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PERENNIALLY FROZEN DEPOSITS OF BELIY ISLAND: STRATIGRAPHY, AGE, DEPOSITIONAL ENVIRONMENTS

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This paper is an overview of the study of perennially frozen deposits outcropping in the coastal cliffs of the western and eastern parts of Beliy Island. The obtained results provide information about the composition, structure, stratigraphy, origin and age of Quaternary deposits. It has been established that the cross-section consists of three main units: the lower silts and clays formed during MIS 3 in the marine conditions; the middle sandy unit accumulated between 9 and 5 ka BP as a result of small-scale local relative sea level rise; the upper unit consisting of clays, loam, peat and aeolian sands of terrestrial origin formed in the Late Holocene.

Beliy Island, sea level, Quaternary sediments, Holocene, Pleistocene, stratigraphy, vertical movements of the crust

INTRODUCTION

Structurally, Beliy Island is an extension of the Yamal Peninsula on the Kara Sea shelf. The composition, properties and stratigraphy of its Quaternary sediments are of special interest with regard to investigations of the Late Pleistocene–Holocene relative sea-level (RSL) fluctuations. Given that Beliy Island is the northernmost tip of Western Siberia, standing far out into the sea, the outcrops of marine sediments exposed in the coastal bluffs of the watershed lowlands are most likely to contain the youngest sediment in the area.

The sequence of transgressions and regressions in the West Siberian Arctic have been studied for more than 80 years. Basic information was obtained in the 1950s by the team of the Research Institute of Arctic Geology (NIIGA) during the State Geological Survey [*Saks, 1953; Kulakov, 1959; Sokolov, 1959*]. Among the resulting insights, the opinion that all sediments of Yamal Peninsula have formed on marine terraces at different times during the period spanning the Pleistocene and Holocene [*Danilov, 1970; Trofimov et al., 1975; Generalov et al., 2000*] prevailed for a long time.

An alternative hypothesis suggests that the youngest marine sediments of the Yamal and Gydan plains accumulated not later than MIS 5 (Marine Isotope Stage 5) [*Astakhov and Nazarov, 2010*], followed by the dominance of lacustrine, alluvial or glacial sedimentation [*Forman et al., 2002*], while RSL didn't rise above the present-day level.

The complexity of the situation is fueled by controversies in opinions to the extent that even the end of Late Pleistocene and Holocene remains subject to differing palaeogeographic reconstructions. It is generally considered that in MIS 2 (Sartan time at the regional scale) the shelf was partially exposed, and RSL was below present [*Kaplin and Selivanov, 1999*]. In the Holocene, it gradually rose, likewise in other regions, e.g., Eastern Siberia [*Bauch et al., 2001*]. However, some argue that in MIS 2 (Sartan time) Beliy Island was under water, and the beginning of the Holocene was marked by a RSL fall [*Slagoda et al., 2014a*]. To resolve this controversy, more field data on Quaternary sediments of the northern Yamal Peninsula and Beliy Island are required.

Studies of permafrost on Beliy Island have been conducted since the second half of the 20th century. Thus, the 1972 and 1978 field works of the Tyumen engineering-geologic expedition of Lomonosov Moscow State University (the teams guided by V.G. Kudryashov and Yu.K. Vasil'chuk) resulted in descriptions of permafrost temperatures and properties, cryogenic processes, and ground ice composition [*Vasil'chuk and Trofimov, 1984; Vasil'chuk and Vasil'chuk, 2015*].

Recent investigations of cores from permafrost in the western part of the island, have provided more detailed characterization of cryogenic structures, and subsequent reconstructions of freeze-thaw conditions of soils [*Slagoda et al., 2013, 2014b*]. Nevertheless, the lengthy coastal outcrops on Beliy Island which may provide abundant evidence of composition and stratigraphy of the main sedimentary units still remain largely understudied. There is a definite lack in geochronologic data as well. The presently available data include individual dates from Holocene peat in the western part of the island [*Vasil'chuk et al., 1983*], from near-surface peat in its west and south [*Artemieva et al., 2016*] and peat from pingos near the Popov polar station [*Orekhov et al., 2017*]. However, there is no exact evidence of the age of major sedimentary units outcropping in the coastal bluffs.

This study set out to reveal the stratigraphy, origin and age of Quaternary sediments of Beliy Island, based on field studies of its coastal outcrops. Another task involves reconstruction of the paleogeographic conditions of their formation.

STUDY AREA AND RESEARCH METHODS

Permafrost sections were studied in the bluffs of the eastern and western coast of Beliy Island in 1994 (The Russian-Swedish tundra ecology '94 expedition), in 2012–2013 during the Yamal-Arctic expeditions and in 2016 and 2017 under the support of the "Arctic" Interregional Expedition Centre. On the eastern coast, a section outcropping in the 5–6 to 8–10 m-high thermoerosional cliffs of the lowland to the south of the "Futshtochniy" radar sign and the Salyalekabtambada-Yakha River mouth was described (Fig. 1, *A*; 2, *A*). The observed here abrupt bluff 4–5 m in height, is gradually lowering southwards. The low cliff exposures on the western coast were examined within a stretch from Cape Ragozin in the north to the Salalavayakha River mouth in the south (Fig. 1, *B*; 2, *B*) where the plain elevations in watersheds are found to be lower (up to 3.0–3.5 m) compared to the spot eastern part. The composition, structure and position of the main stratigraphic units established in the outcrops were documented. The contacts between geological bodies were traced all the way along the coastal bluffs. In separate locations, the sections not less than 2 m in width and to the whole bluff's height were thoroughly cleaned and described, providing valuable details on sediments composition, their textures, inclusions and cryogenic features.

Radiocarbon dating was done in the Köppen Laboratory of Geomorphologic and Paleogeographic Investigations of Polar Regions and the World Ocean, Institute of Earth Sciences, Saint-Petersburg State University (SpSU) (15 samples); grain size analysis was performed using sieve measurements for large fractions (>1 mm) and a Malvern Mastersizer 3000 laser diffrative grain size analyzer for fractions of less than 1 mm (9 samples) in the evolutionary geography laboratory, Institute of Geography of the

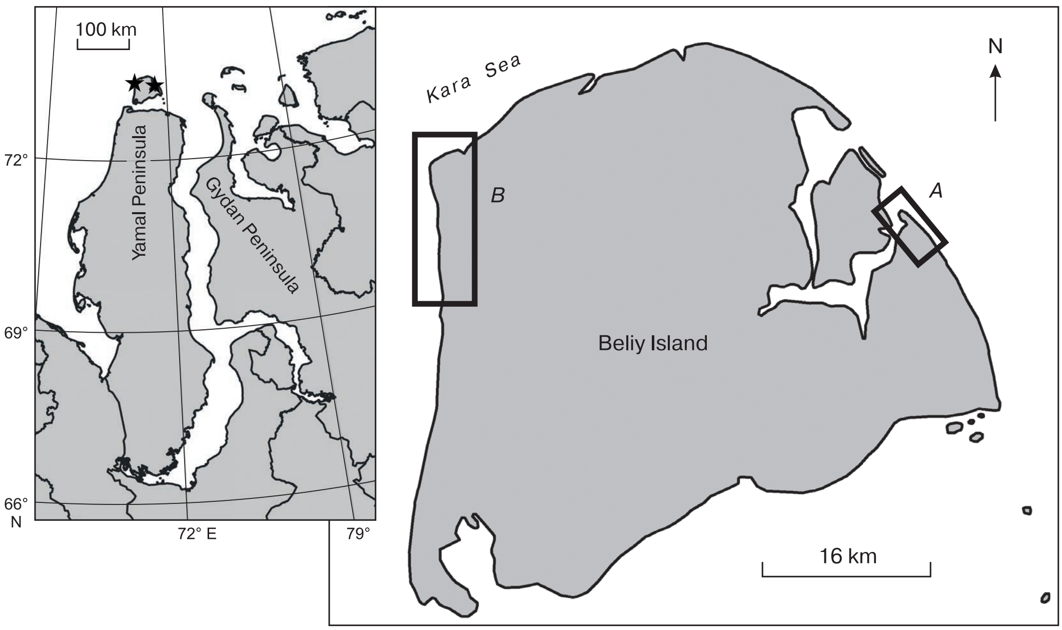

Fig. 1. Location of the study areas:

A) eastern coast of Beliy Island to the south-south east of the "Futshtochniy" radar sign and Salyalekabtambada-Yakha River Mouth; *B*) western coast of Beliy Island from Cape Ragozin to Salalavayakha River mouth.

Russian Academy of Sciences (Moscow). Analysis of the isotope composition of wedge ice was done in the Climate and Environmental Research Laboratory, Arctic and Antarctic Research Institute (AARI), St. Petersburg (10 samples). Diatom species analysis was performed by Z.V. Pushina at the Gramberg VNIIOkeangeologia, St. Petersburg (8 samples). Analysis of water-soluble salt content was carried out under the guidance of I.Z. Kostenko in the accredited laboratories of the Gersevanov Research Center of Construction (Moscow) (5 samples) and Fundamentproject Company, Moscow (10 samples).

STRUCTURE AND COMPOSITION OF QUATERNARY SEDIMENTS OF BELIY ISLAND

The Beliy Island coastal outcrops distinctly exhibit three major sedimentary formations loamy and clayey (lower unit); sandy (middle unit), while the topmost part is composed of peat, loam and sand (upper unit) (Fig. 2).

The lower loamy and clayey unit lies at the basal part of cliffs (up to 2.5 m a.s.l.); its undulating top goes up and down and often drops below modern sea-level, with its bottom never exposing, though. The sediments are composed of interbedded badly washed fine-grained dark grey sands, bluish grey loams, and clays with plant detritus, mostly wood chips and moss felt.

In terms of grain size, the unit consists mostly of silty (0.005–0.05 mm) and clayey (<0.005 mm) particles (Fig. 3, sample 356-2); however, a second maximum of fine sand is seen on the differential curve. The lower unit appears poorly sorted, since all fractions – from fine clay to coarse sand – are present.

During sediment thawing and subsequent re-freezing, the initial lamination has been considerably deformed into small scalloped folds, and pseudomorphs are frequent upon former ice wedges. However, it can be seen that sands were parallel bedded and rippled at the time of their formation; beds are accentuated by abundant plant detritus and peat felt (Fig. 4, *c*).

The lower unit is characterized by massive, reticulate-blocky and reticulate cryostructures. Thickness of ice veins and lenses varies from 0.5 to 1 cm. The bottom tips of younger (epigenetic) ice wedges

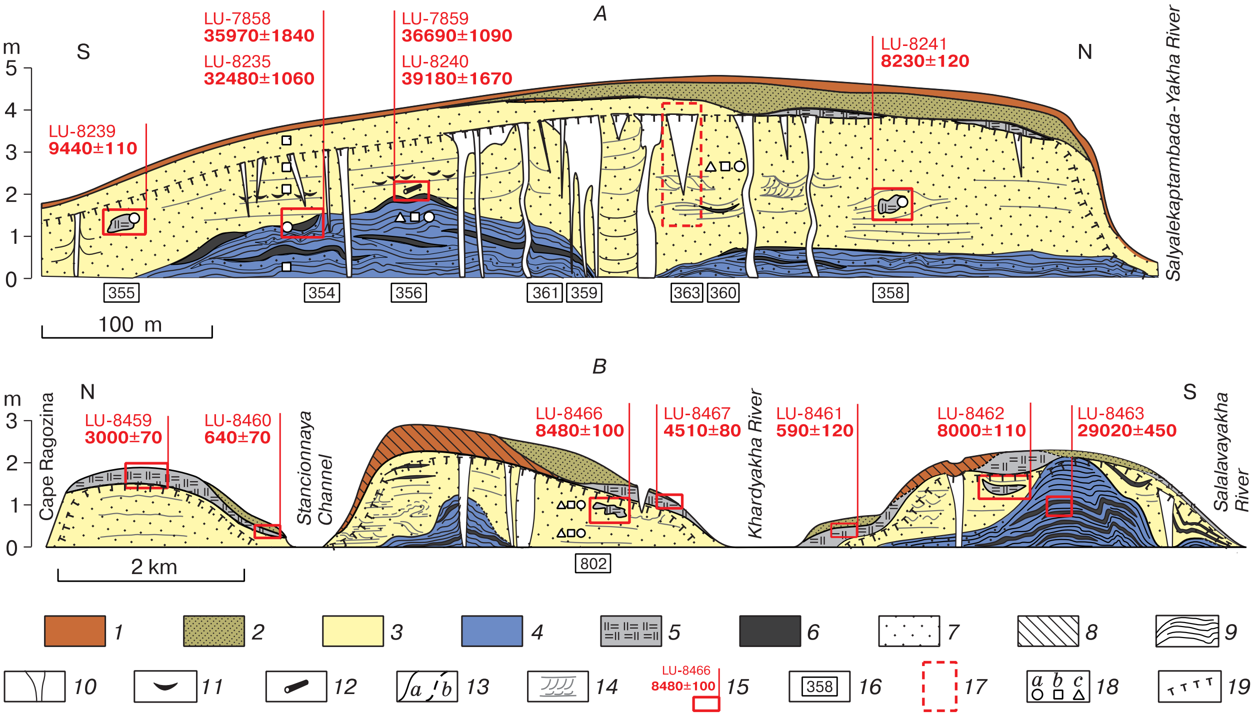

Fig. 2. General section of Beliy Island:

A) eastern coast, *B*) western coast. Composition and origin of sediments: *1* – cover sediments: sandy loams and loams with peat (upper unit); *2* – Aeolian sediments: fine-grained sands (upper unit); *3* – coastal marine sediments: sands with plant detritus, allochtonuous peat and driftwood (middle unit); *4* – marine sediments: clays, sands and loams with parallel lamination, with traces of thawing and re-freezing, with lenses of re-deposited moss felt and plant debris (lower unit). Lithological sediment composition: *5* – peat; *6* – redeposited plant debris and moss felt; *7* – sand; *8* – loam; *9* – clay. Other: *10* – ice wedges; *11* – lenses of plant (splinter) debris; *12* – wood; *13* – geological boundaries: *a*) reliable, *b*) assumed; *14* – bedding; *15* – laboratory number and radiocarbon age, ^{14}C years BP; *16* – outcrop number; *17* – location of sampling of an ice wedge for isotopes of δ^{18}O and δD (Fig. 5); *18* – location of sampling: *a*) for diatom analysis, *b*) for grain size analysis, *c*) for the water extract chemical composition analysis; *19* – active layer boundary.

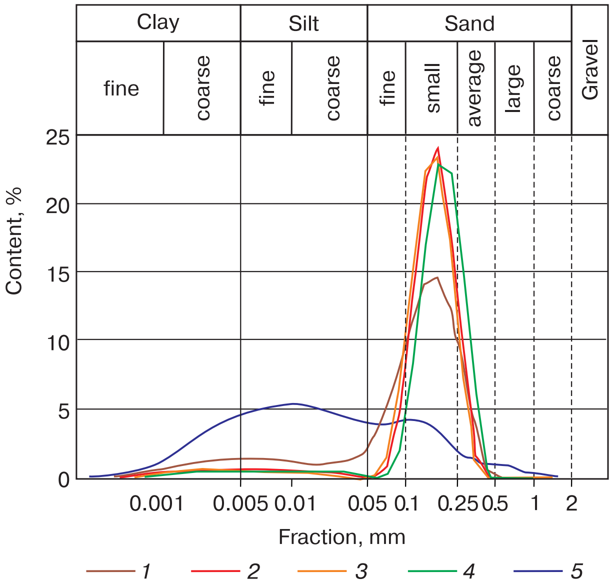

Fig. 3. Grain size differential curves of Beliy Island: results of grain size analysis.

Samples: *1* – 802-2 (upper unit); *2* – 802-3 (middle unit); *3* – 802-4 (middle unit); *4* – 363-9 (middle unit); *5* – 356-2 (lower unit).

(IW) penetrating into the lower unit from above have brown edges at their borders.

Results of the chemical analysis of the water extract, as well as of clays, loams and sands from the lower unit have revealed high salt content (the amount of water-soluble salts D_{sal} is 1.33 %) and a sodium-chlorine salinity type (Table 1). The examined materials exhibited sporadic remnants of Palaeogene extinct diatoms *Paralia grunowii*, along with non-identifieable debris of marine centric diatoms and sponge spicula. Several freshwater boggy diatoms *Eunotia parallela* Ehr. and *Pinnularia* sp. were reported from the moss felt layers.

The upper boundary of the unit is uneven; the topmost layers of loams and clays comprising the thickest (5–10 cm) interlayer of plant detritus follow its undulated shape (Fig. 2). This was probably caused by the ground thawing and sinking in the past, when separate layers experienced deformation together with the whole unit, which affected its top, accordingly. Radiocarbon dating of such upper layers of peat felt showed radiocarbon ages of 35 970 ± 1840 (LU-7858) and 32 480 ± 1060 (LU-8235) years in the eastern part and 29 020 ± 450 (LU-8463) years in the western part of the island (Table 2). Therefore, keeping in mind that the plant detritus may have been older than the sediments containing it, since organic remains had formed prior to their redeposition, the time of the lower unit formation can be estimated as MIS 3 (Kargin time, at the regional scale).

The middle sandy unit, lying atop the lower one, is composing most of the outcropping section. It consists of light grey and greyish yellow fine-grained well-washed well-rounded sands with interlayers of plant detritus. Immediately above the boundary with the lower clayey unit, the overlying sands are layered horizontally parallel, which, as is seen due to dark layers of plant detritus, begin to form directly on their contact. At this, straight horizontal layers fill the depressions in the top of the lower unit, without repeating the shape of the contact (Fig. 2). The parallel beds are persistent to a considerable distance and can be traced in the outcrop for several meters.

Wood fragments were also found above the contact in the lower part of the gently rippled sands of the middle unit (Fig. 4, *a*, sample 356-1). Dating of the wood yielded radiocarbon ages of 36 690 ± 1090 (LU-7859) and 39 180 ± 1670 (LU-8240) years. According to its position (in local depression, bordering the contact) and lamination of the surrounding sediments and considering that such wood remnants were not found above this part of the section, we can assume that the wood was redeposited form the lower unit, its age providing evidence of the formation time of the latter.

At the elevation of 1.7–2.3 m a.s.l., the prevailing parallel lamination gives way to rippled. The ripples cut each other; their steep slopes are directed northwards. The “leeward” slopes are accentuated by layers of black plant debris (Fig. 4, *b*). Series of such beds are not more than 0.3–0.4 m in thickness and are partitioned by horizontally parallel layers. Occasionally present is feathered lamination, while cross-lamination with S-shaped (with concave-convex pattern in the section) series is rare. The middle part of the sandy unit is distinguished by incisions filled by similar sands with moss felt and plant debris (Fig. 4, *d*).

Above 2.3 m a.s.l., the lamination becomes parallel again, which is seen due to increased moss felt concentration in separate beds.

The sands of the middle unit are remarkably well-sorted: fine sands (0.125–0.250 mm) make more than 97 %. The differential curves for grain size distribution show a single peak of fine sandy fraction (samples 802-3, 802-4, 363-9, Fig. 3).

Contrarily to the eastern part, sands in the western part of Beliy Island are not so well-sorted; layers of loam are occasionally present (Fig. 4, *e*), and climbing ripples with eroded counter-current slopes and little inclination of the false beds are encountered (Fig. 4, *f*). Flaser bedding which includes undulated and lens-like ripples with numerous curved silty bands is also present, as well as thick (up to 1–2 m) parallel series with alternating horizontal and rippled sands (Fig. 4, *g*).

The sands are characterized by massive cryotexture; they are dissected by numerous ice wedges of

Table 1. **Water soluble salt content in sediments of the coastal outcrops on Beliy Island**

Sample and outcrop No.	Sediment composition	Elevation, m a.s.l.	pH	Anions, mg-eq/%			Cations, mg-eq/%			Amount of salts, %	Type of soils [*GOST-25100-2011 State standards*]
				HCO_3^-	SO_4^{2-}	Cl^-	Ca^{2+}	Mg^{2+}	$Na^+ + K^+$		
Sediments in the coastal outcrops											
356-2	Clayey silt with sand	1.0	7.29	1.20	1.12	21.20	2.06	4.00	17.46	1.33	Highly saline
363-9	Sand	2.5	7.68	0.33	0.22	0.30	0.28	0.33	0.25	0.06	Weakly-saline
802-2	Sand	1.2	7.70	0.73	0.20	0.10	0.30	0.33	0.40	0.08	»
802-3	Sand	0.8	7.60	0.28	0.24	0.09	0.15	0.23	0.22	0.04	Non-saline
802-4	Sand	0.2	7.55	0.30	0.18	0.13	0.20	0.30	0.10	0.04	»
Modern beach sediments											
1/16	Sand	–0.5...–1.5	6.71	0.20	0.55	3.33	0.35	0.54	3.19	0.237	Moderately saline
2/16	Sand	–0...–0.1	6.73	0.28	0.59	4.03	0.34	0.79	3.78	0.283	»
3/16	Sand	–0.1...–0.2	6.51	0.24	1.49	5.42	0.53	1.35	5.27	0.419	Highly saline
4/16	Sand	–0.30...–0.36	7.36	0.34	0.63	4.81	0.33	0.78	4.68	0.335	»
8/16	Sand	–0.04...–0.07	6.06	0.24	0.29	0.13	0.11	0.08	0.47	0.040	Non-saline
9/16	Sand	–0.15...–0.18	6.44	0.26	0.15	0.10	0.10	0.08	0.34	0.030	»
10/16	Beach sediments	–0.28...–0.38	6.91	0.37	0.30	0.10	0.13	0.26	0.39	0.044	»
11/16	Beach sediments	–0.50...–0.55	7.08	0.40	0.31	0.14	0.11	0.28	0.45	0.048	»
12/16	Beach sediments	–0.7...–0.8	8.20	1.26	0.85	0.22	0.16	0.38	1.79	0.136	Weakly-saline
13/16	Sand	–0.5...–0.6	6.41	0.20	0.92	0.89	0.34	0.45	1.21	0.122	»

Table 2. **Results of radiocarbon dating of sediments on Beliy Island**

Lab. number	Description	Latitude, N degr.	Longitude, E degr.	Elevation, m a.s.l.	Ragiocarbon age, yrs	Calibrated age (calendar), cal. yrs
LU-7858	354-1, plant detritus	73.27	71.55	1.5	35 970 ± 1840	40 260 ± 1840
LU-8235	354-1, plant detritus	73.27	71.55	1.5	32 480 ± 1060	36 900 ± 1270
LU-8239	355-1, peat	73.27	71.55	2.0	9440 ± 110	10 740 ± 200
LU-7859	356-1, wood	73.27	71.55	2.1	36 690 ± 1090	41 180 ± 1130
LU-8240	356-1, wood	73.27	71.55	2.1	39 180 ± 1670	43 720 ± 1610
LU-8241	358-1, peat	73.27	71.54	1.8	8230 ± 120	9200 ± 160
LU-8459	Interbedded sand and badly decayed peat	73.37	70.02	1.8	3000 ± 70	3180 ± 100
LU-8460	Peat	73.34	70.04	0.5	640 ± 70	610 ± 50
LU-8461	Sand with peat sod	73.26	70.04	0.3	590 ± 120	590 ± 90
LU-8462	Curved peat lens	73.24	70.04	2.0	8000 ± 110	8860 ± 160
LU-8463	Debris layers up to 2 cm thick in laminated clays	73.24	70.04	1.0	29 020 ± 450	33 060 ± 550
LU-8464	Dark grey peat	73.32	70.04	1.2	Modern ($\delta^{14}C$ = 13.34 ± 1.6 %)	1957–1958 (7.0 %); 1989–1999 (88.5 %)
LU-8465	Brown decayed solid peat	73.31	70.04	1.8	Modern ($\delta^{14}C$ = 3.07 ± 0.9 %)	1955–1957 (87.4 %); 2008–2009 (8.0 %)
LU-8466	Well-decayed peat lens	73.30	70.04	0.6	8480 ± 100	9460 ± 110
LU-8467	Peat	73.30	70.04	0.5	4510 ± 80	5150 ± 130

Note. Radiocarbon measurements were made by the Köppen laboratory for geomorphologic and paleogeographic investigations of the Polar regions and World Ocean, Institute of Earth Sciences, SpSU (Saint-Petersburg). Calendar ages were obtained using the "OxCal 4.2" software (calibration curve IntCal 13), Christopher Bronk Ramsey (https://c14.arch.ox.ac.uk).

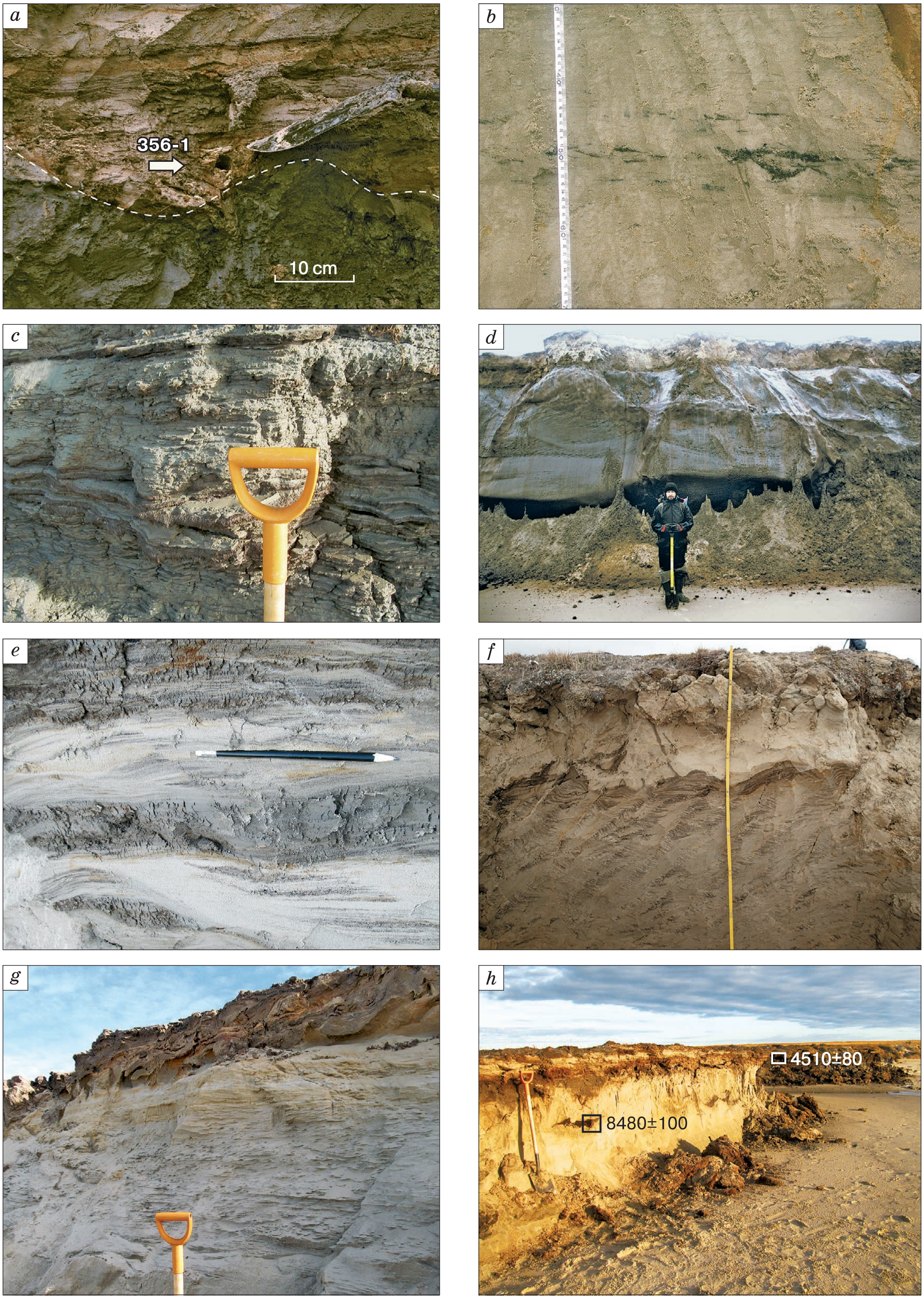

Fig. 4. Details of the loose sediments structure in outcrops of Beliy Island.

a) Location of wood sample (356-1) above the contact of the lower and middle unit (shown by an arrow); *b*) Ripples with dark beds of plant debris with high organic matter content in the middle yellowish grey sands at the elevation of 1.7–2.3 m a.s.l., point 354; *c*) Lamination of the clays and loams with moss felt in the lower unit; *d*) General view of the section with ice wedges; cross-bedding with S-shaped series is visible ; it is truncated by trough-like incisions; in the upper part of the section, layers of autochtonuous peat are seen within the active layer; *e*) Layers of loams and climbing ripples in the middle unit in the west of Beliy Island near Popova polar station; *f*) Climbing ripples in the west of Beliy Island near the Popov polar station; *g*) Parallel and rippled lamination of the middle unit to the south of the Khardyakha River in the west of the island; the section is covered by autochtonuous peat; *h*) Lens of re-deposited (allochtonuous) peat in the light grey and yellow sands of the middle unit to the south of the Popova polar station (point 802); interbedded sandy loams and Late Holocene autochtonuous peats crown the section (photos *a*, *b*, *d*, *f* by A. Baranskaya, photos *c*, *e*, *g*, *h* by F. Romanenko).

different shape and thickness, which are likely to be assigned to several generations. Of them the oldest, up to 2–4 m thick wedges composed of non-transparent white ice of complicated shape are dissected by thinner ice veins.

Younger ice wedges differ in morphology: some of them are thin (<0.5 m) with the thickness not changing downwards, others are V-shaped, whose thickness may reach 1.5–2 m; these consist of transparent ice. Such single wedge found in the eastern part of the island was sampled for oxygen and hydrogen isotope analysis (Fig. 5). The average air temperatures of the coldest month during the wedge formation reconstructed from the obtained $\delta^{18}O$ values. Calculations using equations by *Yu.K. Vasil'chuk* [*1990*]

$$t = 1.5\ \delta^{18}O\ (\pm 3\ ^\circ C)$$

and by *I.D. Streletskaya et al.* [*2015*]

$$t = 1.12\ \delta^{18}O - 6.43\ (\pm 3.8\ ^\circ C)$$

provided similar values: during the wedge formation, the temperature of the coldest month gradually increased from –28...–29 °C to –25...–26 °C. In the western part of the island, a similar $\delta^{18}O$ value of –17.3 ‰ was obtained from ice of a similar wedge [*Romanenko et al., 2015*], corresponding to average temperatures (–26...–27 °C). The calculated temperatures are close to modern ones, slightly lower, though (–25.5 °C is the mean temperature of February, the coldest month, for the period of 1967–1990, according to the RIHMI-WDC data http://meteo.ru/). On the eastern coast of Beliy Island, sands are generally weakly deformed, with the layers rising only at contacts with ice wedges. In the west, on the contrary, single and small in size (up to 1.0–1.5 m across) folds were reported from the upper part of the sandy unit. They indicate that part of the sands experienced thawing and subsequent refreezing.

According to the water extract chemical analysis results, the sands are either non-saline or have weak salinity; the values of D_{sal} vary from 0.04 to 0.06 % (Table 1).

There are few microfossils in the sands of the middle unit, and their preservation is low. On the eastern coast, only fragments of a freshwater species *Pinnularia brevicostata* were found, along with fragments of extinct Palaeogene diatoms *Paralia grunowii* Gles., and non-identifiable debris of marine centric diatoms and sponge spicula. In the samples from the western coast (point 802), microfossils were not discovered.

Besides the plant debris, emphasizing the lamination, sporadic peat lenses are encountered in sands (points 355 and 358, Fig. 2, *A*; lenses to the north of Khardyakha River mouth, Fig. 2, *B*). They are up to 0.5–1 m in length and up to 0.2–0.5 m in thickness, and have an irregular shape with torn edges (Fig. 4, *h*). This allows to infer that they were redeposited and can therefore be considered allochtonuous.

Sands around the peat form draping structures. Radiocarbon dating of such peat lenses in the eastern part of the island yielded ages of 9440 ± 110 (LU-8239) and 8230 ± 120 (LU-8241) ^{14}C years; lenses from the western part of the island provided ages of 8480 ± 100 (LU-8466) and 8000 ± 110 (LU-8462) years (Table 2, Fig. 2).

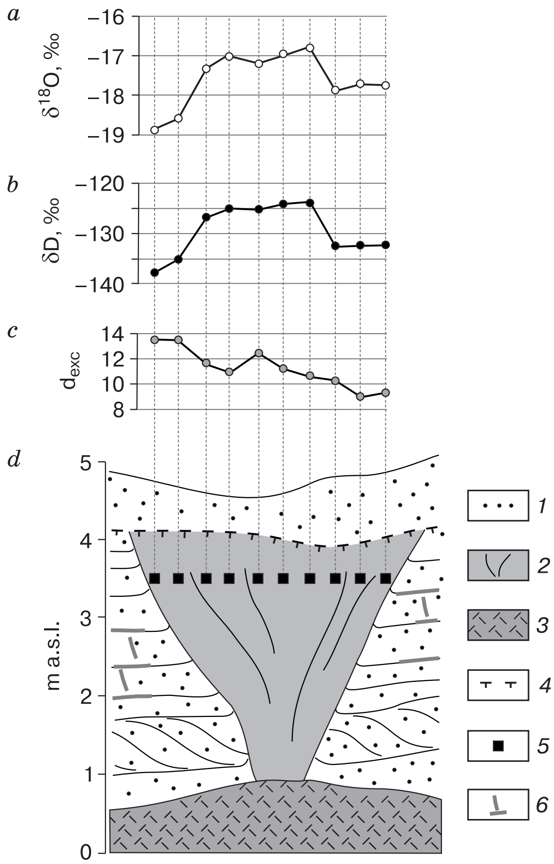

Fig. 5. Stable isotope content:

a) oxygen; *b*) hydrogen; *c*) deuterium excess in an ice wedge (outcrop 363, Fig. 2); *d*) sampling scheme. *1* – sand; *2* – wedge ice; *3* – slope deposits; *4* – active layer lower boundary; *5* – sampling location; *6* – ice veins. For other legends see Fig. 2.

Unlike in the draping sands, abundant freshwater diatom complexes were found in the lenses of peat. In the peat from outcrop 355 (Fig. 2, *A*, age 9440 ± 110 (LU-8239) radiocarbon years), the freshwater complex consists of 32 species. Cysts of yellow-green algae *Chrysophytes* were found. The prevailing *Tabellaria flocculosa* (Roth.) Kütz. (35 %) typical of peat bogs are accompanied by boggy species, genus *Eunotia* (7 species, 13.9 %), benthic alkaliphilic species *Staurosira venter* (Ehr.) Cleve et Möller (10 %), *S. construens* Ehr. (7 %), *S. pinnata* (Ehr.) Will. et Round (4 %), planctonic species of the genus *Aulacoseira* (5 species, 11.3 %). Foulers are represented by alkaliphilic diatoms *Gomphonema parvulum* Grun./ *angustum* (Kütz.) Rabenh., *G. gracile* Ehr., *G. lagerheimii* A. Cl. (6.2 %).

In peat aged 8230 ± 120 (LU-8241) radiocarbon years (point 358, Fig. 2, *A*), the diatom complex consists of 17 species. Boggy diatoms of the genus *Eunotia* prevail (3 species – 57 %); typical of peat swamps *Tabellaria flocculosa* (Roth.) Kütz. (10 %), alkaliphilic diatoms *Fragilaria constricta* Ehr. (7 %) and *Staurosira* sp. (7 %) are also present. Cysts of yellow-green algae *Chrysophytes* (5 %) are more rare.

In both cases (peat from points 355 and 358, Fig. 2, *A*), peat accumulated on a swampy littoral zone of a freshwater lake or pond with subacidic reaction of the environment, which can be proved by the significant number of boggy species. Planctonic stenotherm species *Aulacoseira alpigena* (Grun.) Krammer, and cryophilic *Eunotia praerupta* Ehr. and *Pinnularia brevicostata* Cl. give evidence of cold conditions during peat formation. The dominance of oligogalobes implies low mineralization of water.

The upper unit is composed of continuous layers of peat or peaty loam, either overlapped or facially superseded by badly washed fine-grained greyish brown sands. On the eastern coast, they are present in the northern part of the outcrops only; their thickness doesn't exceed 0.3–0.4 m. Whereas on the western coast, they form a continuous cover, with thickness reaching 0.5–1 m. The sands are parallel and cross-laminated; their salinity is low (the amount of water soluble salts in the water extract is 0.08 %, Table 1). They contain few microfossils, likewise the sands of the middle unit: single fragments of the extinct Palaeogene diatoms *Paralia grunowii*, non-identifiable fragments of marine centric diatoms, sponge spicula. The grain size analysis results (Fig. 3, sample 802-2) showed that in comparison with the middle unit, the greyish brown sands are not well-sorted, whereas the proportion of silty and clayey particles is greater.

Peats and peaty silts of the upper unit form a cover of large lenses extending to considerable distances. Given the undisturbed enveloping occurrence, their origin is interpreted as autochthonous. Radiocarbon ages of such peat varies from 4510 ± 80 (LU-8467) and 3000 ± 70 (LU-8459) years (Table 2, Fig. 2) to several hundred years [*Orekhov et al., 2017*]. On low laida (salt marsh) surfaces up to 2 m in height, peat accumulation still continues today, which is corroborated by modern radiocarbon dates (LU-8464, LU-8465, Table 2).

THE ORIGIN AND DEPOSITIONAL HISTORY OF QUATERNARY SEDIMENTS

The interpretation of the origin of the **lower unit** is challenged by its most part occurring below sea-level, while in the visible part, the structure is considerably deformed by the freezing- thawing processes. However, the prevailing parallel lamination, along with the accentuating moss felt layer and alternation of sandy, silty and clayey units implies sedimentation from water, with little impact of waves and currents, aggravated by changing sediments flux.

High salinity of the lower unit and the potassium-chlorine salinity type are inferred both from the borehole data obtained in the western part of the island [*Vasil'chuk and Trofimov, 1984; Slagoda et al., 2013; Vasil'chuk and Vasil'chuk, 2015*] and from our data (Table 1), suggesting its marine origin. The sediments could have formed in the upper part of the tidal zone, where the wave impact does not affect the sediments, prompting the formation of a silty horizontal tidal flat with thin layers of sand. Alternatively, sedimentation could take place at the bottom below the wave action zone, where clays and silts accumulated in conditions of weak currents. However, for deepwater sediments, the lower unit contains too much moss felt whose source could not be situated far from the place where they were redeposited.

According to the studies of cryogenic microstructures of the lower unit [*Slagoda et al., 2014b*], the sediments were freezing syngenetically, i.e. simultaneously with their accumulation, which favors the hypothesis about their formation on a tidal flat. Then they thawed, with the uneven shape of the unit top repeating by the lower layers, and froze again (epigenetic freezing).

The age of the upper part of the unit determined from cradiocarbon dating of the plant debris and wood could be estimated as MIS 3. It presumably formed as a result of a small (not higher than 3–4 m) RSL rise. Because of such small height, it covered the northernmost, lowest part of Yamal and Gydan only. Whereas in the middle and southern part of Yamal and Taz Peninsulas, MIS 3 sediments are composed of alluvial, lacustrine-boggy, slope and other deposits [*Nazarov, 2011*], on Sibiriakov Island, situated at the same latitude as Beliy Island, similar MIS 3 marine sediments are reported to include allochtonuous peat and inwashed moss felt [*Gusev et al., 2013*]. The existence of a MIS 3 shallow sea is also suggested by studies of cryogenic structures of deposits on the western coast of the Gulf of Gydan at Yavay Peninsula near the Yery-Maretayakha River mouth [*Oblogov et al., 2012*].

However, in the northern part of Yavay Peninsula, autochtonuous peat of MIS 3 age were found in sandy loams of continental origin [*Baranskaya, 2015*], lying in the section of a higher plain (up to 12–15 m a.s.l.) at heights of up to 3–4 m a.s.l. This plain was probably left uncovered by water, as low transgression height (up to 3–4 m) was suggested. The Yavay Peninsula and northern Yamal plains were likely to be the source of the moss felt and plant debris, re-deposited in the marine sediments of Beliy Island.

The origin of the **middle unit** appears more disputable. The general sequence of sedimentary textures gives evidence of underwater deposition. There are few traces of erosion at the lower contact; filling, rather than draping of the depressions in the top of the lower unit is typical of accumulation from water. The fine-grained sands with plant debris forming the lower part of the unit were deposited by fast currents in conditions of no wave impact. Such environments are typify, in particular, the sub-littoral zone in seas below the wave impact area, with constant longshore currents. Due to decrease of the currents' velocity, parallel lamination is replaced with ripples upwards.

The trough-like channels, cutting the cross-laminated and rippled sands in the middle part of the unit are typical of the littoral. Tidal currents form incisions differing in size largely dictated by the height of tides. The climbing ripples described in the eastern part of the island formed under the conditions of recurrent fast sedimentation from water. Flasers whose formation requires simultaneous presence of suspended sands and silts in water, along with alternating periods of high and low current activity, indicate changing hydrodynamic conditions.

As such, all of these sedimentary textures provide evidence of deposition in a large water body – a lake or sea. The continuous coverage of the whole island's area and the presence of textures typical of tidal facies (trough-like channels) make the lacustrine origin doubtful. However, the salinity of sands is low or even absent. According to results of permafrost drilling [*Slagoda et al., 2013*], the middle unit has increased amounts of bicarbonates and lower chloride content compared to the lower unit, which implies freshwater sedimentation.

For marine genesis, the sands are also unusually well-sorted, which might be more typical of aeolian deposits (fine sands make up to 97 % of the unit). Moreover, it is primarily the dark plant detritus that make lamination distinctly visible, rather than the grain size difference.

The reasons of low or zero salinity (D_{sal}) remain thus far unclear. According to the results of the water extract chemical analysis of modern beach sediments sampled in the west of the island (Table 1), salinity in coastal-marine deposits can vary significantly. Within the same beach, both high- and low-salinity, as well as non-saline sediments were reported from different peats at different depths. Just as is the case with the middle unit, modern beach deposits are well-sorted (fine sandy fraction making more than 80 %). This similarity, along with the presence of non-saline sands in the modern beaches, allows to conclude that, despite low salinity and good sorting, the middle unit formed in coastal marine conditions.

The time of its formation can be established based on the dates from peat. The encountered in the sands peat lenses with radiocarbon ages from 8 to 9.5 ka are allochtonuous, judging by their small size and jagged contacts, along with their draping by sands. Their distribution patterns are also lacking continuous layers, exhibiting separate lenses instead (Fig. 4, *h*; Fig. 2, point 355, 358).

The dominance of freshwater diatoms in the peat imply its formation in continental conditions, rather than at low laidas. After accumulation, the peats were eroded during a possible RSL rise and coastal destruction, and redeposited in the sandy unit. The layers of peat of almost identical ^{14}C age: (8580 ± 100 (IGAN 5009) and 8950 ± 90 (IGAN 5010) ^{14}C years) were reported from the southwestern part of the island [*Artemieva et al., 2016*], where they overly lighter grey sands and form a relatively continuous horizon. A very close peat age of 8500 ± 120 radiocarbon years (LU-1139) was obtained by *Yu.K. Vasil'chuk et al.* [*1983*].

On Sibiriakov Island, peat aged 8070 ± 130 (LU-6152) and 8920 ± 360 (LU-6408) radiocarbon years was described in [*Gusev et al., 2013*]. All of this provides evidence of peat accumulation on Beliy Island and in the north of Gydan Peninsula during the Holocene climatic optimum. After an RSL rise, the peat was eroded and re-deposited in lenses encountered in the section.

The middle sandy unit formed therefore not earlier than 8 ka (radiocarbon dating). Its upper age limit is determined by the age of the autochtonuous peat lying above the sands. The oldest date from that peat is 4510 ± 80 ^{14}C years (LU-8467); the peat was encountered in the same outcrop with the lens aged 8480 ± 100 ^{14}C years, to the south of point 802 (Fig. 2, *B*; 4, *h*). These time limits indicate that the middle unit formed in the middle of the Holocene, during the Atlantic period or at the earliest Subboreal period.

The **uppermost heterogeneous unit** crowning the section formed between 5 ka until present on land. The peat and peaty loams accumulated on wet lowlands. The sands covering or facially replacing them are interpreted as aeolian. The still ongoing aeolian sediment transport has resulted in sandy patches on top of the moss of the modern plains.

Therefore, the *most probable sequence of paleogeographic events* leading to the formation of Quaternary sediments of Beliy island can be described as follows:

– *During MIS 3* (correlated with the Kargin time at the regional scale), a local, small-scale (up to 3–4 m) transgression covered the northernmost part of Yamal and Gydan; clays, sands and loams with plant debris of the lower unit accumulated in the upper part of the tidal zone.

– Given that RSL fell at the end of MIS 3, as well as in MIS 2 (Sartan time at the regional scale), the territory was interpreted as a part of the continent. Sediments were in permafrost state; frost heave was accompanied by ice wedge formation; sediment transport and erosion were likely to be activated from the surface of the plains.

– *The beginning of the Holocene* is characterized by a temperature rise and affiliated increase in precipitation; as a result, abundant peat formation occurred at about 8 ka radiocarbon (9–10 ka cal.) years. Soil formation and thermokarst processes occurred along ice wedges, while aeolian processes may have played a critical role. RSL was still much lower than present at that time. The absence of MIS 2 marine sediments contradicts the assumption of a transgression at the end of the Sartan time (MIS 2) and a subsequent regression at the beginning of the Holocene [*Slagoda et al., 2014a*].

Such RSL pattern would be asynchronous with the general post-glacial eustatic sea-level rise of the World Ocean [*Johnston and Lambeck, 1999*]. It would also be in disagreement with fluctuations of RSL in other Arctic seas, and even in the Kara Sea. For example, based on the marine bottom sediments drilling data, to the east of Taimyr Peninsula, about 9300 cal. yrs, its RSL reached the paleo-isobath of 38–40 m [*Polyakova and Stein, 2004*], i.e. it was much lower than today. On Beliy Island itself, autochtonuous peats aged 8580 ± 100 (IGAN 5009) and 8950 ± 90 (IGAN 5010) ^{14}C years [*Artemieva et al., 2016*] challenge the hypothesis of marine conditions existing there in the Early Holocene.

– An RSL highstand, during which the middle unit of light grey and yellow sands accumulated, took place *in the Atlantic period or at the beginning of the Subboreal period* (after 8000 ± 110 and before 5150 ± 130 cal. yrs, according to the dates from peat). Proceeding from the general patterns of Holocene RSL changes in the Arctic, the highstand occurred closer to the end of this period, at 5–6 ka BP, when the eustatic sea-level rise slowed down and many of the regions of the world experienced local transgressions.

Traces of an RSL highstand are found, in particular, on the coasts of southern and central Yamal, where low accumulative coastal segments formed, along with coasts of other Arctic seas [*Romenenko et al., 2015*]. At the same time, the transgression was not high. Even today, because of the flat and low topography of the island, storm surges reach the island's center, as evidenced by fresh driftwood logs on the interfluves. Therefore a 2–3 m RSL rise above present would have been sufficient for accumulation of coastal marine sediments.

Such small highstand might be also explained by the vertical movements of the crust. Even though rates of tectonic movements at Yamal and Gydan Peninsulas were not significant, these areas experienced a Holocene uplift with rates of up to 1–2 mm/yr [*Baranskaya, 2015*]. At the time of the post-glacial transgression, the eustatic sea-level rise exceeded these vertical movements of the coasts, which cancelled them out.

However, about 5 ka the growth of the eustatic sea-level became lower, and the crustal uplifts could influence RSL. The position of Beliy Island on the continuation of the central uplifted part of Yamal Peninsula, and its current existence as an island surrounded on all sides by water suggests some uplift of this large crustal block with respect to the adjacent areas. The impact of such a slow uplift was most likely that the current position of Holocene coastal marine sediments is above modern sea-level.

– After Beliy Island became land, young peat formed after 5150 ± 130 cal. yrs in local boggy depressions; forst heave, ice-wedge growth, thermoabrasion, thermokarst and aeolian processes constitute the major geomorphic and cryogenic forcings affecting its evolution.

CONCLUSION

Studies of the coastal outcrops of the eastern and western parts of Beliy Island have shown that the sections of Quaternary sediments consist of three main units. The lower-sandy, loamy and clayey with plant debris and moss felt-deposited during MIS 3 in the upper part of the tidal zone of a shallow sea. The origin of the middle unit, composed of light grey and yellow parallel and rippled sands is disputable; however, there is substantial evidence of water sedimentation. We suggest the marine origin as the most probable. The middle unit accumulated in the Holocene, in the time span from 9 to 5 ka. The upper thin unit of peaty loams, peat and aeolian sands started forming about 5 ka in continental conditions and is still accumulating today.

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References

Artemieva, Z.S., Yurtaev, A.A., Aleksandrovskii, A.L., Zazovskaya, E.P., 2016. The organic matter of the buried peat soils on Bely island (Kara Sea). Bulletin of the V.V. Dokuchaev Soil Science Institute, iss. 85, pp. 36–56.

Astakhov, V.I., Nazarov, D.V., 2010. The upper Neo-Pleistocene stratigraphy of Western Siberia and its geochronomentric substantiation. Regionalnaya Geologia i Metallogenia, No. 43, 36–47.

Baranskaya, A.V., 2015. The role of the latest vertical tectonic movements in the relief formation of the Russian Arctic coasts. Extended abstract of Cand. Sci. (Geogr.) dissertaion. St. Petersburg, 24 pp. (in Russian)

Bauch, H.A., Mueller-Lupp, T., Taldenkova, E., et al., 2001. Chronology of the Holocene transgression at the North Siberian margin. Global Planet. Change, 31, 125–139.

Danilov, I.D., 1970. Pleistocene transgressions in the north of Western Siberia and in the Pechora lowland, in: The Arctic Ocean and its Coast in nthe Cenozoic. Gidrometeoizdat, Leningrad, pp. 368–373. (in Russian)

Forman, S.L., Ingolfsson, O., Gataullin, V., et al., 2002. Late Quaternary stratigraphy, glacial limits, and paleoenvironments of the Marresale area, western Yamal Peninsula, Russia. Quatern. Res. 57, 355–370.

Generalov, P.P., Faibusovich, Ya.E., Kortosova, V.P., Zarkhidze, V.S., Krasnozhen, A.S., 2000. The state geological map of the Russian Federation (new series), Scale 1:1,000,000. Sheet R-(40)-42 Vaigach island – Yamal peninsula. Map of Pliocene – Quaternary formations. VSEGEI kartigraficheskaya fabrika, St. Petersburg.

GOST 25100-2011 (State Standards). Soils. Classification. MNTKS, Moscow, 2011, 38 pp.

Gusev, E.A., Anikina, N.Yu., Arslanov, Kh.A., Bondarenko, S.A., Derevyanko, L.G., Molodkov, A.N., Pushina, Z.V., Rekant, P.V., Stepanova, G.V., 2013. Quaternary deposits and paleogeography of Sibiryakov island during the last 50,000 years. Izvestia Russkogo geograficheskogo obshchestva (The Russian Geographical Society Herald), vol. 145 (4), pp. 65–79.

Johnston, P., Lambeck, K., 1999. Postglacial rebound and sea level contributions to changes in the geoid and the Earth's rotation axis. Geohpys. J. Intern. 136, 537–558.

Kaplin, P.A., Selivanov, A.O., 1999. Sea-level Changes and Coastal Evolution in Russia: Past, Present, Future. GEOS, Moscow, 289 pp. (in Russian)

Kulakov, Yu.N., 1959. Main features of geomorphology in northern part West Siberian lowland. Trudy NIIGA, 107 (12), 116–126.

Nazarov, D.V., 2011. Quaternary deposits in the central part of the West-Siberian Arctic. Extended abstract of Cand. Sci. (Geogr.) thesis. St. Petersburg, 24 pp.

Oblogov, G.E., Streletskaya, I.D., Vasiliev, A.A., Gusev, E.A., Arslanov, Kh.A., 2012. Quaternary deposits and geocryological conditions of Gydan Bay (Kara Sea), in: Proceedings of the Tenth International Conference on Permafrost (TICOP): Resources and Risks of Permafrost Areas in a Changing World. Pechatnik, Tyumen, vol. 3, pp. 365–369. (in Russian)

Orekhov, P.T., Popov, K.A., Slagoda, E.A., Kurchatova, A.N., Tikhonravova, Ya.V., Opokina, O.L., Simonova, G.V., Melkov, V.N., 2017. Frost mounds of Bely island in the coastal marine settings of the Kara Sea. Earth's Cryosphere XXI (1), 41–51.

Polyakova, Y., Stein, R., 2004. Holocene paleoenvironmental implications of diatom and organic carbon records from the southeastern Kara Sea (Siberian Margin). Quatern. Res. 62, 256–266.

Romanenko, F.A., Baranskaya, A.V., Ermolov, A.A., Kokin, O.V., 2015. Low coasts of the Western Arctic seas. Problems of Geography, 140, 275–306.

Saks, V.N., 1953. The Quaternary period in the Soviet Arctic. Second edition (revised). Trudy Instituta geol. Arktiki. (NIIGAA Proceedings), Vodtransizdat, Leningrad, iss. 77, 627 pp.

Slagoda, E.A., Kurchatova, A.N., Opokina, O.L., Tomberg, I.V., Khodzher, T.V., Firsova, A.D., Rodionova, E.V., Popov, K.A., Nikulina, E.L., 2014a. Cryostratigraphy of the first terrace in Bely island, Kara Sea: permafrost and climate history (Part 3). Earth's Cryosphere XVIII (3), 32–43.

Slagoda, E.A., Kurchatova, A.N., Popov, K.A., Tomberg, I.V., Opokina, O.L., Nikulina, E.L., 2014b. Cryolithologic structure of the first terrace: microstructure and evidence of cryolithogenesis, Bely island, Kara Sea (Part 2). Kriosfera Zemli (Earth's Cryosphere) XVIII (1), 12–22.

Slagoda, E.A., Leibman, M.O., Khomutov, A.V., Orekhov, P.T., 2013. Cryolithologic construction of the first terrace at Bely island, Kara sea (Part 1). Kriosfera Zemli (Earth's Cryosphere) XVII (4), 11–21.

Sokolov, V.N., 1959. Northern part of the West-Siberian lowland, in: Saks, V.N., Strelkov, S.A. (Eds.). Quaternary deposits of the Soviet Arctic. Gosgeotekhizdat, Moscow, pp. 61–80. (in Russian)

Streletskaya, I.D., Vasiliev, A.A., Oblogov, G.E., Tokarev, I.V., 2015. Reconstruction of paleoclimate of Russian Arctic in the Late Pleistocene–Holocene on the basis of isotope study of ice wedges. Earth's Cryosphere XIX (2), 86–94.

Trofimov, V.T., Badu, Yu.B., Kudryashov, V.G., Firsov, N.G., 1975. The Yamal Peninsula. MGU, Moscow, 275 pp. (in Russian)

Vasil'chuk, Yu.K., 1990. Reconstructions of the late Pleistocene and Holocene paleoclimate on the basis of isotope studies of ground ice and waters of the permafrost zone. Vodnye Resursy, No. 6, 162–170.

Vasil'chuk, Yu.K., Petrova, E.A., Vasil'chuk, A.C., 1983. Some paleogeographic features of the Holocene of Yamal. Byulleten Komissii po izucheniyu chetvertichnogo perioda (Bulletin of the Commission on Quaternary Period Research), iss. 52, 73–89.

Vasil'chuk, Yu.K., Trofimov, V.T., 1984. On the findings of strongly saline ice wedges. Izvestia AN SSSR, Ser. Geol., No. 8, 129–134.

Vasil'chuk, Yu.K., Vasil'chuk, A.C., 2015. Engineering-geological and geochemical conditions of polygonal landscapes of Bely island (Kara Sea). Inzhenernaya Geologia, iss. 1, 50–72.

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