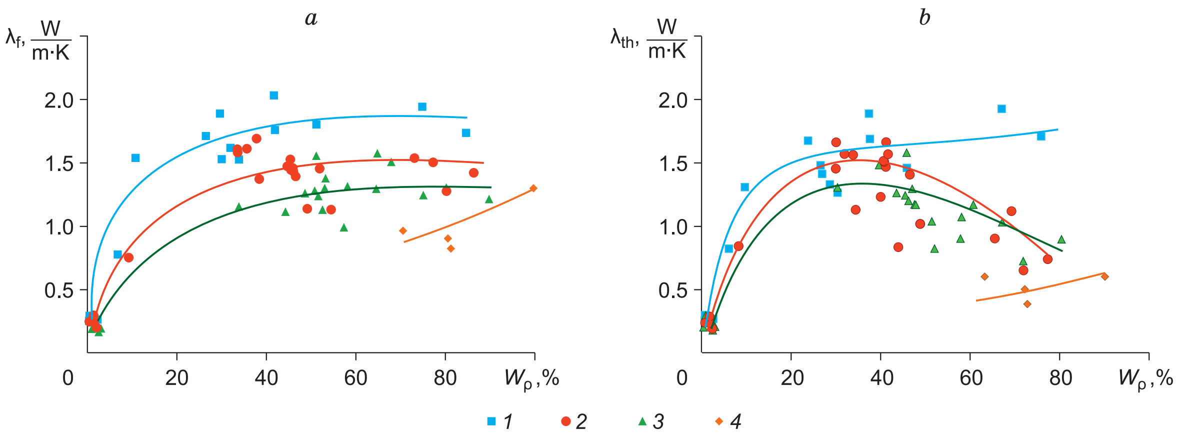

Fig. 10. Dependence of the thermal conductivity index λ on volume water content W_ρ of the deposits in frozen (*a*) and in thawed (*b*) states:

1 – sands; *2* – loamy sands; *3* – loams; *4* – peats.

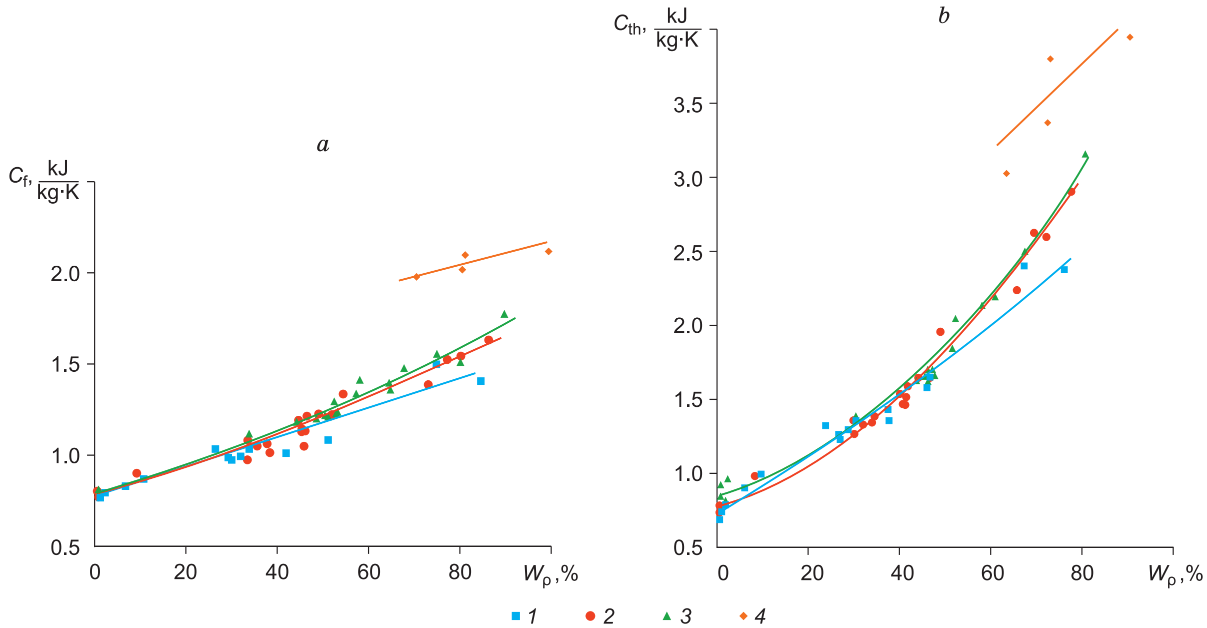

Fig. 11. Dependence of specific thermal capacity *C* on the volume water content W_ρ of the deposits in frozen (*a*) and in thawed (*b*) states:

1 – sands; *2* – loamy sands; *3* – loams; *4* – peats.

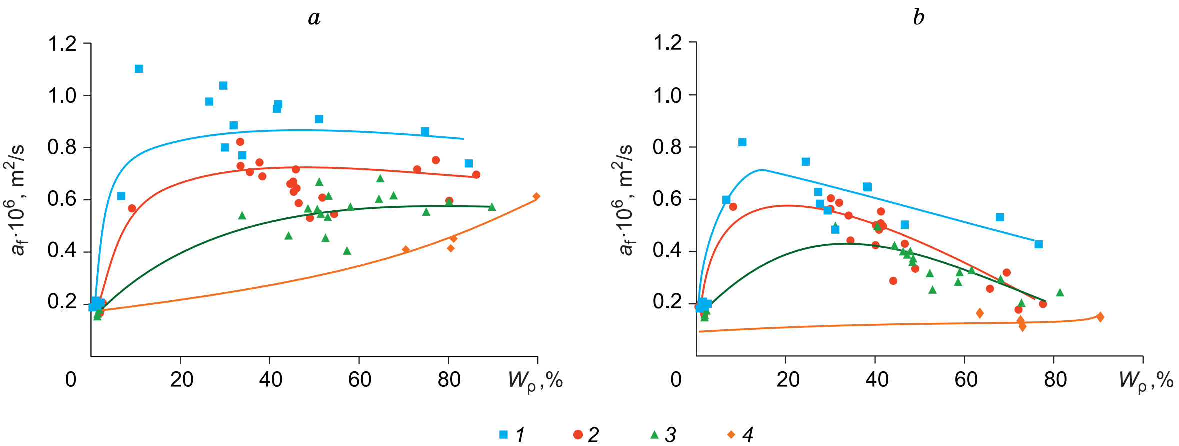

Fig. 12. Dependence of the thermal diffusivity index *a* on the volume water content W_ρ of the deposits in frozen (*a*) and in thawed (*b*) states:

1 – sands; *2* – loamy sands; *3* – loams; *4* – peats.

of soils of different dispersive ability correspondingly for the frozen a_f and thawed a_{th} states of the volume water content.

The thermal diffusivity in the thawed deposits is lower than in the frozen deposits, being practically invariable for the thawed peats ($a_{th} = 0.15 \cdot 10^{-6}$ m/s²). The maximum values of the thermal diffusivity (up to $1.10 \cdot 10^{-6}$ m/s²) are characteristic of frozen sands.

Evaluation of the impact of the organic matter content on the thermal diffusivity showed that in the frozen peated loams and in loams with peat admixture within the range of the volume moisture content variation from 49 to 90 %, the values of a_f are very close ($0.57 \cdot 10^{-6}$–$0.62 \cdot 10^{-6}$ m/s²). In frozen mineral loams a_f changed from $0.54 \cdot 10^{-6}$ to $0.69 \cdot 10^{-6}$ m/s² at W_ρ = 34–65 %.

The influence of deposit salinity. For frozen soils, comparison of the results of studying the thermal diffusivity of the deposits revealed that salinity reduced a_f by 35–50 % [*Aleksyutina and Motenko, 2016*].

THE RESULTS OF COMPARING THE DEPOSIT CHARACTERISTICS BY DEPTH

Shown in Fig. 13, 14 are the data for boreholes 3 and 4, reflecting changeability of the characteristics of the deposits in the thawed and frozen states in the lower terrace. Borehole 3 is located on the terrace surface with the mouth mark of 5.2 m above the bay's average level and penetrates the marginal part of the ice vein (Fig. 13). The terrace deposits in this place are represented mainly by loamy sands; the loam horizon appears only at the mark corresponding to the coastline. Borehole 4, located 60 m northwest of borehole 3 and having the mark of 4.8 m, was drilled in more loamy deposits (Fig. 14). The study of the physical characteristics of the upper part of the section (the first 3 m from the surface) showed a high ice content (i_{tot} from 50 to 75 %); when thawing, the deposits had the moisture content from 45 to 150 %, with the density in the range of 1.2–1.7 g/cm^3. The lower part of the section was composed of less humid deposits (W_{tot} varied from 19 to 40 %) and of more dense saline deposits (ρ < 2.0 g/cm^3). The degree of salinity increased with the depth. The thermal characteristics changed with the depth, for nonsaline sands λ_{th} = 1.7–1.9 W/(m·K), λ_f = 1.8–2.0 W/(m·K), for saline sands, up to 1.3 W/(m·K) in the thawed

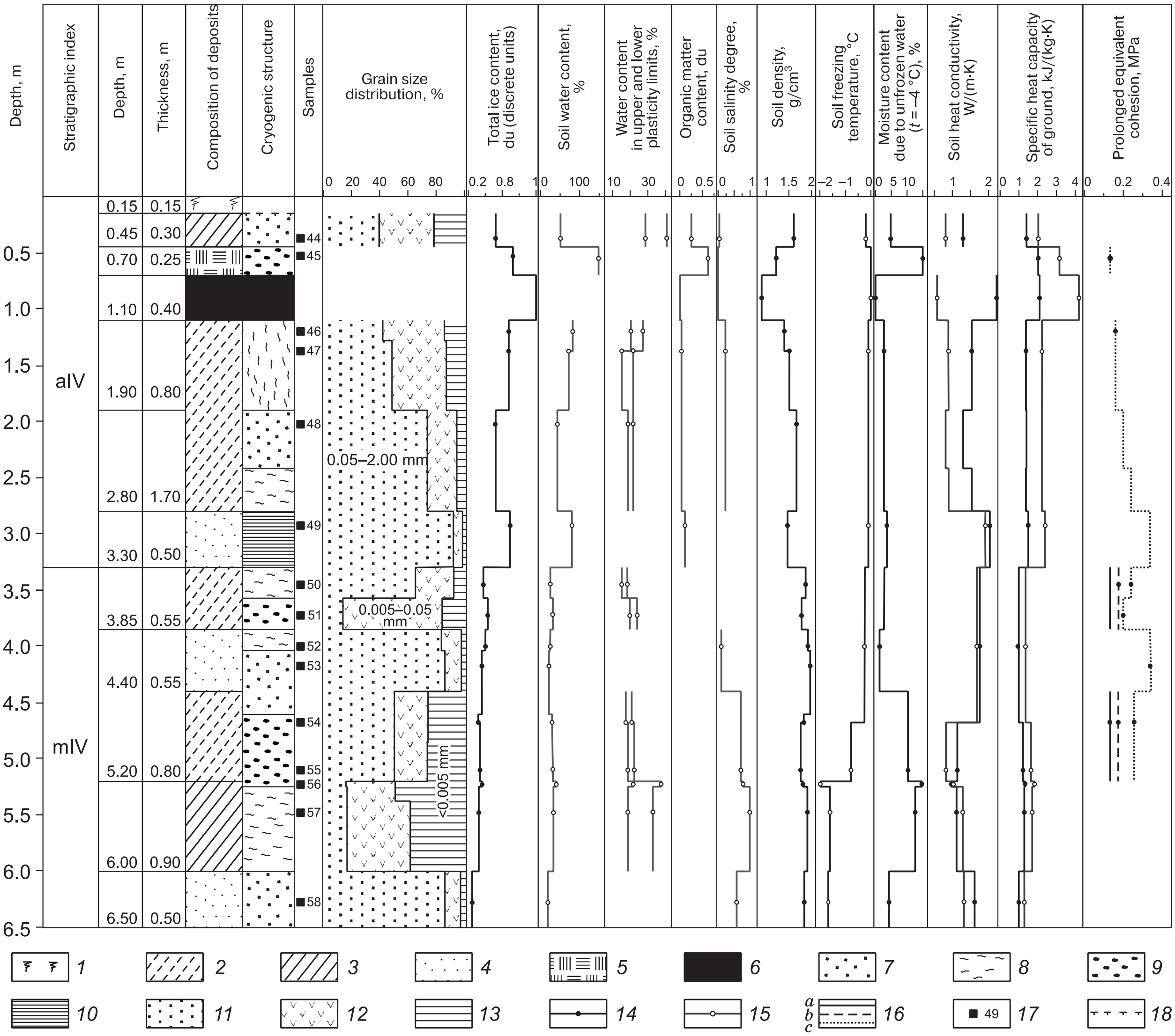

Fig. 13. A section of borehole 3.

1–5 – lithology of deposits (*1* – soil and vegetation layer, *2* – loamy sand, *3* – loam, *4* – sand, *5* – peat); *6* – ice; *7–10* – cryogenic structures (*7* – massive, *8* – lens-shaped, *9* – porphyritic, *10* – flaky); *11–13* – total content of particles (*11* – sand particles 0.05–2 mm, *12* – silty particles 0.005–0.05 mm, *13* – particles less than 0.005 mm); *14* – frozen samples; *15* – thawed samples; *16* – prolonged equivalent cohesion at temperatures of –3, –5, –8 °C (*a*, *b*, *c*, respectively); *17* – sampling point; *18* – borderline between thawed and frozen deposits.

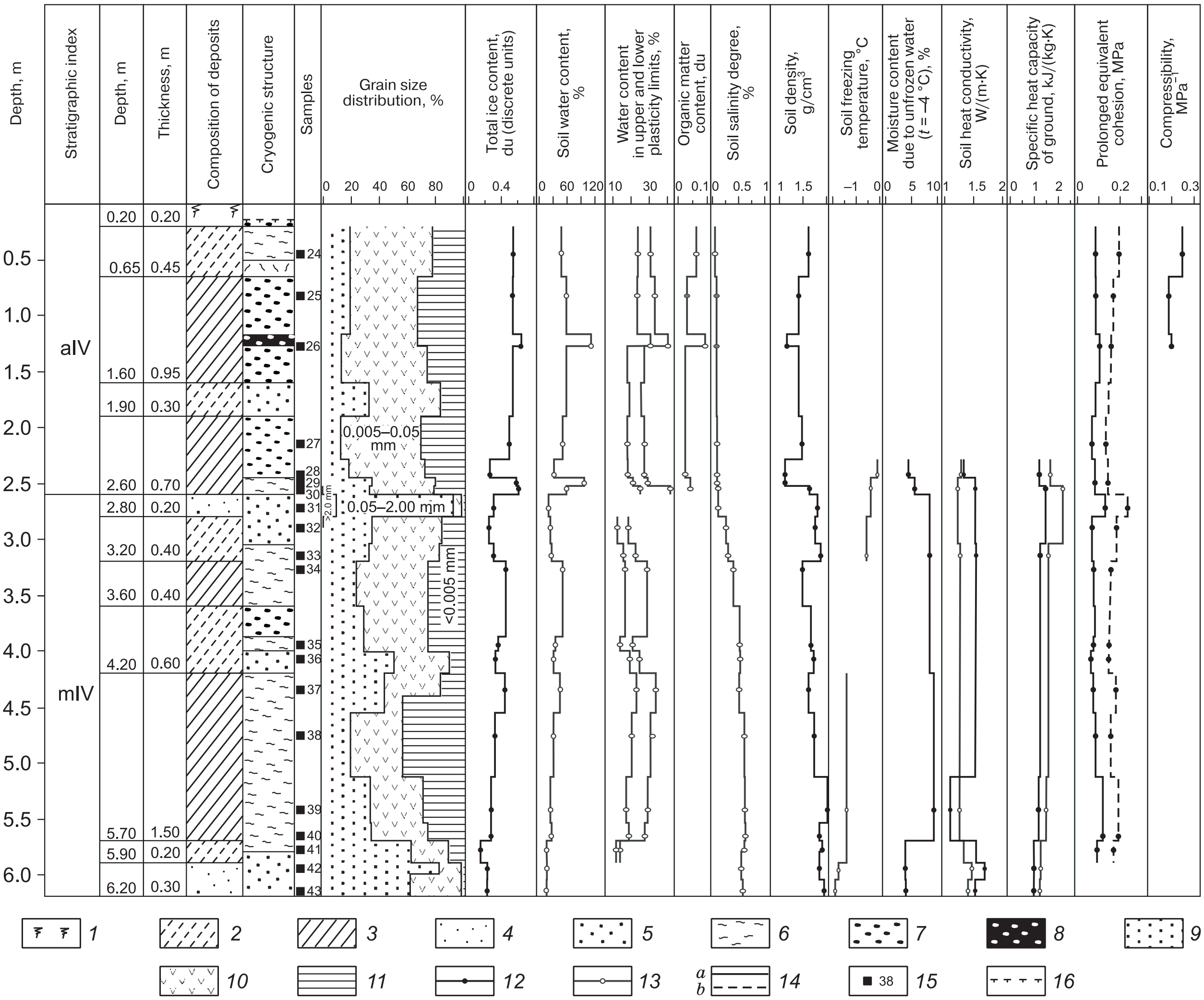

Fig. 14. A section of borehole 4.

1–4 – the lithology of deposits (*1* – soil and vegetation layer, *2* – loamy sand, *3* – loam, *4* – sand); *5–8* – cryogenic structures (*5* – massive, *6* – lens-shaped, *7* – porphyritic, *8* – ataxite); *9–11* – total content of particles (*9* – sand particles sized 0.05–2 mm, *10* – silty particles, sized 0.005–0.05 mm, *11* – particles less than 0.005 mm); *12* – frozen samples; *13* – thawed samples; *14* – prolonged equivalent cohesion at temperatures –3, –5 °C (*a*, *b*, respectively); *15* – sampling point; *16* – borderline between thawed and frozen deposits.

state and up to 1.6 W/(m·K), in the frozen state. In loams λ_{th} = 1.1–1.2 W/(m·K), λ_f = 1.3–1.5 W/(m·K). Reduction in the specific heat capacity was recorded as the depth increased, which is attributed to reduction in the peat prevalence and moisture. For the upper part of the section, primarily composed of loamy grounds and peat, the specific heat capacity in the thawed state varied from 2000 to 3000 J/(kg·K), in the frozen state, from 1400 to 2000 J/(kg·K). Beginning with the depth of 2.8 m. the section became more sandy, i.e., it was primarily composed of loamy sands and sands (Fig. 14); the values of C_{th} varied from 1300 to 1800 J/(kg·K), the values of C_f, from 900 to 1300 J/(kg·K). The equivalent cohesion practically did not change with the depth.

DISCUSSION OF RESULTS

The study of the deposits of the coast of Baydaratskaya Bay showed a great variety of their composition, structure and characteristics. The variancy ranges were revealed for the deposit characteristics, whereas a large amount of the data obtained allowed us to analyze, compare and make conclusions relarding different parameters of the deposits.

It follows from the analysis of the thermal properties of the deposits that the formal division of the deposits into sands, loamy sands and loams, carried out based on the index of plasticity [*GOST 25100-2011, 2011*], may sometimes be conventional. This is manifested, for example, when the thermal conductivity of sandy loamy sands is close to that of silty sand, and that of silty sand is close to the thermal conductivity of light loam (Fig. 10), or when data on unfrozen water in frozen deposits are compared (Fig. 6). As indicated above, loamy sands and loams had different cryogenic textures with visible ice schlieren, and, when thawed, the humidity content of these deposits could be higher than 100 %. The study has shown that, at high values of the volume water content the thermal conductivities of loamy sands and loams are close and are determined by the thermal conductivity of water (λ = 0.56 W/(m·K)). Although specific heat capacity is an additive value, in the case of summarizing all the data for natural loose deposits, the character of its dependence on the moisture content is not linear. As the moisture content increases, C increases, too; however, when the values of the volume water content are higher than 50 %, the heat capacity of the deposit matrix exerts lesser impact on the specific thermal capacity of the deposit than the thermal capacity of water or ice.

Varied as the deposits of the coast of Baidaratskaya Bay investigated are, the obtained results of the study of the thermal properties of the deposits may be summarized for each type of the deposits by one curve with deviations in the values for individual samples, which is related to salinization and the content of organic matter in these variations.

The obtained regularities of variations in the thermal physical properties, the temperature of the beginning of freezing and the content of unfrozen water in the frozen deposits depending on different factors are similar to those described previously [*The phase composition..., 1979; The thermophysical properties..., 1984*]. These data obtained for each individual sample reflect several characteristics, analysis and comparison of which allow the natural variability of the deposits in space and in depth to be evaluated.

The data on salinity and the freezing point of soils allow two deposit strata to be identified in the section of the lower terrace: the upper part is composed of nonsaline deposits of primarily continental origin, while the lower one is represented by saline sandy and loamy sandy deposits of marine origin.

The detailed study of the deposits of the lower terrace showed their broad variety, for example, in the grain-size distribution, ice content, etc., even within several dozens of meters.

The deposits of the upper part of the section (up to the marks of 2 m above the current level of the bay water) differ very much for their dispersity: in the deposits revealed by borehole 3, the sandy fraction prevails, and in the deposits located northwest (borehole 4), the silty fraction is dominant. According to the data presented in [*Baulin et al., 1997*], within the limits of the lower terrace in the upper part of the section, lacustrine-palustrine deposits are common, up to 4–10 m thick. The authors suppose that the deposits here have an alluvial origin but refer to different facies, resulting in different structures and compositions of the deposits.

CONCLUSIONS

Field and laboratory studies have been conducted, the ranges of changes in the characteristics of dispersive deposits have been found, the regularity of changes in the composition, structure and properties of thawed and frozen deposits have been revealed. Connection among all the parameters studied has been identified, as well as their occurrence in space and depth.

- As far as the deposits' grain-size distribution is concerned, the deposits vary from heavy silty loams to medium-grain sands, the greater part of the marine terrace section represented by loamy sands. For all the deposits considered, a high content of large silty particles is characteristic (up to 30–40 %).
- The deposits are characterized by wide ranges of changes in the natural moisture content and density; in loams W_{tot} varies from 19 to 205 % with density of 1.1–1.7 g/cm^3; in loamy sands W_{tot} varies from 9 до 162 % with ρ = 1.2–2.1 g/cm^3; in sands W_{tot} varies from 5 to 90 % with ρ = 1.5–2.0 g/cm^3. For organic grounds, the maximum values of the natural moisture content W_{tot} = 115–955 % have been obtained from varying density from 0.9 to 1.2 g/cm^3.
- Studying the salinization of the deposits in the lower part of the section of the lower terrace has revealed a marine type of salinization. The range of variation of D_{sal} for all the investigated samples was 0–1 %, while the maximum values were found for loams.
- Peated deposits occurred mainly in the upper part of the section, the content of organic matter in sands reached 11 %, that in loamy sands was 15 %, and in loams – 25 %.
- Regularities in the changes of unfrozen water in frozen deposits were revealed depending on the temperature, salinity and the content of peat. The largest amount of unfrozen water was observed in organic grounds, while the lowest amount was found in sands. With the mean annual temperature of the deposits being (–4 °C) W_w in sands varied from 0.5 to 4.6 %, in loamy sands the variation was from 1.1 to 11.5 %, in loams – from 4 to 15.2 %, in peats – from 13 to 40 %.
- Dependences were obtained for changes in the thermal physical properties of grounds on dispersity, moisture content, salinity and the peat content. The highest values of thermal conductivity were established for sands and loamy sands. The thermal conductivity of frozen deposits varied from 0.80 to 2.03 W/(m·K) in sands, in loamy sands it varied from 0.75 to 1.65 W/(m·K), in loams it varied from 0.97 to 1.55 W/(m·K), in peats, from 0.8 to 1.3 W/(m·K). In the thawed state λ_{th} of sands varied from 0.85 to

1.91 W/(m·K), that of loamy sands varied from 0.8 to 1.65 W/(m·K), that of loams changed from 0.8 to 1.57 W/(m·K), that of peats, from 0.38 to 0.6 W/(m·K). The highest values of the thermal capacity were observed in peated deposits of different dispersity.

• The specific heat capacity of the sands was 770–2400 J/(kg·K) in the thawed state, reaching 1500 J/(kg·K) in the frozen state; in loamy sands C_{th} varied from 770 to 2900 J/(kg·K), C_f – to 1620 J/(kg·K); in loams C_{th} varied from 840 to 3150 J/(kg·K), C_f reached 1770 J/(kg·K).

• Evaluation of deposits variability in space and at depths has revealed that the upper part of the section is composed of deposits which are likely to be of alluvial origin, while the lower part is composed of marine saline variations.

The obtained data relating to the composition, structure and properties of the deposits should be used as input parameters in modeling the behavior and the rate of the coast denudation.

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