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FROST MOUNDS OF BELY ISLAND IN COASTAL MARINE SETTINGS OF THE KARA SEA

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This paper presents the pioneering study of the morphology and structure of frost mounds on Bely Island in the Kara Sea, which also includes radiocarbon dating of peat and determinations of carbon isotope composition of peat and gas inclusions in ice, crystalline structure of ice, and sediment particle size distributions. By their shape, the identified frost mounds are grouped into cone-shaped, toroid-shaped, thaw-weakened frost mounds crosscut by polygonal network, and perennial flat-topped palsas with ice core. Modern palsas are distributed in laida zones regularly flooded by sea waters. Cone- and toroid-shaped frost mounds represent relict permafrost landforms developed in the Late Holocene. Relict frost mounds in Western Yamal and on the Arctic islands can indicate coastal-marine settings of their growth on low elevations in the Late Holocene.

Palsa, thaw-weakened frost mounds, age of peat, gas composition, crystalline structure of ice, granulometric composition of sediments

INTRODUCTION

Frost mounds bear the evidence of cryogenic exogenous processes whose impacts appear hazardous for engineering facilities and economic infrastructure in the permafrost zone. In the last century, most researchers [*Popov, 1965, 1967; Dostovalov and Kudryavtsev, 1967; Vasil'chuk et al., 1983; Vasil'chuk and Lakhtina, 1986; Trofimov et al., 1989; Romanovsky, 1993; Vasil'chuk et al., 2012*] believed that the permafrost zone in the northern Western Siberia equally as the present-day environments was lacking favorable conditions for the formation of perennial frost mounds in the Holocene. Largely accounted for by severe climate, this fact was linked to the high rate of freezing, low thickness of the active layer, and too little moisture, to form a core of ice. Perennial frost mounds designating the southern boundary of the permafrost zone [*Vasil'chuk, 2013*] are widely distributed on Yamal, Gydan and Taimyr peninsulas [*Yevseev, 1975; Vasil'chuk et al., 1983, 2008, 2013*]. Given that data on the occurrence of frost heaved mounds on islands in the Arctic tundra zone are available from very few publications [*Belorusova and Ukraintseva, 1980; Alexanderson et al., 2002; Roujanski, 2008; Kasymskaya, 2014*], they have scarcely been studied on Bely Island [*Vasil'chuk Yu.K. and Vasil'chuk A.C., 2015*].

Frost mounds are differentiated by: duration of their existence (seasonal and perennial); size and shape; composition and ice content of sediments; mechanisms of the formation of ice (resulting in injection, migration, or mixed (pressure-migrational) cryogenic structures). Large and small frost mounds are generally confined to relief depressions – low terraces, hasyreys, laidas and inundated river deltas [*Mackay, 1973; Yevseev, 1975; Seppälä, 1980; Yershov, 2002*].

STUDY AREA

Minor prominent terrain features, or frost mounds (palsas) (Fig. 1), were discovered in the northwest of Bely Island in 2015. With absolute elevations ranging between 0–12 m a.s.l., the relief of the island is described as low-lying, leveled, whose geomorphological elements include shoals, beach, laida, floodplain, first (3–7 m a.s.l.) and second (6–12 m a.s.l.) marine terraces (1st MT and 2nd MT) (Fig. 1). The lowlands are flooded by the sea during tides, storms, surges, which is evidenced by the driftwood. As can be concluded from the data available from (www.rp5.ru), Bely Island is characterized by a long winter season of 6 months, summer lasting 2.5–3 months, and short transition seasons (observations over the period of 2009–2015). Mean annual air temperature ($t_{m.air}$) is –10.2 °C; January $t_{m.air}$ is –24.4 °C; $t_{m.air}$ for August is +5.3 °C. Steady transition of average daily temperatures through 0 °C to below temperatures occurs around 30 September. The average precipitation is 258 mm/year, with the snow cover depth increasing from 11 cm in October to 50 cm in early May. The snow starts thawing intensely in June at $t_{m.air}$ = –1.3 °C (www.rp5.ru).

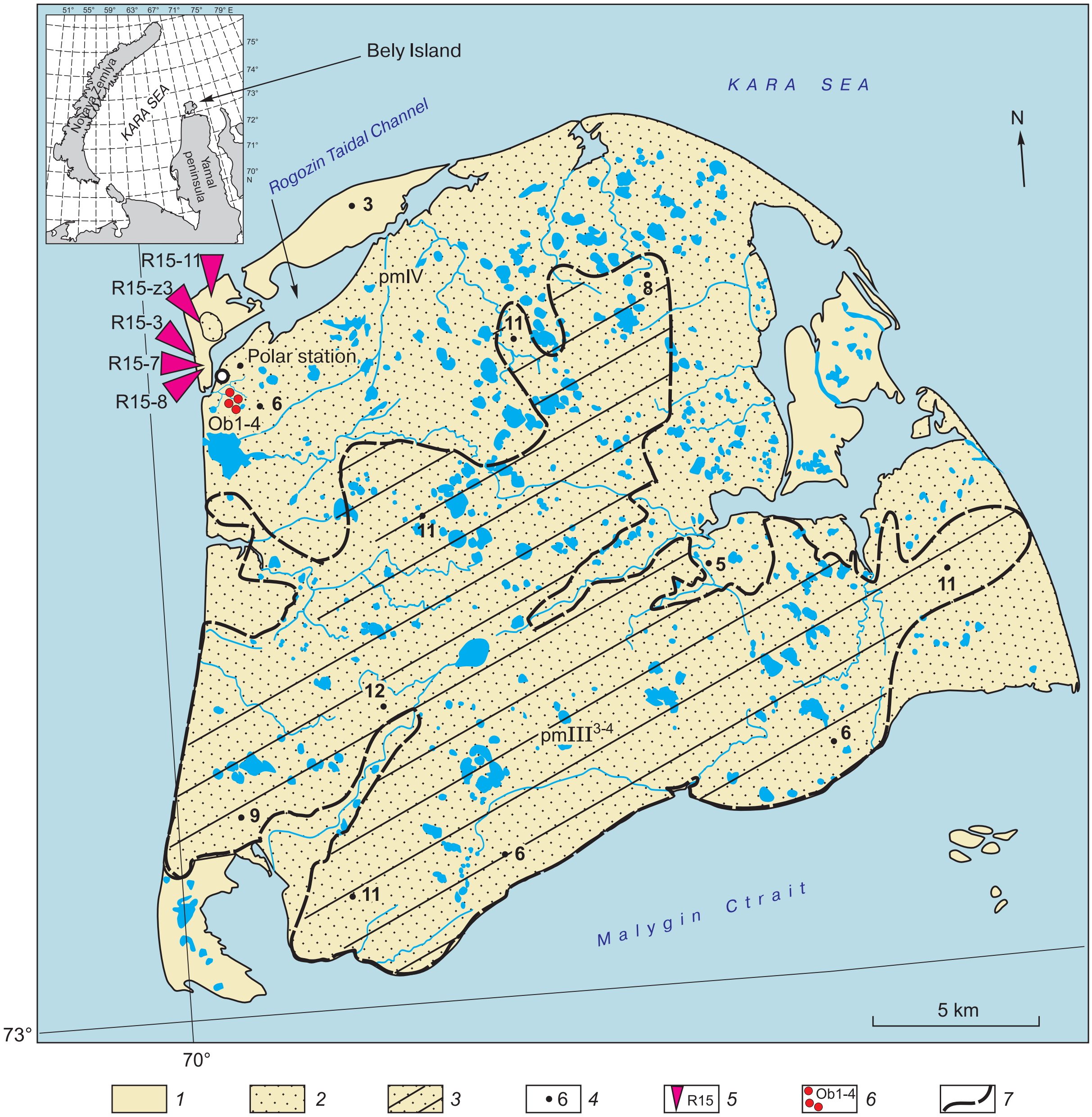

Fig. 1. Map of the study area showing the location of cleared sites:

1 – laida, beaches, inundated deltas and islands adjacent to Bely Island; *2* – Ist coastal-marine terrace (pmIV); *3* – IInd coastal-marine terrace (pmIII$^{3-4}$); *4* – elevations relative to sea level (absolute elevations); *5* – cleared site and its number (No.); *6* – wells drilled in 2010; *7* – speculative boundaries of geomorphologic levels.

Geological structure and geocryological conditions of Bely Island. Paleogene clays with interlayers of sandstones, siltstones of the Tibeisale Formation (thickness: 130 m) and Quaternary deposits are encountered within the Cenozoic sequence (in total 230 m thick) [*Bro, 1986*]. By analogy with Northern Yamal, there have been identified Upper Neopleistocene–Lower Holocene silty-sand (sand loam)-sandy, clayey-silt (clay loam) marine sediments of the 2nd MT and 1st MT with thickness reaching 20 m, and syngenetically frozen Holocene silty sands interlayered with silty sand, clayey silt and allochthonous peat composing laida and watercourse valleys [*Dubikov, 2002*].

The permafrost thickness derived from temperature measurements was found to be 350 m [*Bro, 1986*] on the 2nd MT of Bely Island. According to other sources, much like on Yamal, the permafrost thickness is assumed to be up to 240 m on the 2nd MT in the eastern part of the island, and 65–165 m on the 1st MT in the western part. Permafrost thickness along the coastline is 2–10 m, while that of underlying the interior part of laida is 80 m [*Trofimov et al., 1987; Badu, 2011*].

Permafrost temperatures estimated for Bely Island also differ. According to *Yu.K. Vasil'chuk and A.C. Vasil'chuk* [*2015*], the permafrost temperature increased from –8.5 to –6 °C in the period from 1972 to 2009 on the 1st MT at a depth of 9–10 m, while on laida it was as low as –3.7 °C at a depth of 2 m, in 1978. According to well measurements at the 7–10 m depth interval in 2009, permafrost temperature ranged between –8.7 and –12.2 °C at elevated sites on the 1st MT, and in stream valleys averaged –4.2 °C [*Leibman et al., 2011*]. The thaw depth constituted up to 0.3 m on laida and 1st MT beneath the 0.1 m thick moss cover [*Vasil'chuk Yu.K. and Vasil'chuk A.C., 2015*]. The active layer thickness measured during 2015, reached 0.2–0.3 m on marshy laida overlain by the peat cover.

The vegetation cover of Bely Island is governed by the low-lying poorly drained terrain and is representative of a boreal subzone of the Arctic tundra. Marshes, lake depressions and watercourse valleys are dominantly overgrown by gramineous-cotton grass, hypnotic, sphagnum-hypnoid communities, while grassy-cotton grass-mossy, willow-wood rush-racomitrium-lichen and rarely grass-willow-sedge-moss tundra are widely spread on flat beach ridges and drained slopes of the 1st MT. The beach ridges are generally colonized by spotted-fissured motley grass-willow-racomitrium – gymnomitriaceae tundras with widely developed low polygonal relief and *Racomitrium lanuginosum* fringe-moss. The halophytic meadow communities have developed on a flooded laida environment within the valleys of watercourses [*Walker et al., 2009*].

RESEARCH METHODS

An expedition to Bely Island included routes capable to enable the study of landscape features, botanical composition and seasonal thaw depth, exogenous geological processes. Conductivity/TDS-meter DIST-4 was used to measure electrical conductivity, as well as palustrine and lacustrine water salinities. The detailed morphological and lithologic descriptions were derived from the five sections of sediments composing frost mounds and included particle size distribution analysis on 16 samples with Malvern 3000 laser particle size analyzer, coupled with the study of the chemical composition of air bubbles occluded in ice, and crystalline structure of ice from thin sections. Isotope mass spectrometry analysis was done with DELTA-V Advantage complex for five peat samples from frost mounds, to determine their carbon isotopic composition (^{14}C, ^{13}C, ^{12}C). The sediment samples were subjected to radiocarbon dating by liquid scintillation counting method with Quantulus spectrometer-radiometer at Tomsk Common Use Center SB RAS. The age calibrated against $\delta^{14}C$ prior to calculating, with isotope fractionation taken into account (with 16 years correction for each 1 ‰ $\delta^{13}C$ to the –25 ‰ standard for wood) [*Vagner, 2006; OxCal Program, 2016*].

RESULTS OF THE STUDY OF FROST-HEAVE MOUNDS (PALSAS) ON BELY ISLAND

Palsas were discovered on a smaller low-lying elongated island with absolute elevations of 3.5 m, separated from Bely Island by the Rogozin tidal channel. This islet includes laida, beaches, drained stretches of streams, with the lowered outlier, probably, of 1st MT in the south-west (Fig. 1).

Morphology of palsas. Palsas 0.5–1.2 m in height, with a diameter from 1.0 to 8.0 m, are differentiated by their shape into four types:

Flat-topped peat mounds (peat plateaus) are 0.7 m in height, from 2.0 to 8.0 m in diameter, have an ice core and are covered with peat and dead vegetation (cleared site R15-z3). Surrounded by a 0.2–0.5 m deep waterlogged hummocky bog with open water patches, peat plateaus are confined to a lake-dotted and saline laida with elevations of 1.0–2.5 m a.s.l. which is annually flooded by the sea during storm surge episodes (Fig. 2, *a, b*), with pieces of driftwood carried by tide (weathered tree trunks) unevenly scattered throughout the site.

Cone-shaped, separately standing undisturbed frost mounds (cleared site R15-8) appear regular in shape, 0.6–0.8 m in height, 2.7–3.0 m in diameter, and have a pedestal (step) of 0.3 m in height and 0.7–0.9 m in width. The pedestal is overgrown by the vegetation represented by grass-moss communities, and dense moss-lichen cover on the mound slopes. The summit of the peaty mound bears the evidence of disturbance exhibiting randomly oriented narrow (5–10 cm) open fissures, from 0.3 to 0.5 m deep. As such, these mounds are not infrequent on higher terrain landscapes and on the slope of the terrace outlier with elevations of 3.0–3.5 m a.s.l. and are confined to water-filled depressions with developed slightly saline sedge-moss and grass-moss swales (Fig. 2, *c, d*).

Toroid-shaped frost mounds are round or oval, irregular-encircled features prominent in the terrain and are 0.5–0.8 m in height, 1.0–5.0 m in diameter, and up to 0.5 m in width. Their central portion is typically hollow, with both encircling ridge and pedestal jacked upwardly (cleared site R15-7). These features often contact with each other, to form chains or elongated ridges (Fig. 2, *e, f, i*). The vegetation on the encircling rings is represented by a lichen-moss cover

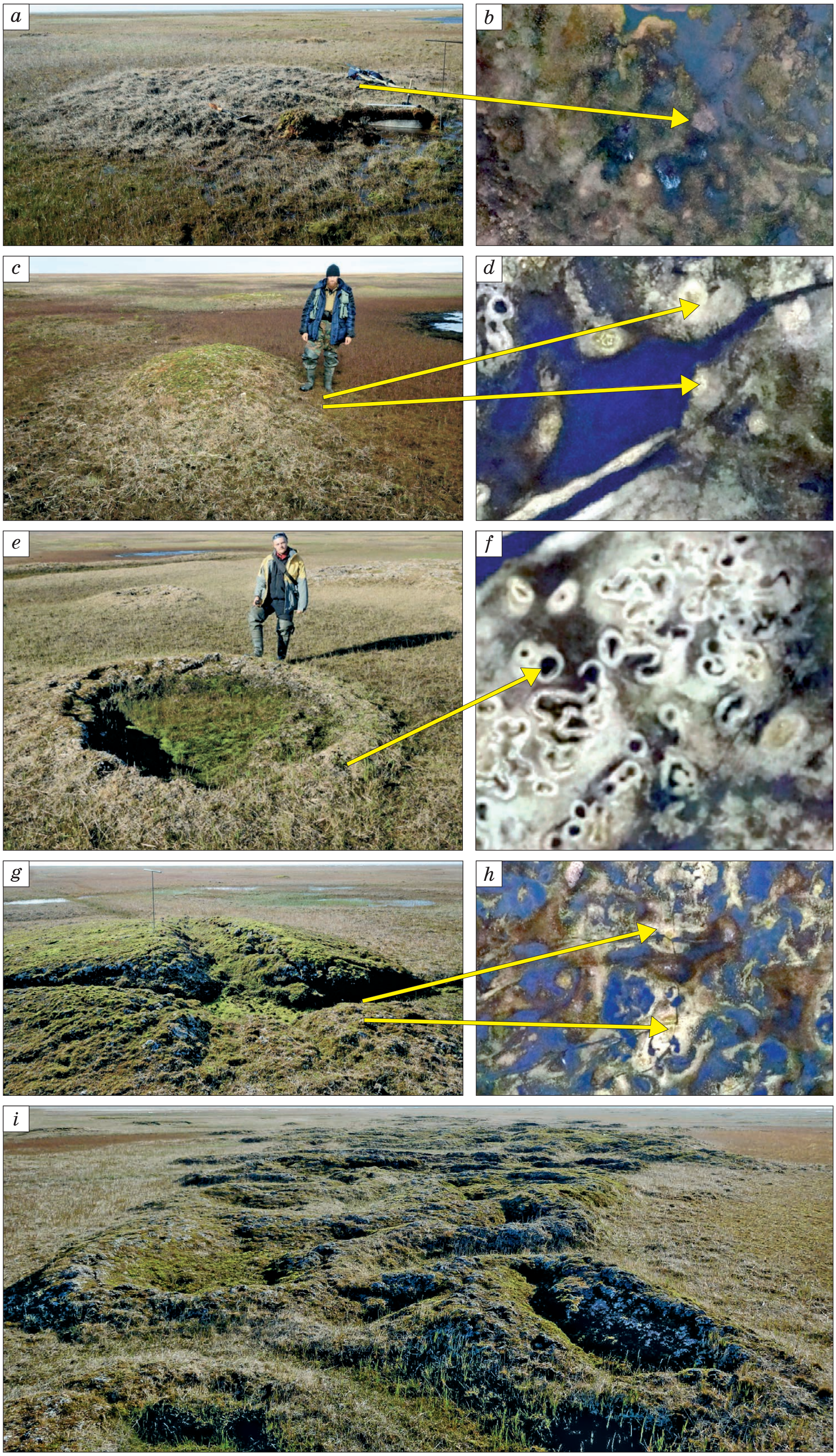

Fig. 2. Morphotypes of frost mounds on Bely Island:

a – flat-toped peat plateaus, with a core of ice; *c* – cone-shaped; *e* – toroid-shaped; *g* – subsided along ice wedges; *i* – ridges of toroid-shaped mounds; *b*, *d*, *f*, *h* – multispectral aerial photographs (AFS) scaled 1:500 (as of 2015) of frost mound types. Photograph by P.T. Orekhov.

dominated by lichens (projective coverage is 70 %). The collapsed central portion of the mound separated from the encircling rings by gaping concentric fissures is covered overwhelmingly by green mosses (projective coverage is 100 %). The moss cover thickness at the crests of circular ridges is 0.5 cm, which is 5 cm on their sides. Moss is underlain by the 3–7 cm thick layer of peat on the encircling ridges, which is up to 10–15 cm in the center of the subsidence. This type of mounds is most likely observed in the upper part of the slope drained along polygonal network, with their elevations reaching 3.5 m above sea level, and in drained bogs.

The second and third types of frost mounds are localized in zones lying above the locations of contemporary driftwood, i.e. not regularly inundated by the sea.

Polygonal peat plateaus are up to 1.2 m in height, 3.0–7.0 m in diameter, with a moss-lichen cover, are crosscut by up to 0.5 m deep ditches, dividing the mounds into 2, 3 or 4 parts. The peat plateaus are surrounded by a slightly saline swale with swampy hollows in the flat-lying lowered laidas with elevations of 1.5–2.5 m above sea level (Fig. 2, *g*, *h*).

Structure of frost mounds. The deposits of beach, outlier of 1st MT and flat-topped, cone- and toroid-shaped palsas were exposed as the sites were cleared.

In the section of a flat–topped peat plateaus with ice-cored palsas (cleared site R15-z3, Fig. 3, *A*), the 0.1–0.2 m thick peat layer is underlain by ice in the central portion of the mound, while water-saturated thawed and frozen peat and dark gray silty sand occur on the edges of palsas. The core of ice has a distinctly columnar partitioning closer to the surface, which makes it “mushroom shaped” (Fig. 4, *a*). The ice contains scattered inclusions of small plant debris. The crystalline structure of ice is vertically stratified, showing vertically elongated crystals, 1.0–1.5 cm in width. On their edges and inside, the crystals abound with gas bubbles of isometric (~0.5 cm) and elongated (up to 1 cm in length, ~0.3 cm in diameter) shape, as well as chains of elongated bubbles (Fig. 4, *b*, *c*).

The chemical composition of gas occluded in ice determined by M.D. Zavatsky revealed the following components: CO_2 ~1.17; O_2 ~15.71; N_2 ~74.91 as volume percent (vol.%); hydrogen ~ 0.0009, methane ~ 7.35 vol.%; admixtures of propane, isobutane, n-pentane. According to other determinations by K. Knoblich (University of Hamburg, Germany), methane was found to have $\delta^{13}C$ at –61.88 ‰.

The section of a cone-shaped palsa (cleared site R15-8, Fig. 3, *A*) exhibited black and gray sands with cryoturbations are sandwiched between the peat cover with its thickness increasing from 0.01 to 0.3 m from top to the periphery and a lens of ferruginized sand gradually pinching out to the mound edges which, in turn, is underlain by a biconvex lens of light gray sand and interbedded water-saturated sands, gray silty sand with involutions. Frozen deposits occur at a depth of 0.65 m beneath the mound summit, and underlie the circular ridge and pedestal at 0.4–0.5 m below surface. The radiocarbon-dated age of peat at the summit is 546 ± 88 years, and 370 ± 71 years at the periphery (Fig. 3, *A*, Table 1).

In the section of the toroid-shaped frost mound (cleared site R15-7), peat was dragged down from the collapsed summit to a depth of 0.5–0.6 m. The mound is composed of thawed sands and silty sands with folded lamination as is evidenced by involutions and numerous spots of ferrugination. In the marginal parts of the frost mound, the layers are jacked up, whereas in its middle they are subsided, exhibiting a remarkably hollow portion in place of the melted out core of ice.

The thaw depth on the periphery of the mound is 0.5–0.8 m, and 0.8–1.2 m beneath the collapsed central portion. Older peat (664 ± 97 yr BP) overlies the circular ridge of the toroid-shaped mound at a depth of 0–0.1 m, while the younger peat (622 ± 90 yr BP) in the subsided part occurs at a depth of 0.6 m (Fig. 3, *A*, *B*, Table 1) as a result of ice core melting out during summer. Given that modern mosses continue to grow in the hollow portion above the subsidence, the crumpled peat is likely to be rejuvenated.

The section of the terrace outliers (cleared site R15-3, Fig. 3, *A*) exhibits sands with roots of modern plants atop and parallel shallow close-grained stratification, with lenses and clots of allochthonous peat and thin interlayers of autochthonous peat; thickness of the exposed sediments is 2.0 m. Sandy sediments display ochreous spots and strips on the contacts between layers. A sharp, gently inclined interface at a depth of 0.5–0.6 m is indicative of erosion processes in the underlying sediments. The sedimentary layering of AL deposits is disturbed by cryoturbations (to a depth of 0.5 m). Permafrost deposits with massive cryotexture include ice wedges featured as narrow elementary (0.03–0.05 m) and broad (up to 0.6–0.8 m in the topmost part) ice veins. Broad ice wedges correspond to arcuate, linear troughs and open fissures on the drained terrace outlier. Ice of narrow ice wedges is transparent, with a clear joint in the middle and occluded bubbles normal-oriented to the sides; ice is ferruginized at the contact with sand.

Beach deposits encountered in the R15-11 section (Fig. 3) are represented by thawed layered sands with penetrated thickness of 1.1 m, interspersed with nodules and lenses of inwashed plant residues, with small humus tongues and visible traces of cryoturbations and ochreous spots and bands.

By their particle size, the deposits composing raised laida, the outlier of 1st MT and frost-heaved mounds are found to be identical. They are represented mainly by fine-grained sands admixed with silt and clay particles, with their fraction not exceeding 12 %. The beach deposits are represented by medium-

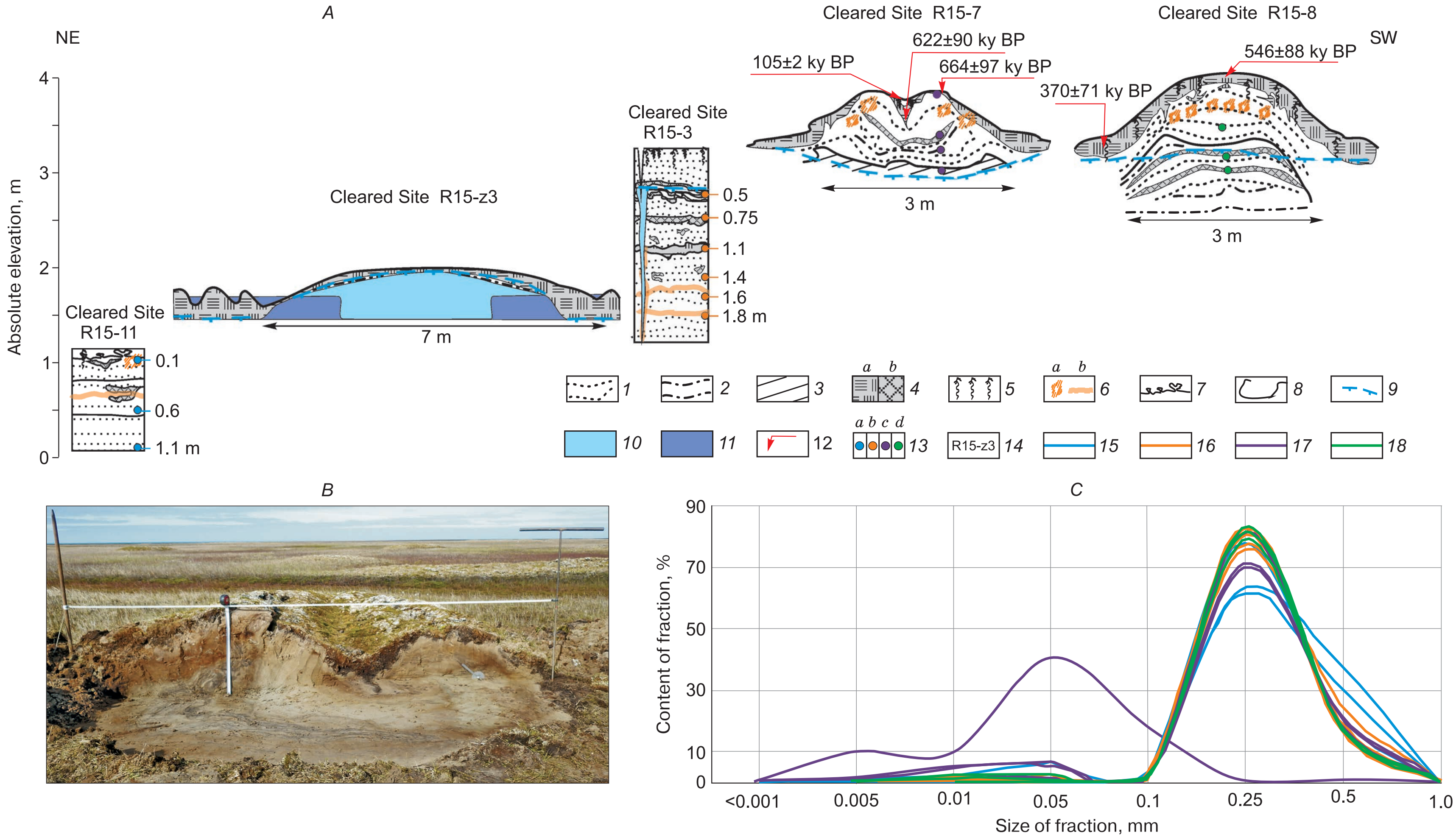

Fig. 3. Subsurface structure (*A*), cleared site R15-7 (*B*), characteristics of sediment particle size distribution (*C*) of frost mounds and the outlier of coastal-marine terrace on Bely Island:

1 – sands; *2* – silty sands; *3* – clayey silts; *4* – peat: autochtonous (*a*), allochtonous (*b*); *5* – topsoil, plant roots; *6* – ochreous spots (*a*), strips (*b*); *7* – cryoturbation; *8* – involutions of layered deposits; *9* – permafrost limit; *10* – ice; *11* – water. *12*, *13* – sampling sites (*12* – organics sampling for radiocarbon dating, *13* – sediment sampling for particle size analysis); *14* – pit/section number (No.); *15*–*18* – histograms for particle size distribution in sediments from sections (*15* – R15-11; *16* – R15-3; *17* – R15-7; *18* – R15-8). Photograph by P.T. Orekhov.

and fine-grained sands. Average contents of fractions in sands are as follows: 0.1–0.25 mm ~84 %; 0.25–0.5 mm <38 %; average particle diameter (Md) is 0.19–0.23 mm, 0.34–0.43 mm at the most. Sands are generally well-sorted S_0 = 1.2–1.3 (Fig. 3, *B*). Aquiclude horizons are localized in the lower part of the cross-section of frost mounds composed of medium-sorted (S_0 = 2.6) clayey-sandy silts (Md – 0.034 mm) whose fractions is described as follows: <0.005 mm – 10.6 %; 0.005–0.05 mm – 50.6 %; 0.05–0.1 mm – 17.8 %; 0.1–0.25 mm – 19.0 %.

Identification of palsa frost mounds. The identified palsas are distinctly discernible in Landsat (Google Earth) satellite imagery, high and super high

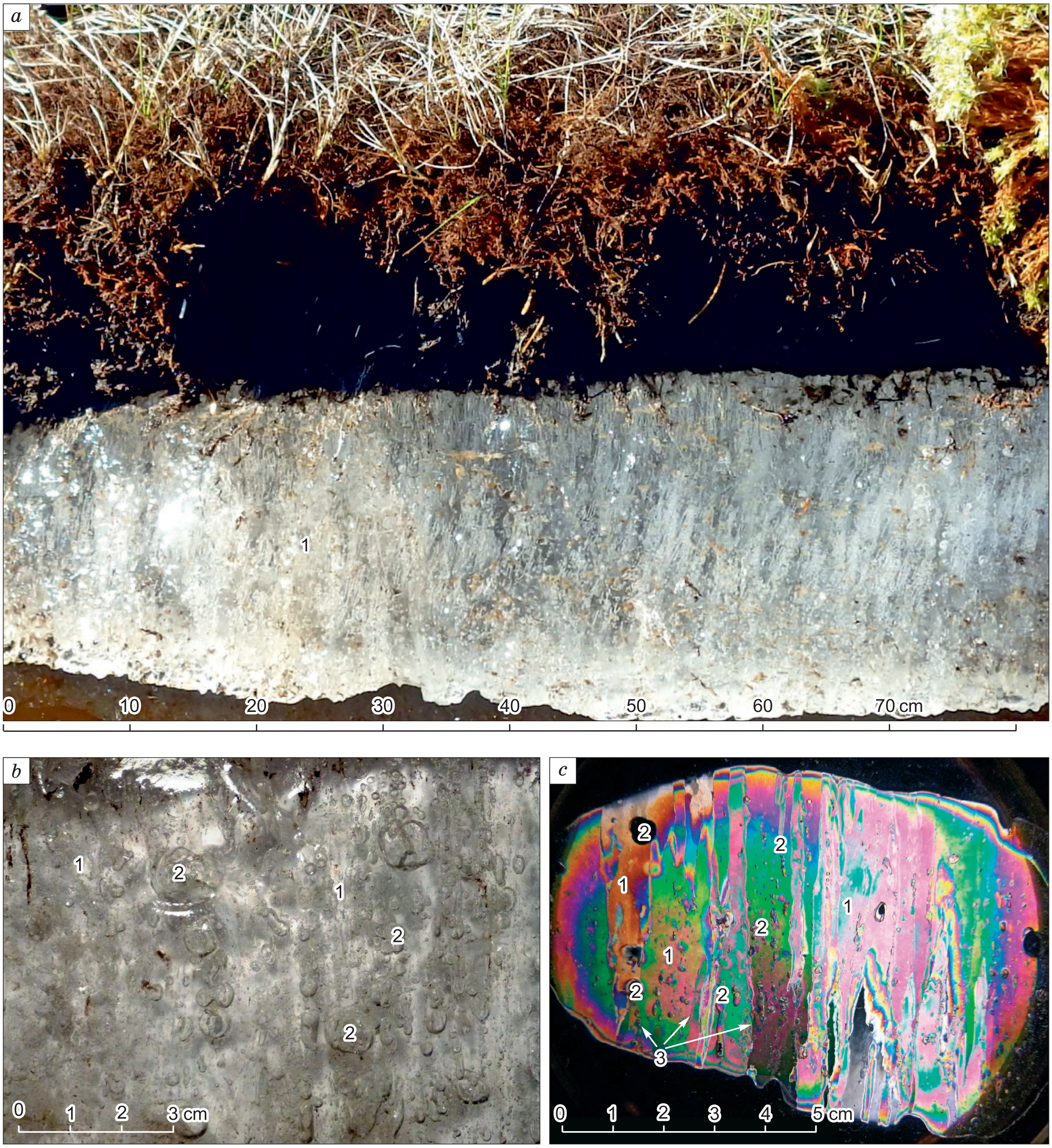

Fig. 4. Structure of frost mound on Bely Island: columnar structure of ice (*a*), air bubbles occluded in ice (*b*), crystalline structure of ice (*c*).

1 – ice; 2 – air bubbles; 3 – edges of ice crystals. Photograph by A.N. Kurchatova.

Table 1. **Radiocarbon dating and carbon isotopic composition of peat from frost heaved mounds on Bely Island**

Cleared site	Coordinates	Depth, cm	^{14}C-years (from 1950 AD)	Calendar years	Lab No.	$\delta^{13}C$	Sample description
R15-7	73°21′12.6″ N, 70°02′47.1″ E	60	622 ± 90	1220–1450	IMKES-14C841	–24.2	Toroid-shaped mound, peat from subsided portion of mound
R15-7	73°21′12.6″ N, 70°02′47.1″ E	0–10	664 ± 97	1160–1450	IMKES-14C849	–23.9	Toroid-shaped mound, peat cover of mound
R15-7	73°21′12.6″ N, 70°02′47.1″ E	55	105 ± 2	Present-day situation	IMKES-14C828	–24.9	Toroid-shaped mound, modern peat from subsided portion of mound
R15-8	73°21′13.4″ N, 70°02′46.8″ E	21	370 ± 71	1420–1660	IMKES-14C840	–22.1	Peat cover of the cone-shaped mound (periphery)
R15-8	73°21′13.4″ N, 70°02′46.8″ E	7	546 ± 88	1270–1520	IMKES-14C831	–24.1	Peat cover of the cone-shaped mound (summit)

Note. $\delta^{13}C$ measurement error is not more than ±0.2 ‰.

resolution images and multispectral 1:500 aerial photographs (AFS) made in August 2015 by the *Planer-T* unmanned aerial vehicle (UAV), commissioned by Russian Center for Arctic Development (Salekhard, YaNAO).

The flat-topped mounds in the images (in visible range of the spectrum) are identified by the light gray round spots with a uniform fine-grained texture (Fig. 2, *b*) amidst dark and light green irregular spots (moss tussocks) against the bluish lacy background dotted with lakes and puddles of raised laida.

Cone-shaped mounds are distinguished as rounded white spots with a bright green or dark gray lining against the backdrop of meandering-banded green moss-grassy ridges and dark swampy hollows on the slopes of 1st MT outlier (Fig. 2, *d*).

Toroid-shaped mounds are differentiated in the photographs by white rings and curved closed circular ridges with a dark, green central portion (Fig. 2, *f*). The separately standing frost mounds, their clusters and elongated chains are highlighted against the light gray surface of the drained bogs (Fig. 2, *i*) on the slope of 1st MT outlier with fuzzy polygonal network. In the middle part of the outlier, trapezoid-shaped polygon patterns (up to 10–12 m) are cross-cut by linear and arcuate cracks, while polygons are rhombus-shaped on the periphery.

Mounds with wedge ice morphostructures differentiated by dark-green stripes that partition the white spots either into 2, 3 or 4 parts, are distributed in the water-filled depressions of raised laida (Fig. 2, *h*).

DISCUSSIONS OF RESULTS

Ice-cored palsas were investigated in August. Given that at AL depth of 0.2–0.3 m, ice had not melted out completely prior to the commencement of freezing at the end of September, suggesting that the mounds are perennial, which is also evidenced by their representations on satellite imageries from different years, and by a veneer of dead vegetative on the mounds.

Genesis of palsas. The occurrence of ice core under the cover of peat is inherent in palsa mounds. Generally, transparency, vertical crystalline structure, columnar partitioning, absence of mineral impurities and ice lamination represent signatures of both segregated and injection (intrusive) ice [*Vtyurin, 1975; Popov et al., 1985*]. However, the following phenomena: pinching out of elongated large ice crystal; air bubbles occluded inside, along the contacts; small fragments of mosses from the peat cover; and the absence of inconformity in the occurrence of crystals and ice with a fine crystalline structure indicate slow aggradation of ice core as moisture migrates to the freezing front under semi-enclosed conditions. The “stipe” of the ice core usually forms during flooding episodes when slightly saline waters ingress to the mound base, thus weakening the ice core by lateral thawing.

The chemical composition of gas bubbles occluded in ice is close to that of the ambient air, however showing elevated values of carbon dioxide, methane and the absence of helium, while $\delta^{13}C$ = –61.88 ‰, which is characteristic of marsh gas and sedimentary rocks, and indicative of the ongoing organic decomposition processes [*Galimov et al., 1975*]. The distribution of bubbles along the boundaries and inside the crystals also attests to a gradual contributions of gas in parallel with aggradation of ice. Probably, the formation of large crystals was facilitated by the salinity of laida sand soaked with marsh and coastal-marine waters. According to the research findings, ice-cored frost mounds discovered on the annually inundated laida of Bely Island are classified as perennial palsas that form due to moisture migration and frost heaving.

The cone- and toroid-shaped varieties of frost mounds are interpreted to be relict, as their ice cores are in the thawed state and the sediments are accordingly subjected to subsiding and tend to be impregnated with the released ochreous iron compounds, while their layering will experience deformation driven by the action of heaving and subsidence. These mounds are confined to the outlier of 1st MT whose berm is not prominent in the terrain, and their position is parallel to its outer contours.

Carbon isotope composition of peat covering frost mounds. Relict frost mounds contained the ice-rich sandy core occurring between the peat cover and clayey sediments. As such, they may well have been migration frost heaved mounds. Given that peat decomposition proceeds slow under cold climatic conditions, its isotopic composition is found to be similar to the carbon isotope composition of the organic matter [*Skrzypek et al., 2008*]. The isotopic composition ($\delta^{13}C$) of terrestrial plants of the Arctic zone varies from –29 to –20 ‰, and that of marine plankton from –21 to –19 ‰ [*Alewell et al., 2011; Krüger et al., 2014*].

Peat investigations in the subarctic continental Canada showed that changes in $\delta^{13}C$ are also associated with variations of the summer air temperature, which when increases by 1 °C, makes the isotope composition heavier by 1.6 ‰ [*Skrzypek et al., 2007*]. The $\delta^{13}C$ values for migration-heaving peat mounds on Bely Island range from –24.9 to –22.1 ‰, which basically corresponds to the palustrine phytocenoses (Table 1).

Depositional environments and conditions for formation of frost mounds. Frost mounds are composed of predominantly stratified (layered and sorted) sands in the context of deficiency of fine particles, and are covered with a layer peat. Sands were likely accumulating in a dynamic environment: in the wave run-up area of littoral zone, on beaches and low laida, and in active watercourses [*Trofimov et al., 2005*].

By their composition and cryogenic structure, sands are similar to sediments of 1st coastal-marine terrace (CMT) of Bely Island [*Slagoda et al., 2013*]. The peat-forming environments are interpreted to have been quiet and stagnant in the drainage-inundation zone exposed to saltwater intrusions during the formation of boggy laida on the lower-lying terrace outlier. Therefore, peat heaving and formation of large ice crystals in the core of ice building up in the

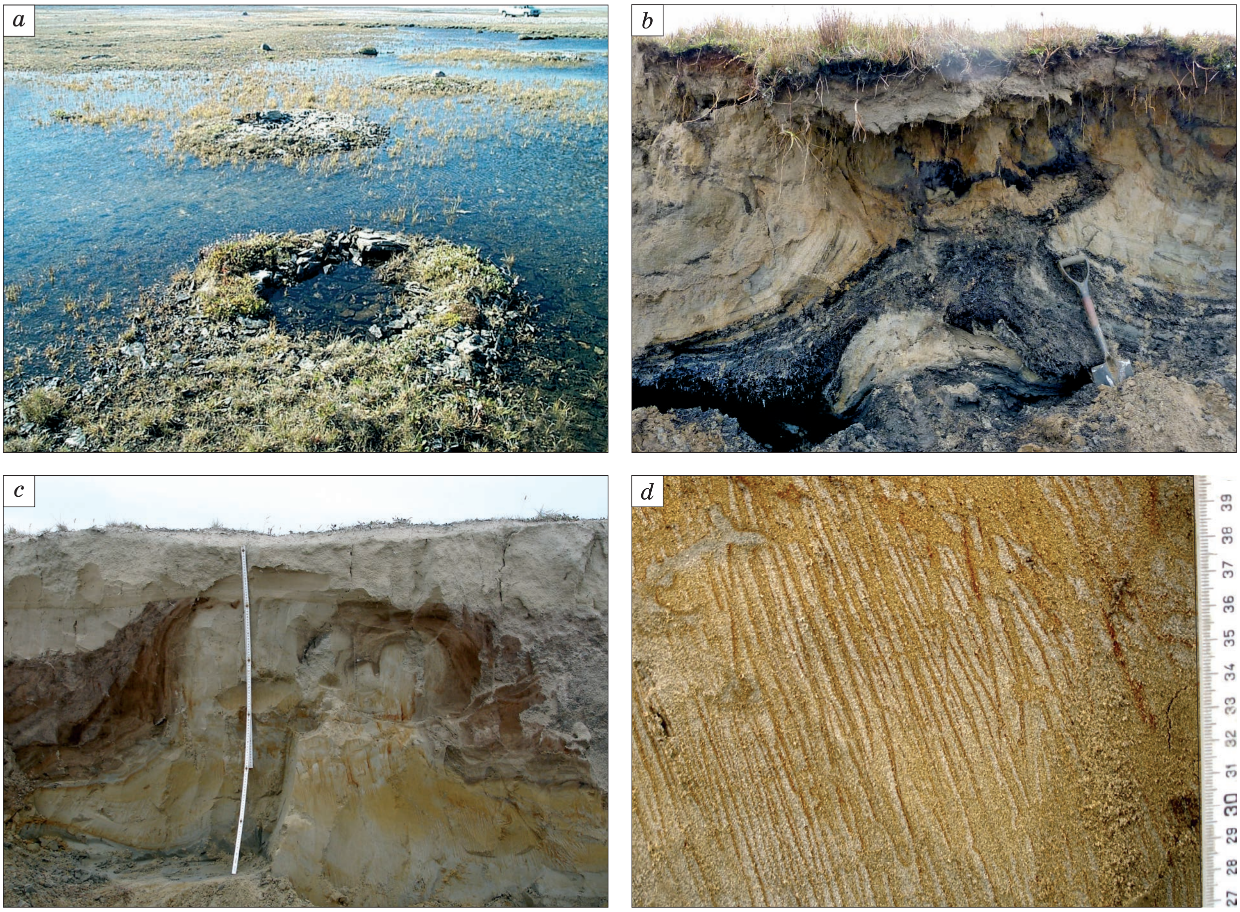

Fig. 5. Frost mounds:

a – seasonal, occurring on inundated sites of Victoria Island, Canada (Photograph by V.E. Roujanski); *b* – relict buried in khasyreys inundated by sea, Sibiryakov Island (Photograph by E.A. Slagoda); *c* – on Marre-Sale Koshky, Yamal Peninsula (Photograph by O.L. Opokina); *d* – vertical-banded ferritization of sands (evidences of the melting of ice core of frost mounds) (zoomed fragment Fig. *c*; Photograph by O.L. Opokina).

mound were largely promoted by salinity of palustrine waters and sediments due to the temperature lowering and thereby slowing down processes of ice formation [*Fotiev, 2011*].

Peat on the cone- and toroid-shaped frost mounds formed during the 1400–1814 cold period of the Late Holocene (Table 1) [*Khantemirov, 2009*]. Arcuate clusters of cone-shaped mounds are located on the marine terrace outlier slope and are likely to have formed during the surface flooding and draining along the coast. Given that toroid-shaped mounds are grouped into ridges, this may indicate their growth during the episodes of the coast being flooded by sea waters through tidal channels migrating on laida. The middle portion of mounds could melt out with the increasing active layer depth both during the short warming period ~250 years ago [*Bolshiyanov et al., 2009*], and when the terrain experienced relative rises and draining. In the absence of driftwood, there is no indication as to whether these frost mounds were flooded by the sea.

Distribution of relict mounds in the Kara region. The prominence of the mounds in the relief of the Bely Island laida, along with preservation of remnants of melted landforms is accounted for by their being relatively young. Similar seasonal frost mound forms were observed on laida and in littoral zone of Victoria Island (Canada) (Fig. 5, *a*) [*Roujanski, 2008*].

On Sibiryakov Island, deposits are characterized by involution of layers, peat injections and signature of the thawing lenses of vertically layered ice observed as parallel rusty striae in sands in the section of the khasyrey side (Fig. 5, *b*). The uppermost feature is eroded and overlain by slopal deposits. The formation of frost heaved mounds with a core of segregated ice was likely associated with regular flooding of the thermokarst depression by the sea 4–3.5 ky BP [*Opokina et al., 2014*].

On the low terraces of Western Yamal, the remnants of frost mounds appear to be rare landforms in the terrain and their descriptions are not available. However, they were exhibited in the sections of the Yavar-Yakha river mouth and in the khasyreys of 1st MT of Marre-Sale Cape flooded by the sea during storms. The upper portions of the mounds are washed out, exhibiting decomposed peat, polygonal wedge ice structures, deformed sand cores with ochreous striae (traces of thawing of ice with columnar partitioning), silty sand with involutions (Fig. 5, *c*, *d*) [*Opokina et al., 2011*].

CONCLUSIONS

The distribution of contemporary small-sized perennial migration-heaving ice- cored mounds have been studied within the flooded laida of Bely Island. The formation of the ice core is interpreted to be coincident with the slow freezing of palustrine waters enriched with methane and carbon dioxide, as is evidenced by the crystalline structure and isotopic composition of ice.

Thawed relict cone- and toroid-shaped landforms are common on the beach and on the Bely island terrace outlier inundated by the sea in the Late Holocene, in place of the migrating tidal channels. They are characterized by peat subsidence, sandy ferruginized core, and by deformed stratification of sediments.

The remnants of frost mounds prominent in the terrain and sections of permafrost in the Kara region, can serve as an indicator of the developing cryogenic heaving in the coastal-marine setting in the Holocene, with laida and khasyreys on low-lying terraces subjected to flooding by saline waters.

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