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CRYOGENIC PROCESSES AND FORMATIONS

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LABORATORY MODELING OF FORMATION OF THE CRYOGENIC STRUCTURE OF MARINE SEDIMENTS

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The article is devoted to peculiarities of formation of the cryogenic structure of modern coastal sediments using laboratory simulation. The authors have conducted comparative analysis of the results of laboratory and field studies and have shown how the cryogenic structure of coastal sediments depends upon the composition, salinity and moisture. They have also analyzed redistribution of soil moisture in different types of soils and the features of ice formation in the zone of contact between shore ice and sea bottom.

Cryogenic structure, ice formation, crystallization differentiation, salinity, water content

INTRODUCTION

Marine cryolithogenesis has been investigated for several decades. This subject is discussed in the works by V.N. Saks [*1953*], P.A. Shumsky [*1955*], E.M. Katasonov [*1962*], N.F. Grigoryev [*1966*], V.A. Usov [*1967*], E.N. Molochushkin [*1973*], F.E. Are [*1976*], I.D. Danilov [*1978*], Ya.V. Neizvestnov [*1983*], B.A. Savelyev [*1989*], L.A. Zhigarev [*1997*], T.E. Osterkamp [*2001*] et al. Nevertheless, this subject is far from being completely covered. The diversity of the granulometric and mineral compositions of marine sediments, the wide range of the values of salinity and water content, different conditions of freezing on land and in shallow waters make it difficult to reveal the general regularities of formation of their cryogenic structure under field conditions. Modeling the cryogenic processes in the laboratory conditions allows these challenges to be met by selecting the characteristics of the used soil samples and the freezing conditions.

This paper presents the results of long-term studies conducted by the authors in the permafrost laboratories of the Production and Research Institute for Construction Engineering and in the gecryology chair of the Lomonosov Moscow State University, Faculty of Geology [*Khimenkov, 1985; Khimenkov and Minaev, 1990; Khimenkov and Sheshin, 1992; Khimenkov and Brushkov, 2003; Khimenkov et al., 2016*].

During the laboratory experiments, typical conditions of ice formation in marine sediments were modeled.

1. Formation of ice in water given a large amount of admixtures and in water-saturated silts with weight water content, 2–3 times exceeding the fluidity limit.

2. Formation of ice in the region of contact between shore ice and sea bottom.

3. Formation of ice in the mass of sea sediments of different compositions, different degrees of salinity and initial water content at downward freezing from above.

FORMATION OF ICE IN MINERALIZED SOLUTIONS AND IN SUSPENSIONS

Primary freezing of sea sediments begins under subaquatic conditions. Therefore, the peculiar features of ice formation in sea water should be considered first. Ice crystals formed in it have a laminar structure. In the course of the crystal growth, dissolved salts become distributed among elementary plates inside crystals and between them (Fig. 1). Such a structure of saline ice crystals and the conditions of their formation were described by P.A. Shumsky in 1955: "In saline ice, brine forms interlayers in the basic planes of the crystals dividing the crystals into a number of plates. The faster crystallization occurred and the greater the salt concentration was, the thicker the brine layers were (reaching several millimeters at the water temperature close to zero) and the thinner were the elementary ice plates relatively separated by them" [*Shumsky, 1955, p. 102*].

Benthic waters are known for the large amount of suspended particles and often have the form of suspensions. Experiments were conducted on freezing of

Fig. 1. The structure of sea ice crystals [*Borodachev et al., 1994*].

distilled water with gradual increase of the admixture concentration (Fig. 2, *a*) [*Khimenkov and Brushkov, 2003*]. Kaolin clay was used as admixture. In the experiments, when the concentration of mineral admixtures in the water was 3.2 % or less, strips began to form in the ice due to mineral inclusions (Fig. 2, *b*). As the concentration of mineral admixtures in the water grew to 13.5 %, parallel chains of soil inclusions were visible (Fig. 2, *c*). The pattern formed by mineral inclusions was similar to the structure of sea ice crystals (Fig. 1). As the share of admixtures increased to 28.3 %, single soil inclusions merged into dark mineral layers divided by strips of transparent ice (Fig. 2, *d*). The planes of the soil layers were oriented

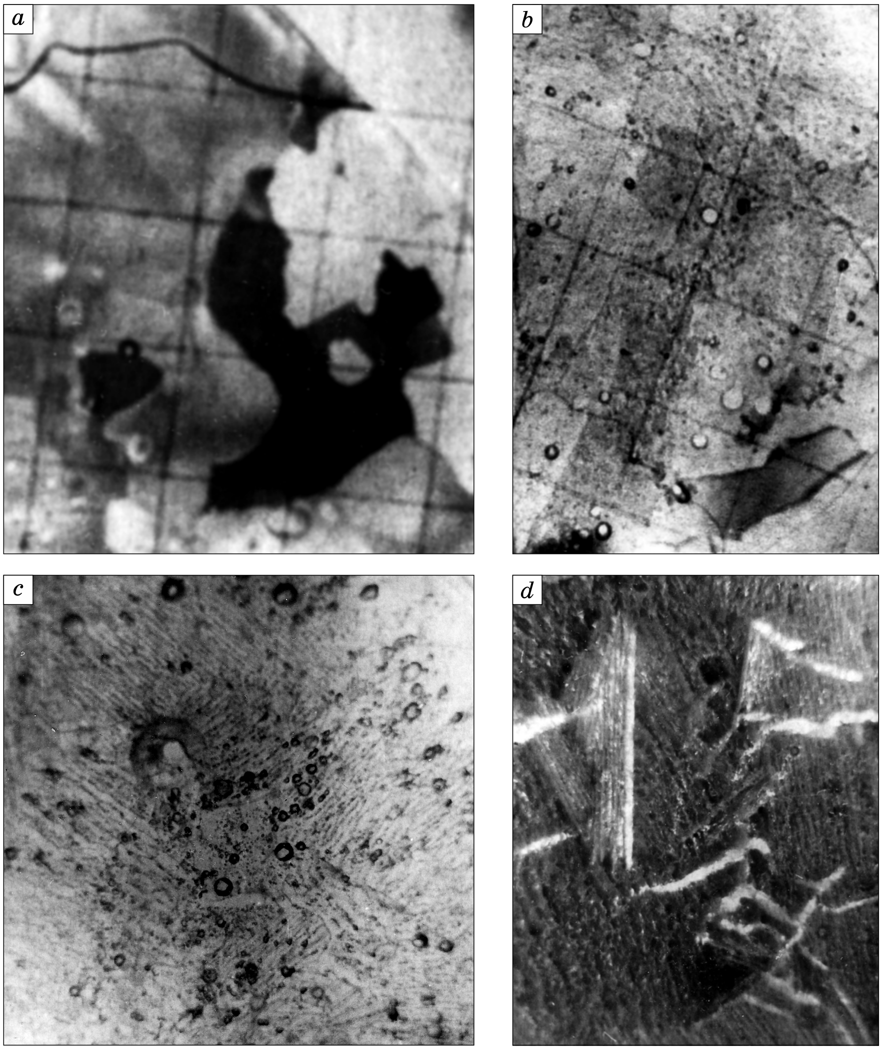

Fig. 2. Distribution of soil particles in ice crystals at different contents of soil admixtures in water:
a – distilled water (a photo taken in polarized light); *b* – 3.2 %; *c* – 13.5 %; *d* – 28.3 %. *(The photo taken by A.N. Khimenkov).*

Fig. 3. The cryogenic structure of a kaolin sample with initial weight water content 156 %:

a – the horizontal cross-section; *b* – the vertical cross-section. *(The photo taken by A.N. Khimenkov)*.

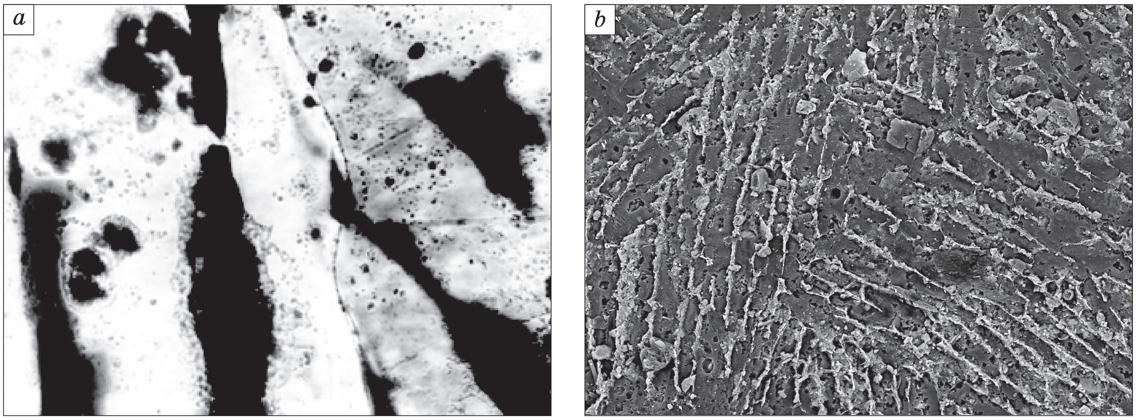

Fig. 4. Crossing the zones of differently oriented soil inclusions:

a – kaolin suspension in polarized light (magnification 45). *(The photo taken by A.N. Khimenkov)*; *b* – sea silt suspension (magnification 600). *(The photo taken by V.V. Rogov)*.

in parallel to the basic planes of the ice crystals (Fig. 3). As the fraction of admixtures increased, both the soil layers and the interlayers of ice became thicker from fractions of a millimeter to 2–3 mm. Each region of alternating parallel soil and ice strips behaves as a single crystal. No internal boundaries are visible in these regions, and they have one interference coloring in polarized light (Fig. 4, *a*). It can be well seen from the photo of a sample of frozen benthic silt of the Sea of Okhotsk, provided by V.V. Rogov, that extended inclusions of salts, mineral admixtures and ice form similar series of parallel layers (Fig. 4, *b*). Thus, when the above media get frozen (seawater, fresh water with different content of clay particles and sea silt, similar processes of redistribution of admixtures in the growing ice occur. Laminar crystals are formed, in which interlayers of pure ice without admixtures alternate in parallel with the basic planes.

FORMATION OF THE CRYOGENIC STRUCTURE OF THE REGION OF CONTACT BETWEEN SHORE ICE AND BENTHIC SEDIMENTS

The shallow riparian part of the sea, where annual ice becomes frozen with the bottom, plays an important role in terms of geocryology. It is there that the factor internal in relation to marine sediments, the process of winter water freezing, begins to act [*Romanovsky, 1993; Osterkamp, 2001*]. A layer of water with increased mineral content with slow water exchange is formed between the growing layer of the shore ice and the bottom in local depressions, due to freezing of the dissolved salts. The mineral concentration rises 1.5–2 times from the initial value to reach 50–80 g/L, with the water temperature being –4...–5 °C [*Solovyev, 1983; Grigoryev, 1987; Bogorodsky et al., 2007*]. This process leads to increased concentration of salts in the upper layer of the sediment. N.F. Grigoryev [*1966*], who studied shore ice in the riparian part of Bolshoy Lyakhovsky Island, reported the following distribution of the mineral concentration of pore solutions in the sea sediment mass. Immediately under the ice cover 1.5 m thick, in the upper 0.5 m layer, the mineral concentration of pore solutions was 43 g/L, at the depth of 3 m, it was 20 g/L, and at the depth of 4.5 m, 5 g/L. This distribution of the mineral concentration of pore solutions results in the fact that ice is not formed in the upper, most saline, sediment layer [*Grigoryev, 1966*]. Below cryogenic textures are formed. When shore ice freezes together with the bottom, the sediment underlying it gets frozen, too, but in this case, ice formation in them is insignificant. The cryogenic structure of this layer is represented by differently oriented, often subvertical, very thin (from fractions of a millimeter to 1 mm) ice schliers 5–7 cm long [*Zhigarev and Plakht, 1977*]. For its physico-mechanical properties, this layer of frozen soil is practically no different from melted solid precipitation. Between the ice schliers, this soil was not cemented with ice at the temperature of –3 °C. Soil particles are easily moved when even slightly touched [*Plakht, 1977*].

In the permafrost laboratory of the geocryology chair of the Moscow State University, we conducted experiments on simulating freezing together of fast sea ice with precipitation [*Khimenkov et al., 2016*]. Unilateral freezing was done through a layer of saline water overlapping soil samples prepared from light loamy silt sampled on the shore of the Laptev Sea. The original water content of the soil samples was about 35 %, initial salinity was 0.7 %, thickness of the water layer was 2 cm with the mineral concentration being 33 ‰. Freezing was downward at the temperature of –9 °C. As a result of the investigation, two types of the cryogenic structure were revealed. The first type of freezing was formed under conditions when the water layer did not completely freeze. There was a layer of mineralized water from several millimeters to one centimeter between the layer of ice and the soil, depending on the duration of the experiment (Fig. 5, *a*, region 2). In this case, due to significant mineral concentration of the pore water, no ice formation was observed in the upper 2-centimeter soil layer (Fig. 5, *a*, region 3). Below it, cryotexture was formed, consisting of thin (about 1 mm) oblique schliers, typical of sea sediments, the crossing of which forms reticular cryogenic texture (Fig. 5, *a*, region 4). After complete freezing of the layer of water, in the upper part (0–1.2 cm) f the soil sample (Fig. 5, *b*, region 3)

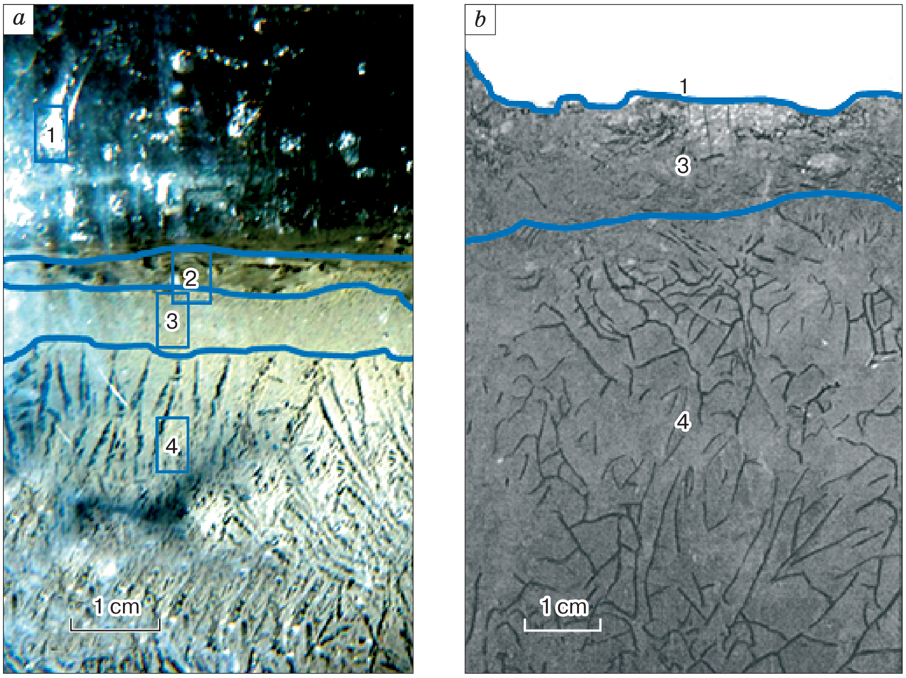

Fig. 5. The cryogenic structure of soils contacting shore ice:

a – the absence of freezing-together of ice and soil; *b* – freezing-together of ice and soil; 1 – ice, 2 – water, 3 – the zone of poor ice segregation, 4 – the zone of formation of cryogenic textures. The soil is light dusty loam. *(The photo taken by V.E. Gagarin)*.

thin-schlier cryogenic texture was formed, having rare chaotically oriented schliers, the soil was in a plastic-frozen state. Below (1.2–4.2 cm), reticular cryogenic texture (Fig. 5, *b*, region 4) was formed, with prevailing vertically oriented schliers up to 1 mm thick and up to 2 cm long.

SIMULATING THE PROCESSES TAKING PLACE IN THE CRYOGENIC SOILS OF MARINE ORIGIN

The following soils were used in the laboratory studies: Middle Pleistocene sea clay of the montmorillonite type (Yamal Peninsula); modern silt of the hydromica composition from the bottom of the Dikson Bay; loam of sea origin of the hydromica composition sampled from the shore of the Kara Sea in the region of the settlement of Amderma; cover loam of primarily hydromica composition from the central part of the Yamal Peninsula; bentonite – monomineral clay of the montmorillonite type; and kaolin clay. The soils selected for the study are typical of rocks of marine genesis spread across the Arctic shore. They are noted for the hydromica and montmorillonite compositions of the clay fraction. Kaolin clay, typical of continental conditions, is included into this group of soils with the mineral composition of sediment accumulation characteristic of marine conditions. Comparison of the processes of forming the cryogenic composition for different types of soils allows us to reveal the characteristic features of ice formation connected with their genesis more precisely. There is a long-lasting tradition of laboratory studies of ice formation in clayey soils by comparing the cryogenic structure of frozen samples of the kaolinite, montmorillionite, and hydromica compositions [*Nersesova, 1961; Zhestkova, 1982*].

In the experiments on determining the impact of the mineral concentration, initial water content and salinity of soils on their cryogenic structure, we used three types of soils: kaolin, montmorillionite clay and modern silt of the hydromica composition. The mineral concentration of their pore solutions is equal to 1 g/L in kaolin, 6.9 g/L in montmorillionite clay and 35 g/L in modern silt. The initial water content varied depending on the values corresponding to the plastic limit, exceeding the flow limit by a factor of 2 or 3 (Table 1).

For each type of soil, the number of samples of different degrees of salinity varied from 9 до 13. Soil salinity varied within the range of 0–2 %. The values of the water content were selected to be close to the upper limit of plasticity. Samples 14 cm long and 7 cm wide were frozen from one side at the temperatures from −4 to −6 °C. The necessary water content was achieved by preliminary compacting of the sample mass. The selected soil compositions, the initial water content, the values of the mineral content of the pore solution, of temperatures and freezing regimes allowed us to simulate a wide range of real conditions accounting for the cryogenic structure of the sea sediments of the Arctic coast.

Table 1. **Values of initial weight water contents (W_0) and freezing temperatures (T_f) of soils**

Soil	W_0, %	T_f, °C
Kaolin	165	−4
	106	−6
	50	−6
	40	−6
Middle Pleistocene sea clay	137	−6
	122	−4
	52	−6
	43	−6
Modern sea silts	128	−6
	55	−6
	39	−6
	30	−6

THE IMPACT OF THE MINERAL COMPOSITION AND OF THE INITIAL WATER CONTENT OF THE SOILS ON THEIR CRYOGENIC STRUCTURE

In the kaolin samples, in which the values of the initial water content were greater than the rolling-out limit and less than the yield limit, soils mostly contained film water (osmotic water). Their migration towards the freezing front is very important for formation of cryogenic structures. As a result, horizontally laminar cryogenic textures are formed (Fig. 6, I, *a*). In the lower part of the samples, a drying zone emerges, having massive cryogenic texture. In the upper part of the samples, the ice content reaches 50–60 %.

When the initial water content grows to reach the values close to the yield limit, gravity water, together with the osmotic water, begins to play a significant role, resulting in a change in the type of ice formation. Just as at the lower water content, migration of the osmotic water towards the freezing front is the leading process. Simultaneously, although at a smaller scale, growth of laminar ice crystals takes place due to the presence of gravity water. They grow into the depth of the soil as subvertical and oblique ice schliers, going ahead the movement of the general freezing front. The thermal conductivity of ice is much higher than that of moist soil; therefore, a subvertical ice schlier, which has grown into the region of the thawed soil, becomes the local center of cooling and ice formation [*Shumsky, 1955*]. This distorts the general picture of the migration flux, directed at the area of lower temperatures. Part of the migration flux deflects to the crystal surface, building it up [*Komarov, 2003*]. The combination of the processes of the growth of subvertically-oriented ice schliers (due to

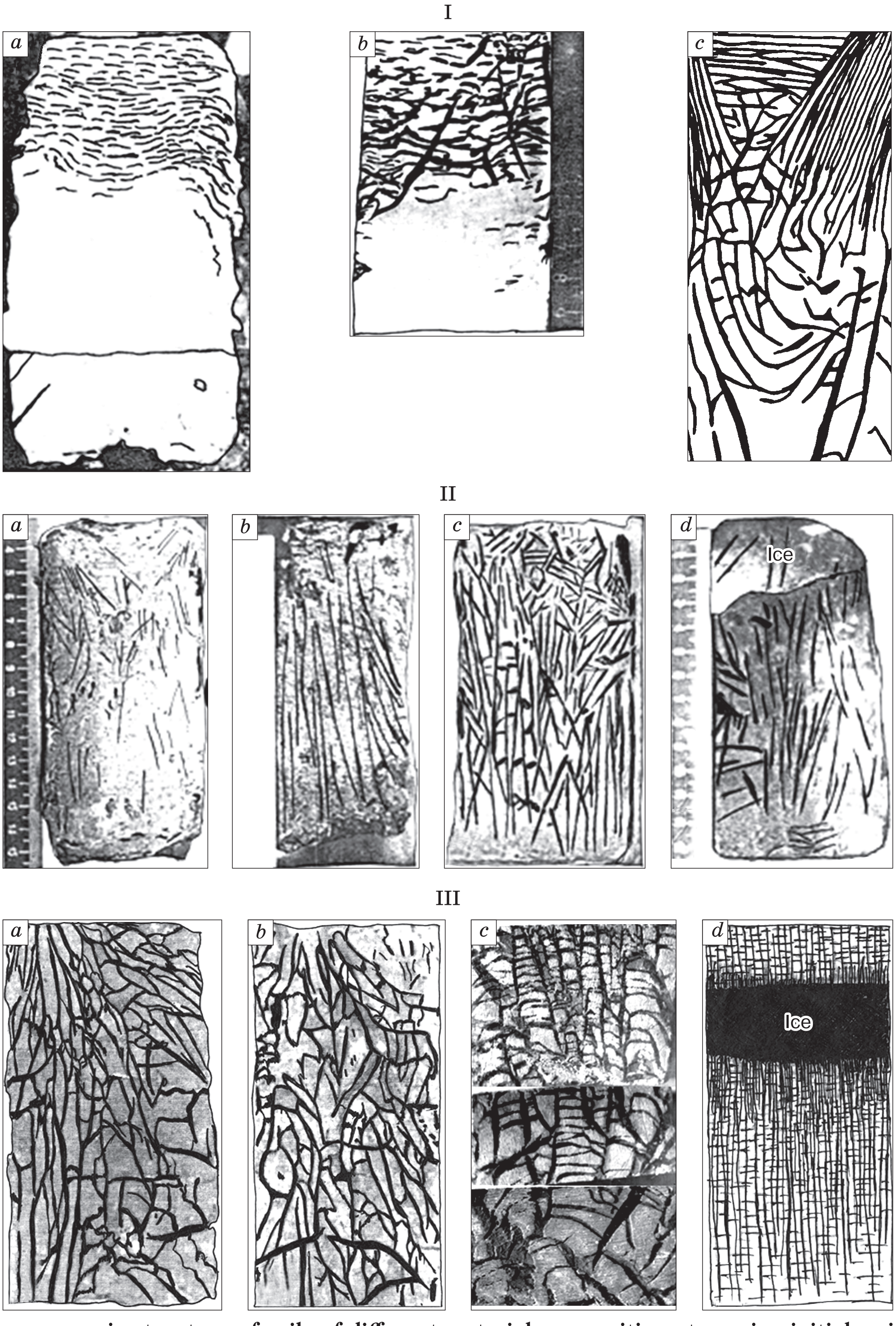

Fig. 6. The cryogenic structure of soils of different material composition at varying initial weight water content:

I – kaolin (W_0, %: *a* – 50, *b* – 106, *c* – 165); II – modern silts of hydromica composition (W_0, %: *a* – 30, *b* – 39, *c* – 55, *d* – 128); III – Middle Pleistocene sea clays of montmorillonite composition (W_0, %: *a* – 43, *b* – 52, *c* – 122, *d* – 137). *(The photo taken by A.N. Khimenkov).*

the presence of gravity water) and horizontal schliers (due to migration of osmotic water towards the freezing front) ensures formation of reticular cryogenic textures in kaolin [*Khimenkov and Brushkov, 2003*].

As the initial water content grows to the values 3 times exceeding the yield limit, the mechanism of ice formation and the type of cryogenic structure change (Fig. 6, I, *c*). In the upper part of the samples, where the ice content reaches 70 %, ice formation is similar to the growth of crystals in suspension or solution. Soil particles become redistributed in accordance with the internal structure of the formed crystals (Fig. 3). Soil inclusions as flat plates up to 1–2 mm thick alternate with the interlayers of ice. In the lower part of the samples, reticular cryotextures are formed, the formation of which has been described above, with prevailing vertical schliers, the ice content is 20–30 %. Total redistribution of the pore water in a sample when freezing is insignificant.

The cryogenic structure of the frozen samples of modern silts of the hydromica composition is practically similar, with vertical and subvertical schliers prevailing (Fig. 6, II) [*Khimenkov and Brushkov, 2003*]. The schlier thickness depends on the initial water content and varies from fractions of a millimeter (at minimum water content values) to 1–2 mm, and the schlier length varies from 2–3 to 12–13 cm, with individual schliers growing through the entire sample. The ice content is proportional to the initial water content and varies from 2–5 % (Fig. 6, II, *a*) to 60–70 % (Fig. 6, II, *c*). No redistribution of water in the vertical direction was observed in freezing (except for the samples with the water content 2–3 higher than the yield limit). In these cases, intense gravity-caused break of suspension takes place, with depositing mineral particles and isolated gravity water. When freezing, a layer of contaminated ice is formed with a large amount of mineral admixtures (the upper part of the sample, Fig. 6, II, *d*). The studies showed the cryogenic structure of the samples of modern silts to be similar to the cryogenic textures of frozen marine sediments occurring in nature [*Usov, 1967; Katasonov and Pudov, 1972*].

No redistribution of water in the freezing process was observed in the samples of the Middle Pleistocene clay of montmorillonite composition. At all the initial values of the water content, reticular cryogenic structures were formed (Fig. 6, III). The size of the soil cells and ice schliers was inversely proportional to the initial water content. At minimum water content, the size of the soil cells was 10–15 mm, whereas the size of the ice schliers was 2–3 mm. When the maximum water content was achieved, the size of the soil cells decreased to 2–3 mm, while the thickness of the ice schliers went down to fractions of a millimeter. At the water content values below the upper limit of plasticity, no redistribution of water in the freezing process was observed. Only at the values of the initial water content 2–3 times exceeding the yield limit, a layer of gravity water was yielded in the upper part of the samples during the freezing process due to gravitation-caused separation of water and soil particles (Fig. 6, III, *d*). As it froze, layers of ice with greater content of admixtures were formed.

THE INFLUENCE OF SOIL SALINITY ON ITS CRYOGENIC STRUCTURE

In non-saline samples of kaolin (the initial water content in all the kaolin samples was 50–60 %), laminar cryogenic textures were formed (Fig. 6, I, *a*). Beginning with the salinity value of 0.05 % and with the laminar textures prevailing, individual vertical schliers appeared (Fig. 7, *a*). As salinity grew from 0.05 to 0.25 %, reticular cryogenic textures were formed, with the increased share of vertically oriented interlayers (Fig. 7, *b*). The total thickness of ice interlayers decreased. At the salinity equal to 0.5–1.8 %, vertically oriented schliers prevailed in the cryogenic structure of the frozen soil (Fig. 7, *c*, *d*) [*Khimenkov and Minaev, 1990*].

In the loams sampled in the vicinity of the settlement of Amderma, the mineral composition of the clay particles was primarily represented by hydromica. In the salinity range 0–0.3 %, laminar-reticular cryotexture was formed, with prevailing horizontal ice layers. The soil was firmly cemented by ice. At the salinity equal to 0.4–1.0 %, the cryogenic structure changed considerably. Together with the increase in salinity, the share of vertical schliers increased, with the size of the ice elements decreasing. The soil was poorly cemented and easily crushed. In the salinity range 1.0–1.5 %, ice layers were hardly visible. Filament-like ice crystals prevailed, as well as individual isometric ice crystals 1–2 mm in size. Even when lightly pressed, soil easily crushed. In the samples with the salinity exceeding 1.5 %, no ice was formed at the freezing temperature (–4 °C).

In bentonite, the increase in the initial salinity from 0 to 1.15 % did not practically affect the formation of the cryogenic structure. In all the cases, the cryogenic structure remained reticular, with the share of vertical ice schliers increasing. Simultaneously with the increase in salinity, firmness of the frozen soil decreased. The mineral composition of bentonite is primarily of the montmorillonite nature; therefore, its cryogenic structure is similar to the structure of Middle Pleistocene clay (Fig. 6, III).

In the Yamal cover loam (primarily of the hydromica composition), laminar-reticular cryotextures were formed in the salinity range from 0 to 0.3 %. In the salinity range of 0.3–1.5 %, the cryogenic texture became of the vertical schlier type.

In the samples of modern saline silts, no redistribution of pore water in the unilateral freezing process

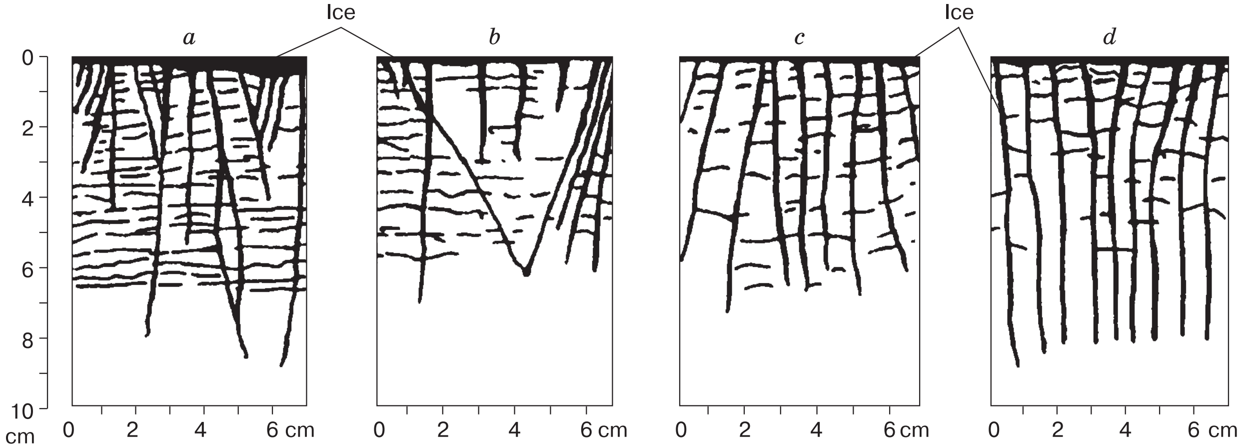

Fig. 7. Change in the cryogenic textures in kaolin depending on initial salinity of the samples:
a – 0.05 %; *b* – 0.25 %; *c* – 0.5 %; *d* – 1.5 %. The freezing temperature T_f = –6 °C, initial water content of the samples W_0 = 46 %.

was observed. Vertical schlier cryogenic textures were formed.

In the samples of sea clays of the montmorillonite composition, no redistribution of water in the freezing process was observed. Reticular cryotextures were formed.

The authors determined the above indicated relation between the cryogenic structure of the soil and the salinity of sediments in natural conditions. In 1986–1988, A.N. Khimenkov and B.N. Sheshin studied permafrost deposits of the lagoon complex (loams of the hydromica composition) in the area of the settlement of Amderma on the coast of the Kara Sea. The materials obtained allowed us to elucidate certain quantitative ties between salinity of sediments and their cryogenic structure (the soil temperature varied from –3 to –6 °C). In loams with salinity of 0.2 % and lower and the water content below 24 %, laminar cryotextures were observed, the mineral particles of which were cemented with ice. At greater salinity of soils, their cryogenic structure changed drastically. At salinity exceeding 0.8 % and the water content equal to 28–51 %, cryogenic textures were not formed, and ice did not cement the mineral particles. Individual crystals or nests of isometric and elongated needle-like crystals several millimeters long grew. Loams had low mechanical durability, were easily broken in hands and preserved plastic consistency even in the frozen state. In sands with salinity equal to 0.1–0.2 % and higher, massive cryogenic texture was formed. At salinity equal to 0.3–1.8 % and higher, the sands were in a plastic or fluid state at the temperature from –3 to –6 °C, formally being frozen, as individual ice crystals several millimeters in size were visible in them [*Khimenkov and Sheshin, 1992*].

The studies conducted allowed us to determine certain quantitative dependences of pore water on salinity at unilateral freezing of soils of different composition. For all the soils used in the experiment, a common trend was observed, which was expressed in attenuation of the migration flux as salinity increased. Shown in Fig. 8 are the results of studying the influence of salinity on redistribution of pore water at unilateral freezing of kaolin clay (the temperature of complete freezing –6 °C) with initial water content of about 40 % (in the plastic state). As a parameter characterizing the final redistribution of pore water, the authors used the difference in the values of the total water content between the upper zone of the frozen sample, which contained the large fraction of ice, and the lower zone, which was most dried. Thus, we were able to analyze the general variation in the initial water content in the course of unilateral freezing. The influence of salinity on migration of pore water was shown to vary much. At salinity 0–0.05 %, this influence proved to be the highest, and the variance between the water content values was 70–80 % (as salinity changed by one hundredth of per cent, the water content changed by 14 %). At salinity equal to

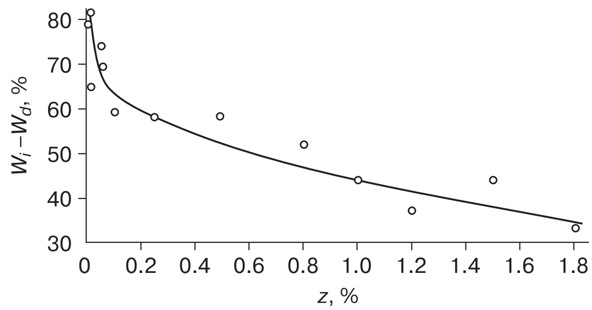

Fig. 8. Dependence of the value of distribution of the weight water content (W_i – W_d) on initial salinity *z* at unilateral freezing of the kaolin samples.

W_i, W_d – weight water content of the ice-rich zone (the upper part of the samples) and of the dry zone (the lower part of the samples), respectively.

0.05–0.25 %, the difference between the water content values reduced to 60 % (the change in salinity by 0.01 % resulted in a 3 % change in the water content). At salinity equal to 0.5–1.8 %, the water content changed by 20 % (the change in salinity by 0.01 % resulted in the change in the water content by less than 0.2 %) (Fig. 8) [*Khimenkov and Minaev, 1990*].

DISCUSSION OF RESULTS

The experiments conducted have shown that at the values of the water content exceeding the yield limit the mineral composition of the soil plays a secondary role in formation of the cryogenic structure. At the initial water content values 2–3 times exceeding the upper yield limit, redistribution of the soil particles by the growing ice crystal is the leading process. It either redistributes the soil particles inside or pushes them to its borders. Admixtures inside the crystal are distributed in parallel with the basic planes. Laminar formation of the crystal, or, to be more precise, of the crystal aggregate, takes place. When the initial water content decreases but remains to be higher than the yield limit, vertical schlier cryotextures are formed. In both cases, the presence of gravity water in the ground is the major prerequisite for the ice crystals to grow.

When the initial water content decreases to the values corresponding to the yield limit and below it, the material composition of the ground begins to play the major role in formation of the cryogenic structure of the sediments. At this water content, kaolin is characterized by reticular cryotextures, growing in two stages, and modern silts of the hydromica composition are characterized by laminar and reticular cryotextures formed due to growth and crossing of subvertical schliers.

Reticular cryotextures are formed in the sea clays of the montmorillonite composition in the wide range of the initial water content values. This process is caused by syneresis, at which compact ground aggregates are formed with water yielded among them. The higher the initial water content of sediments is, the more intense is the formation of cracks, with the total insignificant reduction in the amount of soil [*Gorkova, 1965*]. In cooled sea sediments, the syneresis processes occur more intensely than at positive temperatures [*Maslov, 1988*]. The formed network of fractures penetrates the rock before the beginning of ice formation [*Ershov, 2002*]. In the course of freezing, ice segregation takes place primarily in the formed fractures, with reticular cryotextures formed [*Khimenkov, 1985; Khimenkov and Brushkov, 2003*].

In the samples of modern silts of the hydromica composition in the large ranges of the initial water content values, ice schliers formed the cryogenic structure, having vertical and subvertical orientation. Redistribution of the water content in freezing was insignificant. Such specific ice segregation in silts is primarily attributed to their high salinity.

The leading process in soil freezing is migration of osmotic water to the freezing front. The formed cryotextures serve as the major indicator of the migration conditions [*Popov et al., 1985*]. In our experiments, this process played a significant role only for non-saline samples of kaolin at the initial water content values less than the plasticity limit. Salination of soil samples exerts essential influence on the processes occurring in them during freezing. Interacting with pore water, water-soluble salts, to which sodium chloride belongs, form electrolyte, which disorients the molecules of osmotic water, forming the envelope of the soil particles [*Elovskaya et al., 1966*]. In freezing, this results in the fact that in saline soils the role of the film mechanism of migration of osmotic water decreases, and migration itself reduces. Under these conditions, the growth of crystals occurs similarly to the way it happens in gravity water. Due to anisotropy, among the emerging primary ice crystals, those prevail which are oriented by their basic planes in perpendicular to the freezing front. In this case, we observe similarity between the processes of ice formation in saline soils of different compositions and in sea water.

The cryogenic structure of sediments contacting shore ice under natural conditions is similar to the structure of saline water-saturated soil samples, which were frozen through a layer of mineralized water. Subvertically oriented schliers develop, the crossing of which forms reticular cryogenic textures. The difference between the mineral compositions is insignificant, soil is not cemented with ice at negative temperatures, and soil particles become easily shifted at slight pressing.

CONCLUSION

The studies conducted allowed us to reveal certain common regularities of the impact of the initial water content and salinity of different soils on formation of their cryogenic structure at unilateral freezing. At the water content values greater than the upper plasticity limit and lower than the yield limit in non-saline samples, cryogenic textures are formed, conditioned by the composition of the soils: in kaolin, they are horizontally laminar, in sea clay of the montmorillonite composition, they are of reticular nature, and in the loams of the hydromica composition, they are laminar-reticular (with vertical layers prevailing). At the water content values greater than the upper plasticity limit and at increasing salinity, the proportion of vertically oriented schliers increases.

In the course of the experiments, certain quantitative relations were disclosed between the initial salinity of soil, its cryogenic structure and redistribution of pore water in the process of freezing. Laminar cryogenic textures are formed in non-saline kaolin samples. The variance between the values of the weight water content in the icy and dried zones is 70–80 %. Beginning with salinity of 0.05 %, with the generally prevailing laminar structures, vertical schliers are formed. As salinity grows from 0.05 to 0.25 %, reticular cryotextures are formed with the increasing fraction of vertically oriented schliers. Redistribution of the water content in a sample after freezing results in water content reduction reaching 60 %. At salinity of 0.5–1.8 %, subvertical orientation of the ice schliers prevails in the cryogenic structure of the frozen ground. Water redistribution amounts to 30–40 %.

Similarity of the processes of formation of ice crystals from solutions and suspensions has been ascertained. In both cases crystal aggregates are formed with alternating layers of pure ice and admixtures. The planes of the admixture and ice layers are parallel to the basic planes of the crystal aggregates.

Details of formation of the cryogenic structure of the sea sediments in the zone of their contact with the shore ice have been revealed. A layer of water having a negative temperature and increased (compared to initial) mineral content is formed between the shore ice and the surface of the sediment. Thickness of the layer of water was found to be determined by the ratio between the mineral content of water and its temperature. Thickness of the layer may vary from dozens of centimeters to fractions of a millimeter. In the upper part of the sediment adjacent to the layer of water, ice is either not formed or filament-like crystals are observed. Cryogenic textures develop below with prevailing subvertically oriented schliers.

Formation of ice-rich horizons in the upper part of epigenetic permafrost sea sediments is normally attributed to migration of osmotic water to the freezing front [*Dubikov, 2002*]. It is to be pointed out that these sediments are quite saline, with clays of montmorillonite composition well developed there. The experiments have shown that these factors have a negative impact on the migration properties of soils. The distribution of ice in epigenetic frozen soils of marine origin can be well explained by typical distribution of water in subequal sediments without attracting the migration mechanism.

The cryogenic structure of diacryogenic permafrost soils on the Arctic coast is primarily represented by subvertical oblique laminar cryogenic textures. It is believed that their formation is caused by lateral freezing from the coast. Elongated schliers are situated in parallel to the freezing front [*Katasonov, 1962*]. This type of cryogenic structure was obtained during laboratory studies involving freezing from the top of saline and water-saturated soils of different compositions without any lateral impact. In the authors' opinion, many specific features of the cryogenic structure of the coastal-marine sediments may be explained by common freezing of water-saturated sea sediments on the top of the water under conditions of variable depth of the sea.

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