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PLEISTOCENE-HOLOCENE PALAEOENVIRONMENTAL RECORDS FROM PERMAFROST SEQUENCES AT THE KARA SEA COAST (NW SIBERIA, RUSSIA)

ABSTRACT. The Kara Sea coasts were studied using comprehensive stratigraphic and geocryological methods. The paper presents the new analytical studies of ground ice and Quaternary deposits of Western Taymyr and presents the results of spore and pollen, foraminifera, grain-size, mineralogical, geochemical, oxygen isotopic, and other analyses. Several stratigraphic-geocryological transects from Yenisey and Gydan Bays enable us to refine the stratigraphy and palaeogeographical reconstruction of the environments and freezing of Late Pleistocene-Holocene sediments. Marine sedimentation conditions during the late Kargino time (MIS3) changed to continental conditions in MIS2 and MIS1. Marine sediments were frozen syn- and epigenetically with cryotexture and ground ice formation. Ice wedges formation corresponds to the end of the Pleistocene (MIS2) and during cooler periods of the Holocene.

KEY WORDS: Arctic coasts; permafrost; tabular massive ground ice; stable isotopes; syngenetic polygonal ice wedges; palaeoclimate.

INTRODUCTION

Accumulation of Late Pleistocene sediments in climatic conditions similar or colder than present ones, and wide distribution of polygonal ground ice exclude the presence of large ice sheet in the north of West Siberia [Svendsen at al., 2004]. There is evidence of marine conditions in the lower Yenisey River during the entire MIS5, which excludes the glaciation around 90 kBP [Gusev and Molodkov, 2012]. Such contradictions in currently existing models of development of northern West Siberia in the Middle-Late Pleistocene indicate the need for a more detailed comprehensive study of Quaternary deposits and ground ice sediments of the North.

The Yenisey Gulf and Gydan Peninsula regions are characterized by severe climatic conditions, continuous permafrost, and low ground temperatures. The coasts are composed of fine grained sediments with high ice content and are constantly modified by thermodenudation, thermoabrasion, and slope processes. Geological sections on slopes and surfaces of watersheds are completed by a layer of continental sediments with syngenetic polygonal ice wedges (SPIW). Thick SPIW is part of the section of the second alluvial terrace of the Yenisey River. Parental bedrocks are subjected to intense cryogenic weathering and are composed mostly of fine-grain saline marine Quaternary sediments with a thickness of more than 100 m [Matyukhin and Streletskaya, 2012]. Saline marine sediments contain ground ice: tabular massive ground ice bodies (TMGI) (large tabular ice bodies with volumetric ice content around 100%) and segregation ice. The genesis of the TMGI and the enclosing clay deposits is a subject of the debate [Danilov, 1969, 1978; Kaplyanskaya and Tarnogradsky, 1986; Solomatin, 1982; Streletskaya at al., 2009]. TMGI are classified as buried or intrasedimental in origin.

SPIW and TMGI have unique natural features. They provide important paleogeographic information and are used in paleoclimatic reconstructions.

The main objective of the work presented herein was reconstruction of the paleogeographic conditions and sedimentation environment in the Late Pleistocene-Holocene based on comprehensive research of permafrost exposures along the Kara Sea coasts [Danilov, 1969; Oblogov et al., 2012; Romanenko et al., 2001; Streletskaya et al., 2007; Streletskaya and Vasiliev, 2009; Streletskaya et al., 2011; Streletskaya et al., 2012]. Generalization of analytical studies of ground ice and the sediments with application of new techniques supported by dating of Quaternary sediments allows revising the Quaternary stratigraphy and paleogeographic reconstruction of the conditions on the Yenisey North in the Pleistocene and Holocene.

MATERIAL AND METHODS

The scope of work included investigation of sections of coastal cliffs with a total length of more than 30 km at five sites which allowed detail characterization of permafrost features in the main geologic and genetic Quaternary complexes. The distance between the northern (village Dikson) and southern points (Cape Sopochnaya Karga) is about 150 km, and the distance between the western (Ery-Maretayakha River mounth) and eastern points (Cape Sopochnaya Karga) is about 250 km (Fig. 1).

Complex field and analytical investigation included dating of sediments, determination of ice content, particle size and mineralogical composition, total salinity and composition of water-soluble salts, organic carbon content, and palynological analyses of micro and macro faunas in the sediments. The sediments from the sections were sampled at intervals of 30 cm – 1 m for grain-size and for the investigation of organic matter and biostratigraphic indicators – foraminifers, ostracodes, spores and pollen, diatoms. Peat, wood fragments, and bones were picked for ^{14}C age determination.

Along with recording sediment descriptions, the gravimetric ice content was estimated immediately after thawing by relating the weight of the frozen sample to the weight of the dry sample, expressed as weight percentage (wt%).

Grain size was determined by sieving and pipette analysis. The chemistry: aqueous migrate (Makarov: water extract) analyses were conducted using standard methods in the Laboratory of Lithology and Geochemistry of All-Russian Research Institute for Geology and Mineral Resources of the World Ocean (VNIIOceangeologiya) in St. Petersburg, Russia.

The determination of organic carbon contents (OCC) were carried out using the laboratory mill "Retsch" (Germany) sample preparation.

Radiocarbon dating using the accelerator mass spectrometry (AMS) was determined at the laboratories of the Sobolev Institute of Geology and Mineralogy of the Russian Academy of Sciences and Saint Petersburg State University. All radiocarbon

Fig. 1. Location of the study area in Northern Siberia in the Yenisey Gulf and Gydan Bay. The sites are described in the text

dates through this paper are reported as uncalibrated ages.

The chemical and isotope compositions of ground ice (δ ^{18}O and δ D) were determined in samples of melted water from the ice-wedges and intrasedimental ice. The stable isotope composition of ground ice was determined at the Isotope Laboratory of the Alfred Wegener Institute for Polar and Marine Research, Research Unit Potsdam. δD and δ^{18}O values give the respective permil-difference relative to the international standard Vienna Standard Mean Ocean Water (V-SMOW). The internal 1s errors are <0.8% for δD and <0.1% for δ^{18}O for all measurements (Meyer et al., 2000). Stable isotope data of ice and water are generally displayed relative to the Global Meteoric Water Line (GMWL) [Craig, 1961]. The deuterium excess ($d = \delta D - 8\delta^{18}O$) introduced by Dansgaard [1964] is an indicator for non-equilibrium fractionation processes.

THE STUDY SITES AND RESULTS

The exposure near Sopochnaya Karga Cape

Pleistocene and Holocene sediments containing large inclusions of ground ice as well as sediments with no visible ice inclusions were previously studied in several exposures along 6 km segment of the Yenisey Gulf coast on Cape Sopochnaya Karga (Fig. 2 and Fig. 3) [Streletskaya at al., 2007, 2009, 2011, Streletskaya and Vasiliev, 2009].

Sands from the northern part of the cliff (Fig. 3A) were analyzed by infrared optically

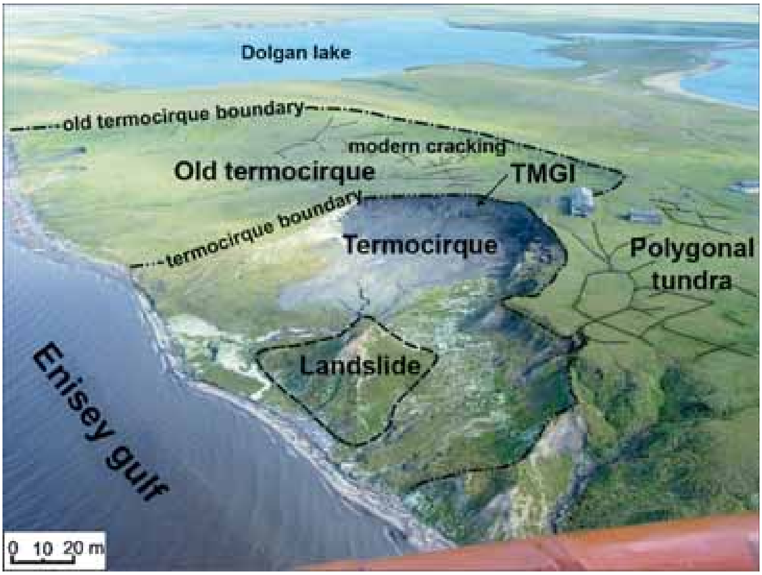

Fig. 2. Location of the Sopochnaya Karga study site. August 2004. (Photo taken from helicopter by E. Gusev)

stimulated luminescence method (IR-OSL). The results allowed us to determine the age of two samples from this section in 112,5±9,6 KA (RLQG 1769-107) and 117,7±10,0 KA (RLQG 1770-107) [Streletskaya et al., 2009; Gusev et al., 2011].

Radiocarbon dating of two peat samples showed that the age of the organic horizons is 7320±130 yrs (GIN 13056) and 8050±60 yrs (GIN 13055), which corresponds to the climatic optimum [Streletskaya et al., 2009] (Fig. 3C).

The range of $\delta^{18}O$ in SPIW is –20.3‰ to –19.0‰, and the range of δD is –150.4‰ to –140.6‰. The deuterium excess is near 13.0‰ [Streletskaya at al., 2011].

The stable isotope content in TMGI is rather constant and is -23‰ for oxygen and -177‰ for deuterium. The deuterium excess is from 4.5‰ to 5.8‰.

The scale of the processes can be inferred from the landslide of 22 m height and 200 m wide, which covers the fragment of the second alluvial terrace of the Yenisei River (Figure 3D).

The landslide body represents partially thawed and later refrozen sandy-clay sediments moved down the slope. The radiocarbon age of the sediments is older than 43,700 yrs. Pollen complex extracted from clay sediments is characteristic of forest-tundra vegetation of the Kargino time of the Late Pleistocene (MIS3).

To the north from the Sopochnaya Karga settlement, the coastal exposure of the Yenisey Gulf is 15–20 m high, the level of the second terrace of the Yenisey River (Fig. 3B).

From the surface of the terrace down to 1 m, there is peat; according to the radiocarbon dating, the formation of the peat layer started 9–10,000 years ago.

Under the peat, layered silty loams and sands 4–15 m thick are found. The horizon is underlined by peat older than 37,200 yrs. A caribou bone was found at the base of the exposure, which was dated 13,770 ± 480 yrs (LU-6998).

At the contact with the underlined clays, the sands have gravel inclusions (Fig. 3B). Sandy-loams and sands have inclusions of SPIW up to 10 m thick and 2–3 m wide in the upper parts of the wedges. Lower parts

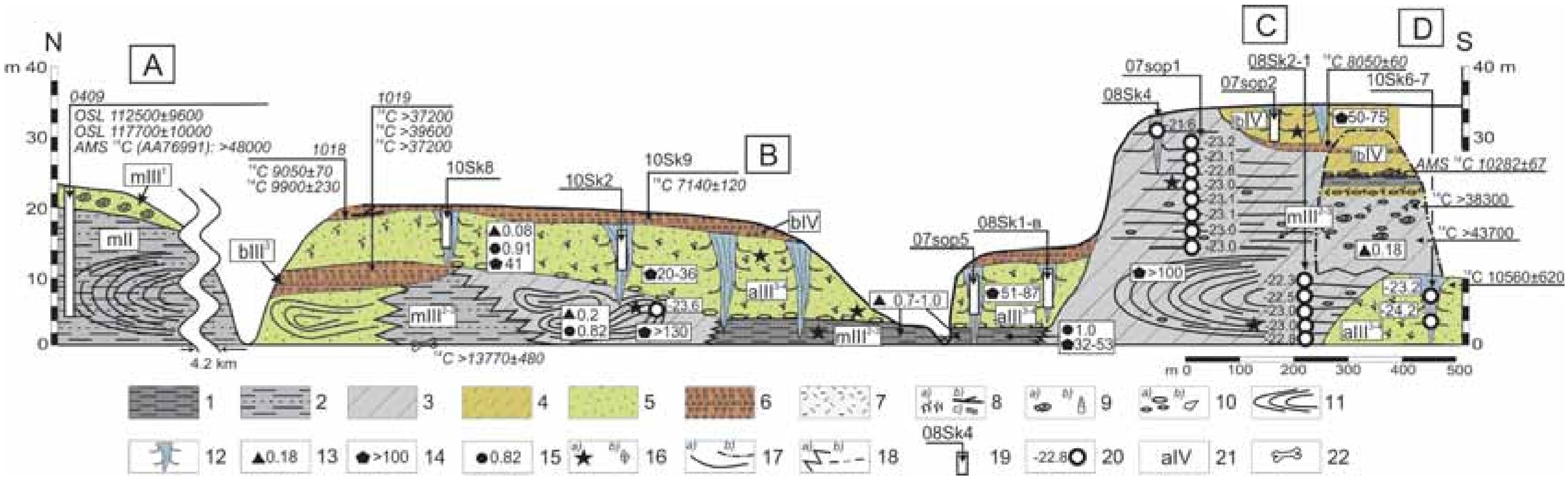

Fig. 3. Schematic representation of the studied Sopochnaya Karga permafrost sequence with ground ice; sample positions, some analyses results and radiocarbon ages:

1 – clays; 2 – clays with sandy silts and sands interlayers; 3 – clay loam; 4 – sandy loam; 5 – sands; 6 – peat; 7 – talus; 8 – inclusions a) detritus, b) wood debris, c) peat debris; 9 – a) sea mollusks, b) fresh-water lacustrine shells; 10 –inclusions a) rounded pebble, b) coarse gravel; 11 –cryoturbations; 12 – polygonal wedge ice (shown outside of scale); 13 – degree of salinization of sediments, %; 14 – gravimetric water content, %; 15 – organic carbon content, %; 16 – sampling for a) granulometric and mineralogical analysis, b) palynological analyses; 17 –boundaries: a) lithological, b) landslides; 18 – boundaries of granulometric facies, 19 – location and number sites of exposed SPWI where isotopic composition was studied; 20 – composition of oxygen ($\delta^{18}O$) stable isotopes of ice, ‰; 21 – genesis and age deposits; 22 – bone

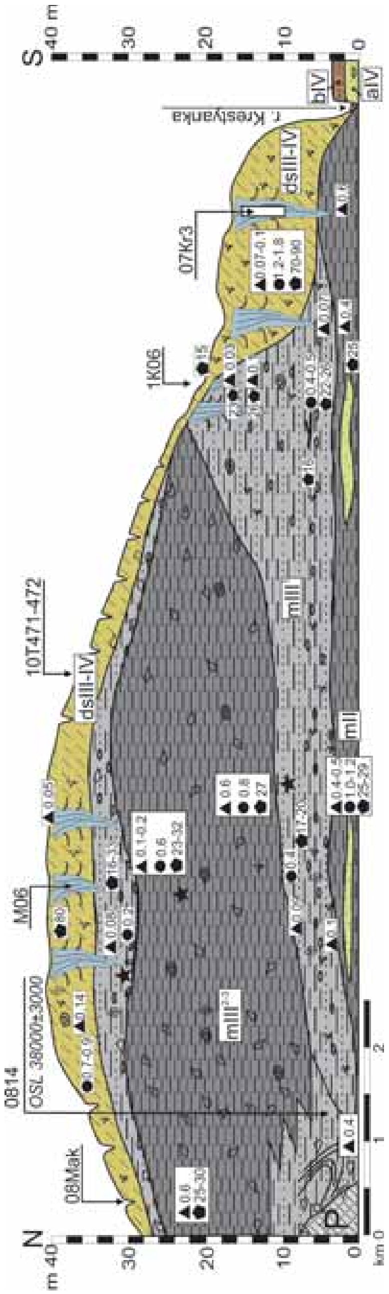

Fig. 4. Schematic representation of the studied Krestianka permafrost sequence with ground ice, sample positions, some analyses results, and radiocarbon data (see legend for Fig. 3)

of the wedges intrude the clays or TMGI up to 0.5 – 1.0 m deep.

The $\delta^{18}O$ content of SPIW is from –24.8 to –24.5 ‰. The deuterium excess is from 6.8‰ to 10.2‰. The same isotope composition is found in SPIW in sands buried by the landslide (Fig. 3D).

The clays below the sands and sandy-loams are saline (salinity up to 1.5%) and characterized as marine (chlorine content is 70–85 mmol/1 %, sodium 97 mmol/1 %). The total gravimetric moisture content of clays is 32–53% and sometimes higher than 130% (TMGI). The organic carbon content in clay sediments is independent of pure ice content and is 0.8–1.0%. Salinity in the icy sediments layer is less (0.2%), but among the ions, the chlorine and sodium dominate.

The stable oxygen isotope content in TMGI is –23.6‰ which is similar to the composition of TMGI in the southern part of the exposure (Fig. 3C). The stable oxygen isotope content from ice of reticulate cryostructure in the clay is relatively heavy (–18.4 ‰).

The profile near the Khrestianka River mouth

Near the Khrestianka River mouth, the Quaternary deposits are overlying the Permian bedrocks, the top of which is located at 5–10 m asl (Fig. 4).

The particle-mineralogical analysis of the sand fraction from the clay showed the distribution of minerals characteristic of marine beaches.

The OSL dating of the sand lens at the bottom of the profile indicated the age of 38.0 ± 3.0 thousand yrs [Gusev et al., 2011].

4. Under the clay horizon, there are yellowish-grey well sorted sub-horizontally layered sands 5.5–10 m thick. The layering is visibly supported by iron oxidation. The granulometric and mineralogical analysis showed that the sediments were

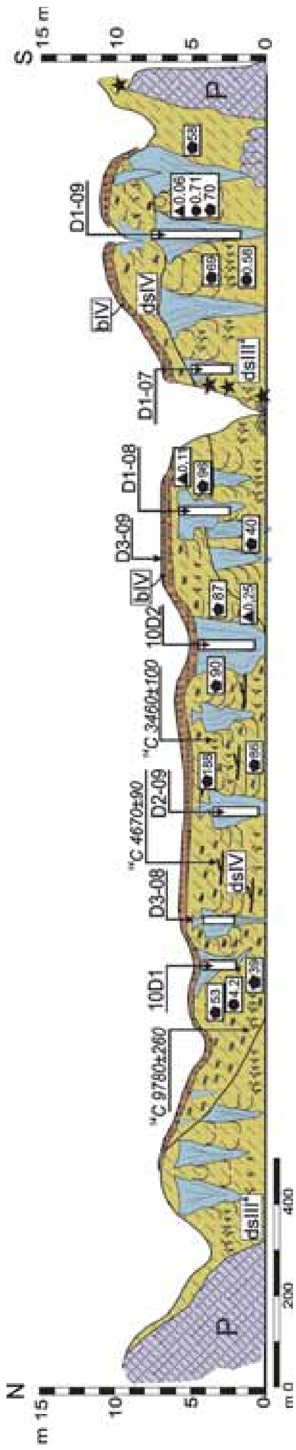

Fig. 5. Schematic representation of the studied Dikson permafrost sequence with ground ice, sample positions, some analyses results, and radiocarbon data (see legend Fig. 3)

accumulating in the underwater part of the delta under wave action at the bottom. The sorting of the sediments by size and density and absence of silt and fine-grained sands show possibility of formation of gravelly sands in the underwater zone of the beach near the mouth of the river.

The pollen spectra from the sands indicated the taiga vegetation type of the Kazantsevo age with extensive meadows.

5. At the base of the exposure (1–2 m above the gulf level), sands transition to dense lumpy loams and clays.

The SPIW on the slopes of the interfluves near the Krestyanka River mouth have a lighter isotope composition compared to the Holocene wedges of Cape Sopochnaya Karga. The values of $\delta^{18}O$ and δD range from –23.7 to –21.3‰ and from –180.0 to –165.0‰, respectively. Deuterium excess is less than 10 ‰ (from 5.2 to 9.9‰).

The exposure near the Dikson village

The most complete section of the Quaternary sediments was studied in the Dikson area where two layers of SPIW penetrate the coastal scarp (Fig. 5).

The deposits are ice-rich (the total moisture content is over 86%) and have a rhythmically-layered structure typical of syngenetic deposits. The cryostructure between the layers is reticulate, ataxitic, and massive, while near the layers, it is micro-lenticular-layered. The apparent thickness of the deposits is about 10 meters, but SPIW continues below the sea level, suggesting that the deposits are very thick.

In the deposits, including the SPIW of the lower layer, organic matter is spread regularly in the section. There are no large inclusions or plant debris.

The results of the analysis of the oxygen ($\delta^{18}O$) and hydrogen (δD) isotopic composition of SPWI showed changes of

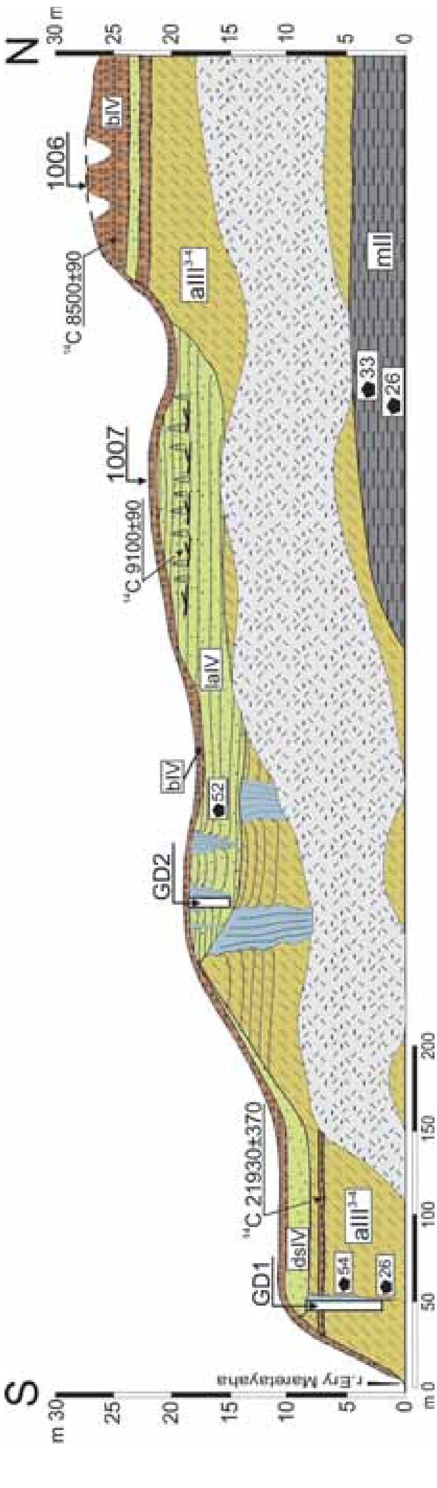

Fig. 6. Schematic representation of the structure of the coastal outcrops of the Ery-Maretayakha River mouth, the Gydan Bay (see legend Fig. 3)

values from –26.8 ‰ to –20.1‰ ($\delta^{18}O$) and from -205.0 ‰ to –150.4 ‰ (δD). The isotopic composition of the upper layer PWI is from –21.7‰ to –19.5‰ ($\delta^{18}O$) and from –161‰ to -147‰ (δD). The isotopic composition of the lower layer SPIW is 6‰ lighter: it changes from -24.3‰ to -26.8‰ for $\delta^{18}O$ and from –205‰ to –184‰ for δD. Currently, the growing ice branches of wedges have a heavier isotopic composition from –17.1 ‰ to –16.2 ‰ for $\delta^{18}O$ and from –124 ‰ to –118 ‰ for δD in the Dikson area [Streletskaya et al., 2011].

The western coast of the Gydan Bay

The coastal cliff structure near the Ery-Maretayakha River mouth was studied. The structure consists of thermodenudational surfaces with the elevations of 10–25 m and a thermoabrasive cliff descending to the modern beach (Fig. 6).

The upper part of the section is represented by frozen lacustrine (lacustrine-boggy) deposits that are characterized by a substantial ice content. Radiocarbon dating by a peat sample showed the age of 8,500 ± 90 yr BP (LU-6535). Radiocarbon dating by plant roots from the depth of 4 m showed the age of 9,100 ± 90 yr BP (LU-6534)

Closer to the Ery-Maretayakha River mouth, in the section of a surface about 10 m high, sandy silts are interbedded with fine sands and peat interlayers. The peat interlayer in sandy deposits at the elevations above the sea level 7.8 m has the radiocarbon age of 21,930±370 yr BP (LU-6542). Yu.K. Vasilchuk [1992] obtained a series of radiocarbon dating at different elevations above the sea level: at 3.5 m – 30,200 ± 800 yrs (GIN-2470), at 4.5 m – 28,600 ± 800 yrs (GIN-2638), 5 m – 25,100 ± 220 yrs (GIN-2471), 5.9 m – 21,900 ± 900 yrs (GIN-2469). The peatland at the elevation of 9.3 m had a radiocarbon age of 3,900 ± 100 yrs (GIN-2468).

Two layers of SPIW (Fig. 6) are exposed in the section: the upper-layer SPIW with the

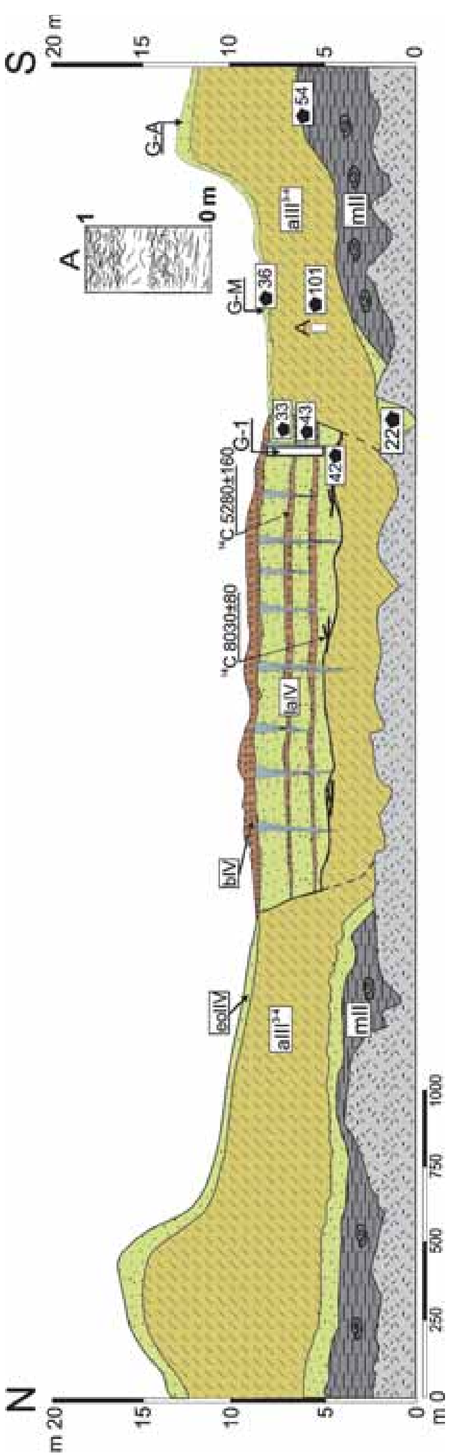

Fig. 7. Schematic representation of the structure of the coastal outcrops of Cape Pakha-Sale, the Gydan Bay (see legend of Fig. 3)

width of 1.2 m on top and the height of 3.6 m and the large lower-layer SPIW with the width of 2.5 m on top and the height of more than 10 m. The isotopic composition of the upper-layer SPIW changes from -23.6 to -18.3‰ for oxygen ($\delta^{18}O$) and from -179.9 to -134.3‰ for hydrogen (δD); the deuterium excess (d excess) changes from 9 to 12‰.

Large SPIW is not observed in the outcrop's southern part. It is possible that it was cropped by slope processes or partly thawed. Here, thin (with the width of up to 0.4 m) ice wedges with the average thickness of 4.5 m (observation point GD1) penetrate sands and sandy silts. The content of oxygen and hydrogen stable isotopes in the ice does not change with depth and is –24.6...–22.6‰ for $\delta^{18}O$ and –193.1...–176.5‰ for δD; the deuterium excess does not exceed 6–7‰.

The eastern coast of the Gydan Bay

The coastal cliff structure near Cape Pakha-Sale was another area of the research (Fig. 7).

Here, marine and coastal-marine sand-aleuric deposits outcrop in coastal cliffs with the height of 15–20 m. More ancient marine deposits are overlaid by the Late Pleistocene-Holocene continental sediments with plant detritus. A large amount of bone debris that was washed out of the coastal cliffs is scattered along the beach.

A lens of lacustrine deposits with the thickness of 4–6 m and the visible length of 1200 m contains layered sandy silts saturated with organic matter.

The age of wood inclusions at the depth of 2.6 m is 5,280 ± 160 yrs (LU 6540) and is 8,030 ± 80 yrs (LU 6541) at the depth of 6 m. The lacustrine deposits lens is embedded along the strike into a band of light dusty sandy silts that form the slopes of a thermokarst depression and surfaces 15 m high. Sandy silts consist of 83% of silt-sized particles. The lacustrine deposits include the SPIW complex. The ice wedges form a polygonal network on the surface with the polygon side of 18–55 m.

Ice-wedges have the width of 20–50 cm on top and the length of 2–5 m. The SPWI isotopic composition is –19.1‰ for oxygen ($\delta^{18}O$) and –146.2 ‰ for hydrogen (δD); the deuterium excess (d excess) is 7.2‰.

The filling of the thermokarst depression occurred in two stages. The deposits accumulated during the first stage in the beginning of the Holocene. They got into the lake during the destruction of the coasts formed by dusty sandy silts with high ice content. The coarser sand sediments accumulated at the end of the filling. A horizon with a relatively low ice content and post-cryogenic cryostructure points to the existence of talik under the lake.

DISCUSSION

The investigated Late Pleistocene and Holocene sediments of the Kara Sea coast were dated using radiocarbon AMS and infrared OSL. The radiocarbon AMS dates can be compared with the Kargino period (MIS3), because the Kazantsevo (MIS5) marine sands dated by IR OSL are located lower in the profile [Gusev et al., 2011; Nazarov, 2011; Gusev and Molodkov, 2012]. The radiocarbon age of peat near Sopochnaya Karga indicates the Kargino age; during the same period, the peat accumulation occurred at the Gydan Peninsula [Trofimov et al., 1986], Sibiryakova Island [Streletskaya et al., 2012], and Taymyr [Bolshiyanov, 2006]. Inversion in the dates in the profile of Sopochnaya Karga (Fig. 3D) can be explained by movement of large landslides from higher surfaces composed of marine saline sediments to the younger lower hypsometrical levels composed of freshwater alluvial sands and sandy loams.

The sediments of the second terrace of the Yenisey River, the coastal cliff of the Gydan Bay near the Ery-Maretayakha River mouth and the sediments including SPIW of the lower layer of the Dikson exposure accumulated during the Late Pleistocene (MIS2) with sedimentation ending about 10 thousand years ago. Climate warming around 10-9 thousand years ago led to thermokarst development and peat accumulation. The coastal exposures near the Khrestianka River mouth have the most complete, for the region, Quaternary geological profile. The lower part of the profile near the Khrestianka River mouth is represented by clay sediments formed in the conditions of a cold marine basin (Sanchugovo formation) in the Middle Pleistocene. Cold climatic conditions characteristic of forest-tundra landscapes along the coasts of the sea basin were confirmed by the palynologic analyses. The layer contains mollusks and single shells of foraminifera. Sediments were freezing right after the sea regression, which allowed preservation of marine salts.

Marine clays of the Sanchugovo formation are overlain by sands of shallow sea. The granulometric-mineralogical analysis indicated that sands were deposited in an underwater beach zone near the river mouth. Results of the palinological spectra from the sands indicated that taiga with vast meadows existed along the coasts, which means that the landscapes characteristic of the Kazantsevo (MIS5) period were present.

High soluble salt content in the sorted sand layer and high ice content indicate that the sands were frozen in shallow marine conditions. Such conditions were favorable for preservation of moss particles, horizontal ice lenses, and fragments of the lower part of SPIW.

Formation of the upper clay layer containing fragments of pebbles, gravel, and boulders and overlaying the sands of the Kazantsevo formation occurred under conditions of shallow ice covered sea. For the conditions of a cold arctic basin with lower salinity, the foraminifera represented by small undeveloped shells are characteristic. Herbaceous and spore plants dominated in forest-tundra along the coasts. The post-cryogenic structure indicates epigenetic type of sediment freezing after sea regression. Peat of the Kargino formation overlays TMGI, which means that their formation occurred in the pre-Kargino (MIS3) time under syngenetic freezing of saturated desalinated alluvial-marine sediments in a shallow sea. It is possible that freezing of sediments was accompanied by formation of large pingoes.

Stable isotope compositions for different generations of ice wedges were analyzed for reconstruction of the palaeoclimate evolution. It is given for 15 ice wedges of five geocryological units. The isotopic composition of ice wedges on the Kara Sea coasts is highly variable throughout time, ranging between -26.8‰ and –16.2‰ for $\delta^{18}O$ and from –209.2‰ to –117.8‰ for δD. Recent ice wedges, sampled in the active layer, have heavier isotopic compositions around -17.0‰ for $\delta^{18}O$ and –121.0‰ for δD [Streletskaya et al., 2011].

The Holocene ice wedges (units Sopochnaya Karga, Dikson, Gydan) can be differentiated by means of stable isotopes, despite heavy isotopic composition in all of them. The ice wedges show a mean isotopic composition around –20.4‰ for $\delta^{18}O$ and –154.2‰ for δD (Fig. 8a).

Formation of alluvial sediments occurred under conditions of drying shelf [Stein et al, 2002]. The composition of pebbles and large grain sands indicates that the Yenisey River mouth was extended more than 300 km north relative to the present position [Streletskaya et al, 2009]. Change from marine to terrestrial conditions occurred rather quickly as there are no signs of thawing found in the roof of icy marine sediments (TMGI). Severe climatic conditions during formation of the second river terrace of the Yenisei supported a gradual increase of silt content from the bottom to the top of the profile and presence of SPIW. A complex of large SPIW of the second river terrace is characterized by light isotope composition and prevalence of HCO_3^- and Ca^{++} in the chemical composition of ice. A similar isotope and chemical composition is characteristic of SPIW of the lower level near the Dikson settlement and SPIW near the Krestianka River mouth [Streletskaya et al., 2011].

Temperature assessment [Vasilchuk, 1992] indicated that mean January temperatures were –40 ± 3°C. This is 12–15°C lower than the present (the January climatic mean for the Dikson weather station is –25.5°C).

Winter precipitation was formed in the continental conditions, with land occupying the modern shelf during the last cold stage (MIS2) up to 120 m depth (see map in Fig. 9).

Presence of ice fine-grained sediments near Dikson is explained by widespread nivation processes corresponding to the development of cold wind-blown snowpacks during cold periods. Such conditions were reconstructed for formation of the ice-complex in the Laptev Sea coast. In their ratio of sand, silt, and clay fraction, the ice rich deposits in the Dikson area are almost identical to the

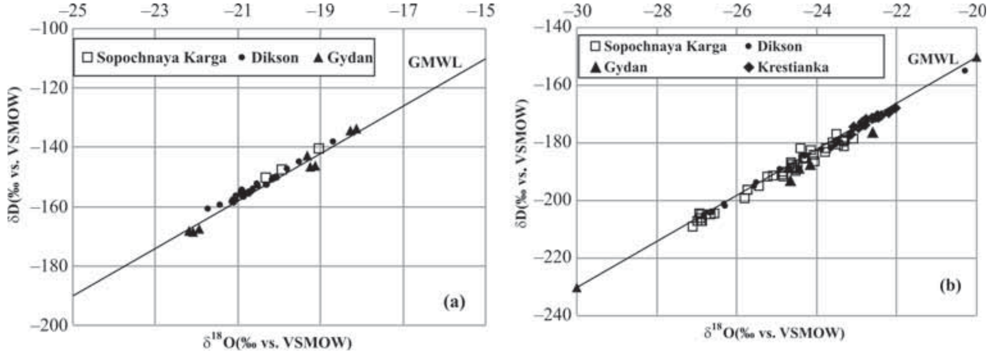

Fig. 8. δ^{18}O-δD diagrams for ice wedges in all geocryological units for different age sediments:
Holocene (a); Late Pleistocene (b)

"ice complex deposits" of known sections of shores of the Yakutia coastal lowlands and Alaska.

The Holocene SPIW isotopic composition reflects a higher winter temperature and an impact of the sea. The number of stable oxygen isotopes in SPIW decreases from the coasts to the inland of the peninsula. The isotopic composition of the Western Taymyr SPIW of the Late Pleistocene/Holocene age is similar in its values to the isotopic

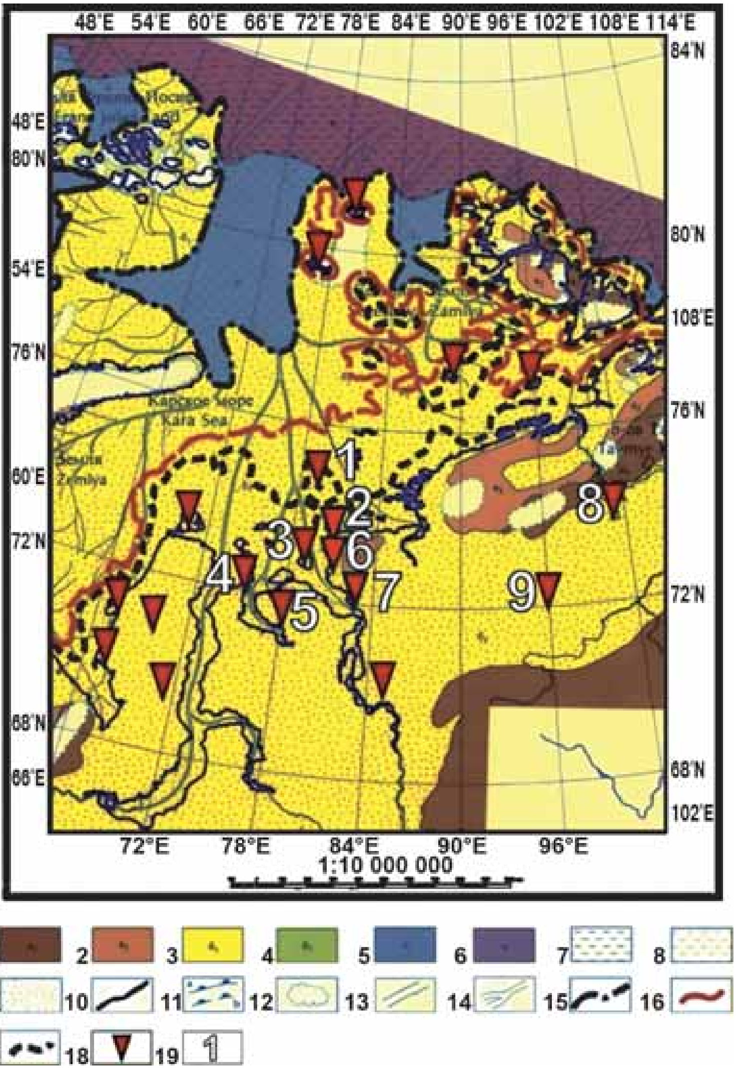

Fig. 9. Relict ice wedges in the Late Pleistocene – Holocene, the Kara Sea (based on the Atlas of paleographic maps (2004) and R. Stein et al., 2002 with additions).

1 – highlands; 2 – hills and lowlands; 3 – alluvial and lacustrine plans; 4 – river valleys and temporary lakes; 5 – continental shelf; 6 –oceanic areas; 7 –mud, clay/mudstone, shale; 8 –silt, siltstone; 9 – sand, sandstone; 10 – present day coastline; 11 – shelf edge at time of map a) determined b) inferred); 12 –ice sheets; 13 –submarine trench, canyon or channel; 14 –river paleovalley, submerged during transgressive phase; 15 –coastline at 18 000 y; 16 – coastline at 11 000 y; 17 – coastline at 9000 y; 18 – relict ice wedges. The sites with SPWI where isotopic composition was studied (see Table 2): 1 – the Sverdrup Island, 2 – the Dikson urban locality, 3 – Sibiryakov Island, 4- the Gydan Bay (west coast), 5 – the Gydan Bay (east coast), 6 – Krestianka, 7 – Sopochnaya Karga, 8 – Lake Taymyr, 9 – Lake Labaz composition of SPIW on the coasts of the Laptev and East Siberian Seas.

The Holocene and Late Pleistocene deposits have similar particle and mineralogical compositions. The Holocene deposits formed in the conditions of close redeposition and freezing of the pre-Holocene icy sediment during the cold periods of Holocene. The Holocene SPIW is characterized by a heavier isotope content relative to the Late Pleistocene. Mean January temperatures during formation of the Holocene SPIW are similar or slightly lower than at the present in the region. Extensive frost cracking and development or degradation of SPIW are attributed to changes in winter snow accumulation (rather than temperature).

CONCLUSIONS

The coastal exposures of the Gydan Bay and the Yenisey Gulf with and without inclusions of large bodies of ground ice were studied using comprehensive stratigraphic and geocryological methods, which allowed a reliable reconstruction of paleogeographic environmental changes in the Pleistocene and Holocene, including sedimentation and freezing conditions.

Transitions from the prolonged marine deposition environment to the terrestrial one were accompanied by freezing of marine sediments, formation of TMGI and SPIW. Marine sediments were replaced by alluvial-marine sediments during MIS5 to MIS4 transition. Reliably dated sediments of MIS4 were not found, but it is possible that the Zyran time (MIS4) corresponds to a break in sedimentation at the Yenisey North. After the terrestrial type of sedimentation, the new transgression occurred at the beginning of the Kargino time (MIS3). The sea level rise was quite short and by the second half of MIS3, the marine conditions of sedimentation transitioned to the terrestrial, which is confirmed by disappearance of foraminifera, sponge spicules, shells of marine diatoms, and their replacement of fresh-water diatoms, ostracodes, and, later, limnitic microflora and ostracodes. The majority of the loamy sediments of MIS3 are significantly saline in the lower part of the profiles with salinity decreasing toward the upper part of the profiles. The spore-pollen spectra derived from the samples of the sediments of the Kargino age (MIS3) are characteristic of the forest-tundra and tundra landscapes. Up the profile section in the direction of the sediments corresponding to the MIS2 age, the spectra are depleted until complete disappearance of palynomorphs.

Lower mean annual air temperatures, sea regression, and climate aridization occurred in the Late Pleistocene, which is inferred from the increase of the silt fraction content in the upper part of the alluvial terrace (Sopochnaya Karga) and on the slopes (Makarevich – Chrestianka), active cryogenic weathering (Dickson), and a light isotope composition of SPIW.

Dating of the sediments with SPIW indicates the Late Pleistocene – Holocene ages. Formation of SPIW occurred in two stages: in the Late Pleistocene (MIS2) and in cold periods of the Holocene, which is inferred from the stratigraphy, chemical and isotope analysis, and SPIW. A lighter isotope content (up to 6‰) and domination of calcium and the hydrocarbonate ions are characteristic of SPIW of the Late Pleistocene. A heavier isotope content and prevailing sodium and chlorine ions are typical for the Holocene ice.

In the Holocene, ice wedges were growing in the thermokarst depressions formed during the Holocene optimum and later filled with silty sediments with high ice content. The profiles are dominated by reworked pre-Holocene material and characterized by a higher organic content.

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REFERENCES

1. Atlas of paleogeographic maps (2004) In: M.N. Alekseev (Ed.), Shelf Regions of Eurasia for the Mesozoic and Cenozoic. Moscow, Nauchnyy Mir, 2, pp. 13–12 (in Russian).

2. Bolshiyanov, D.Yu. (2006) Passivnoe oledenenie Arktiki i Antarktidy (Passive glaciation of the Arctic and Antarctic). AARI, St. Petersburg, 295 p. (in Russian)

3. Craig, H. (1961) Isotopic variations in meteoric waters. Science 133, pp. 1702–1703.

4. Danilov, I.D. (1969) Merzlotno-facial'noe stroenie vodorazdel'nyh plejstocenovyh otlozhenij nizhnego techenija reki Eniseja (Cryofacial structure of the Pleistocene sediments of dividing ridges in the lower course of the Yenisey River). Problemy kriolitologii (Problems of cryolithology), 1, Moscow University Press, pp. 93–105 (in Russian).

5. Danilov, I.D. (1978) Pleistotsen morskikh subarkticheskikh ravnin (The Pleistocene of marine subarctic plains). Moscow University Press, 198 p. (in Russian).

6. Dansgaard, W. (1964) Stable isotopes in precipitation. Tellus 16, pp. 436–468.

7. Gusev, E.A., Arslanov, H.A., Maksimov, F.E., Molodkov, A.N., Kuznetsov, V.Yu., Smirnov, S.B., Chernov, S.B., Zherebtsov, I.E., Levchenko, S.B. (2011) New geochronological data on the Neopleistocene-Holocene sediments from the lower Yenisey area // Problemy Arktiki i Antarktiki, 2(88), pp. 36–44 (in Russian).

8. Gusev, E.A., Molodkov, A.N. (2012) Structure of sediments of the final stage of the Kazantsevo Transgression (MIS5) in the North of Western Siberia // Proccedings, Earth Sciences, 2012. Vol. 443. Part 2. pp. 458–461.

9. Kaplyanskaya, F.A, Tarnogradsky, V.D. (1986) Remnants of the Pleistocene ice sheets in the permafrost zone as an object for paleoglaciological research. Polar Geography and Geology 10, pp. 257–265.

10. Matyukhin, A.G., Streletskaya, I.D. (2012) The Salinity of Cryogenic Quaternary Deposits in the Yenisei North. In: V.P. Melnikov (Ed.), Proceeding of the Tenth International Conference on Permafrost, The Northern Publisher, Salekhard, Russia, 2, pp. 259–262.

11. Meyer, H., Schönicke, L., Wand, U., Hubberten, H.-W., Friedrichsen, H. (2000) Isotope studies of hydrogen and oxygen in ground ice – experiences with the equilibration technique. Isotopes in Environmental and Health Studies 36, pp. 133–149.

12. Nazarov, D.V. (2011) Quaternary deposits of the central part of the West Siberian Arctic. Ph.D thesis. Geol. Mineral. Sciences. St. Petersburg State University. 26 p.

13. Oblogov, G.E., Streletskaya, I.D., Vasiliev, A.A., Gusev, E.A., Arslanov, H.A. (2012) Quaternary deposits and geocryological conditions of Gydan Bay Coast of the Kara Sea. In: V.P. Melnikov (Ed.), Proceeding of the Tenth International Conference on Permafrost, 2012, The Northern Publisher, Salekhard, Russia, 2, pp. 293–296.

14. Romanenko, F.A., Mikhalev, D.V., Nikolaev, V.I. (2001) Podzemnye l'dy na ostrovah u beregov Tajmyra (Ground ice on the islands next to the Taymyr coastline). MGI (Materials of Glaciological Studies. Chronicles, Discussion) 91, pp. 129–137 (in Russian).

15. Solomatin, V.I. (1982) Pogrebennye relikty lednikovogo l'da na severe Zapadnoj Sibiri (Buried relicts of glacial ice in the north of West Siberia). MGI (Materials of Glaciological Studies. Chronicles, Discussion) 29, pp. 233–240 (in Russian).

16. Stein, R., Niessen, F., Dittmers, K., Levitan, M., Schoster, F., Simstich, J., Steinke, T., Stepanets, O. (2002) Siberian river run-off and late Quaternary glaciation in the southern Kara Sea, Arctic ocean: preliminary results. Polar Research 21(2), 315-322. doi: 10.1111/j.1751–8369.2002.tb00086.x

17. Streletskaya, I.D., Vasilev, A.A. (2009) Izotopnyj sostav poligonal'no-zhil'nyh l'dov zapadnogo Tajmyra (Isotopic composition of polygonal wedge ice of Western Taymyr). Kriosfera Zemli (Earth Cryosphere), 13 (3), pp. 59–69 (in Russian).

18. Streletskaya, I.D., Vasiliev, A.A. (2012) The Ice Complex of Western Taymyr. In: V.P. Melnikov (Ed.), Proceeding of the Tenth International Conference on Permafrost, The Northern Publisher, Salekhard, Russia, 2, pp. 433–438.

19. Streletskaya, I.D., Gusev, E.A., Vasiliev, A.A., Kanevskiy, M.Z., Anikina, N.Yu., Derevyanko, L.G. (2007). Novye rezul'taty kompleksnyh issledovanij chetvertichnyh otlozhenij Zapadnogo Tajmyra (New results of Quaternary sediment studies of Western Taymyr). Kriosfera Zemli (Earth Cryosphere), 11 (3), pp. 14–28 (in Russian).

20. Streletskaya, I.D., Vasiliev, A.A., Gusev, E.A., Kanevskiy, M.Z., Medvedeva, M.A., Vanshtein, B.G., Cherkashov, G.A., Bolshiyanov D.Yu. (2009) Chetvertichnye otlozhenija, podzemnye l'dy i dinamika beregov Zapadnogo Tajmyra (Quaternary deposits, ice complex, and coastal dynamics of Western Tayimyr). In: H. Kassens, A.P. Lisitsyn, J. Thiede, E.I. Polyakova, L.A. Timokhov, I.E. Frolov (Eds.), Sistema morja Laptevyh i prilegajushhih morej Arktiki: Sovremennoe sostojanie i istorija razvitija (The system of the Laptev Sea and the adjacent Arctic seas: Current state and history of development), Moscow, Moscow University Press, pp. 357–372 (in Russian).

21. Streletskaya, I., Vasiliev, A., Meyer H. (2011) Isotopic Composition of Syngenetic Ice Wedges and Palaeoclimatic Reconstruction, Western Taymyr, Russian Arctic. Permafrost and Periglac. Process. 22, 101–106. doi: 10.1002/ppp.707.

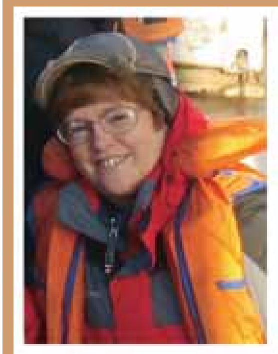
22. Streletskaya, I.D., Vasiliev, A.A., Slagoda, E.A., Opokina, O.L., Oblogov G.E. (2012) Poligonal'no-zhil'nye l'dy na ostrove Sibirjakova (Karskoe more) (Poligonal ground-ice wedges on the Sibiryakov Island (the Kara Sea)). Vestnik Mosk. University, Ser. "Geography" (Bulletin of Moscow University, "Geography"), 3, pp. 57–63 (in Russian).

23. Svendsen, J.I., Alexanderson, H., Astakhov, V.I., Demidov, I., Dowdeswell, J.A., Funder, S., Gataullin, V., Henriksen, M., Hjort, C., Houmark-Nielsen, M., Hubberten, H.-W., Ingólfsson,

Ó., Jakobsson, M., Kjær, K.H., Larsen, E., Lokrantz, H., Lunkka, J.P., Lyså, A., Mangerud, J., Matiouchkov, A., Murray, A., Möller, P., Niessen, F., Nikolskaya, O., Polyakh, L., Saarnisto, M., Siegert, C., Siegert, M.J., Pielhagen, R.F., Stein R. (2004) Late Quaternary ice sheet history of northern Eurasia. Quaternary Science Reviews 23, 1229-1271. doi: 10.1016/j.quascirev.2003.12.008

24. Trofimov, V.T., Badu, Yu.B., Vasilchuk Yu.K. (1986) Inzhenerno-geologicheskie uslovija Gydanskogo poluostrova (The Gydan Peninsula engineering-geological conditions). Moscow, MSU Press, 212 p. (in Russian).

25. Vasilchuk, Y.K. (1992) Izotopno-kislorodnyi sostav podzemnykh l'dov – Opyt paleogeokriologicheskikh rekonstrultsii (Oxygen Isotope Composition of Ground Ice – Application to Paleogeocryological Reconstructions). Moscow State University Publishers, Moscow (in Russian).



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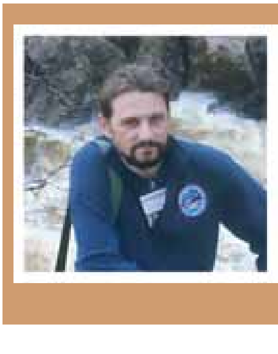

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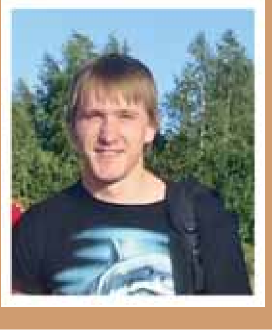

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