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14C AGE, STABLE ISOTOPE COMPOSITION AND POLLEN ANALYSIS OF MASSIVE ICE, BOVANENKOVO GAS FIELD, CENTRAL YAMAL PENINSULA

ABSTRACT. The origin of the massive ice is important for understanding the Quaternary history of the Yamal region and to predict the occurrence of massive ice, which is important for gas exploration and the development of infrastructure. Massive ice bodies occur in the Bovanenkovo gas field area within sediments such as layers, laccoliths, rods and lenses. Maximal thickness of the tabular ice is 28,5 m; mean thickness is about 8 m. Deposits of the third terrace underlying and overlapping the tabular ice had been formed from 25 ka BP to 20 ka BP, according to ^{14}C dates. Oxygen-isotope values ($\delta^{18}O$) of massive ices are ranged from 12, 49‰ up to −22, 95‰. Deuterium (δD) values vary from −91, 7‰ up to −177, 1‰. Deuterium excess (d_{exc}) changes from 3, 4 to 10, 6‰. Both homogenous and contrast distribution $\delta^{18}O$ and (δD) vs. depths in massive ice bodies evidences the segregated and/or infiltrated-segregated manner of ice formation. Pollen, spores and algae spectra from ice are similar to pollen characteristics of modern lacustrine and coastal floodplain sediments in the area. The ingression of cold seawaters on a coastal flood plain caused freezing and ice segregation, with the formation of extensive ice layers under the large but shallow lakes. As a result, syngenetic and genetically heterogeneous ice, such as: segregated, infiltrated-segregated, lake bottom congelation ice etc. was formed.

KEY WORDS: massive ice, stable isotope composition, pollen, ^{14}C age, Yamal Peninsula.

INTRODUCTION

Massive ice is a cryogenic phenomenon that is dangerous for building and the exploitation of construction within a permafrost area. Understanding the origin of the massive ice helps to elucidate the Quaternary history of the Yamal region, and to predict the occurrence of massive ice, which is important for gas exploration and the development of infrastructure. It was often supposed that this kind of ice was a relic of Quaternary glaciations. However, much evidence of intrasedimental origin of massive ice has also been obtained [Mackay, 1989]. However, up to the present, there

is no clear indicator for the selection of intrasediment massive ice from buried ice. We suppose that permafrost conditions are favourable for the formation of segregated or segregated-infiltrated, injected, mixed type of massive ice and also for the syngenetic burial of bottom ice, coast ice, iceberg ice, glacier ice etc.

The folds and deformation of an ice body and surrounding sediment are usually considered as morphological criteria of glacier activity. Intensely folded massive ice, containing structures such as thrusts, recumbent isoclinal folds, augen structures, is a clear sign of glaciotectonic deformation, and could be glaciotectonically deformed intrasedimental ice, glaciotectonically deformed basal ice, glaciotectonically deformed firnified ice. At the other extreme, massive ice containing, e.g. simple anticlines (e.g. Peninsula Point as shown by Mackay, Dallimore [1992]) probably has nothing to do with glaciotectonic deformation, but such cryogenic slide-like deformations are often formed under freezing conditions, as a result of volume changes in the sediment, both in sub-aerial and sub-aqueous environments. Vertical and horizontal tectonic activity also caused fold formation in frozen, melted and even metamorphosed rock. It is clear that the occurrence of any folds is not a guaranteed indicator of the glacier origin of massive ice.

Waller et al. [2009] accentuated the potential benefits of interdisciplinary research into the formation of basal ice beneath glaciers, and the origin of massive ice in glaciated permafrost regions. We found that palynological analysis helps to distinguish buried glacial ice from ice of other types [A. Vasil'chuk & Yu. Vasil'chuk, 2010a, b, c]. In glacier ices, distant, wind-transported pollen grains dominate; a minor part of pollen spectra is presented by regional pollen and spores, and local components are sporadic and limited by several species only [Andreev et al., 1997; Bourgeois, 2000]. In the massive ice of another origin, regional and local tundra pollen spectra dominate as a rule [A. Vasil'chuk, 2005, 2007]. Certainly, it is

necessary to remark that ice derived from groundwater could be identical to basal glacier ice, because it may contain pollen and spores from underlying sediment, which could penetrate into the ice through micro-cracks. Such micro-cracks have been described in glacier models [Knight et al., 2000]. Pollen could also be carried into the basal ice by sub-glacial groundwater flow, and therefore, be flushed out from any periglacial sediments. But the Late Glacial Maximum ice limit is located many kilometers from the Yamal Peninsula [Svendsen et al., 2004], so remnants of Late Pleistocene basal ice are unlikely here.

The chemical composition of the ice may only be an additional method for the detection of massive ice origin because massive ice is mainly fresh or ultra-fresh as glacier ice. Sometimes fresh massive ice is found in salted sediments. Salted ice rarely occurs in salted sediments. In the severe climatic and geocryological conditions of the Yamal Peninsula, the lakes were the exclusive sources which could provide the regular entry of the enormous volumes of ultra-fresh water into the stratum of frozen marine deposits. The hydrochemical similarities of the chemical composition and the mineralization of the repeatedly injected massive ice beds and lake water have been proved [Fotiev, 2012].

The composition of air bubbles have been used as an indicator of massive ice origin in recent studies [Cardyn et al., 2007; Lacelle et al., 2007]. This method will give reliable indicators of massive ice origin in the near future, but it requires high accuracy at all stages of the investigation – at the sampling, preservation and extraction of air bubbles – and contamination is possible at all these stages.

Stable isotope study of massive ice is relatively simple at the sampling and analysis stage, and is sensitive and complex at the interpretation stage. The isotope method requires both detailed vertical and horizontal sampling of all varieties of the ice in the ice

body; for example, milk ice, transparent ice, dirty ice etc. It also requires the analysis of all ice varieties in the exposure, such as ice lens, vertical and horizontal schlieren ice in surrounding sediments. It is possible to create an archive of reference isotope signatures for massive ice of different origins, as a result of the isotope study of massive ice. Intrasedimental ice is generally thought to be formed within the surrounding sediments, and includes segregation ice, intrusive ice and segregation-intrusive ice [Mackay, 1971, 1983, 1989; Rampton & Mackay, 1971; Zhestkova, Shur, 1978; Rampton, 1988; Vasil'chuk, Trofimov, 1988; Mackay & Dallimore, 1992; Vasil'chuk, 1992, 2012, 2014; Dubikov, 2002, Khimenkov, Brushkov, 2006]. Buried ice may be formed by the burial of surface or glacial ice. Probably buried ice [Fujino et al., 1988], glacial ice [Dallimore & Wolfe, 1988; Gowan & Dallimore, 1990; Waller et al., 2009] and snow-bank ice [Pollard & Dallimore, 1988] has been identified at several sites in the Tuktoyaktuk Coastlands and on the Yukon coastal plain.

A considerable effort has been devoted over the past forty years to determining the origin of thick bodies of massive ice, which are common throughout the Yamal Peninsula. Buried ice and glacial ice has been identified at several sites in the Yamal Peninsula. The isotopic composition ($\delta^{18}O$ and δD) of Canadian [Mackay, 1983; Fujino et al., 1983, 1988; Dallimore & Wolfe, 1988; Pollard & Bell, 1998; Murton, 2005, 2009; Murton et al., 2005; Lacelle et al., 2007] and Siberian [Vasil'chuk & Trofimov, 1988; Yu. Vasil'chuk, 1992, 2006b, 2010, 2011a; Michel, 1998; Lein et al., 2003] massive ground ice has been used for the adjustment of the ice origin.

STUDY AREA AND STRATIGRAPHY

The study area is located within the limits of the Bovanenkovo gas field, Central Yamal Peninsula, north of Western Siberia (Fig. 1).

A distinctive characteristic of the stratigraphy is the widespread bodies of massive ice
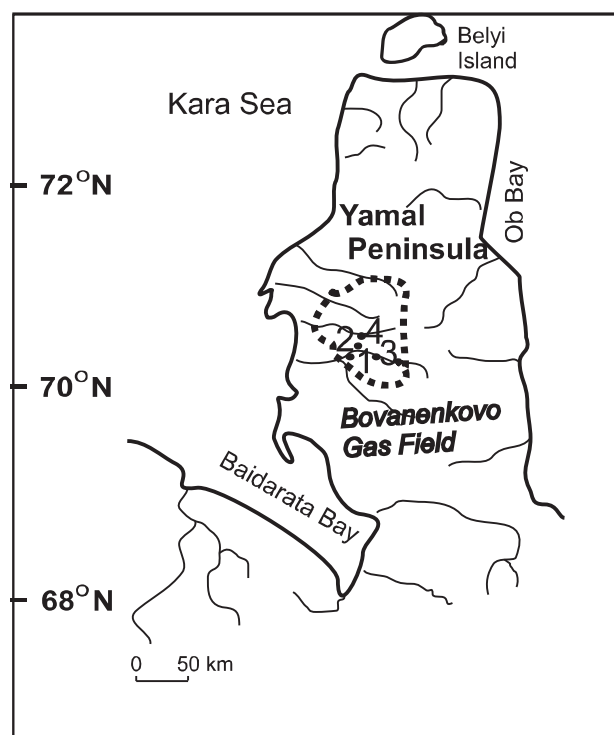

Fig. 1. Location map of Bovanenkovo gas field, Central Yamal Peninsula north of Western Siberia (70°9′N, 68°42′E); and scheme of study sites:

1 – borehole 34; 2 – site Gas compressor stations (GCS); 3 – site K 64; 4 – massive body 4.

revealed in boreholes and natural exposures. We analysed about 260 boreholes drilled in the early 1990s, in the Bovanenkovo area, at the watershed of the Nadujyaha and Nguriyaha Rivers.

As a rule massive ice is found in the borehole profiles at outliers of the third and second terraces (absolute elevation from 15–20 to 40 m), and at the alluvial and lacustrine-alluvial floodplains as well [Solomatin et al., 1993; Parmuzin, Sukhodol'skiy, 1982; Velikotsky, 1987; Baulin et al., 1989; Kondakov et al., 2001; Baulin, 1996; Vasil'chuk et al., 2009; Vasil'chuk, 2006b, 2010, 2012, 2014; Chuvilin, 2007; Streletskaya et al., 2013; Solomatin, 2013]. A massive ice layer from 7 to 9 m was even found under the channel of the Seyaha River [Solomatin et al., 1993]. The cartometric calculations have revealed the insignificant but stable increase of lake areas and number on the low hypsometrical levels over the past 20 years, owing to the melting of icy sediments and ice bodies [Sannikov, 2012].

The massive ice often occurs as layers (Fig. 2, *a*) or interrupted lenses (Fig. 2, *b*, *c*, *d*).
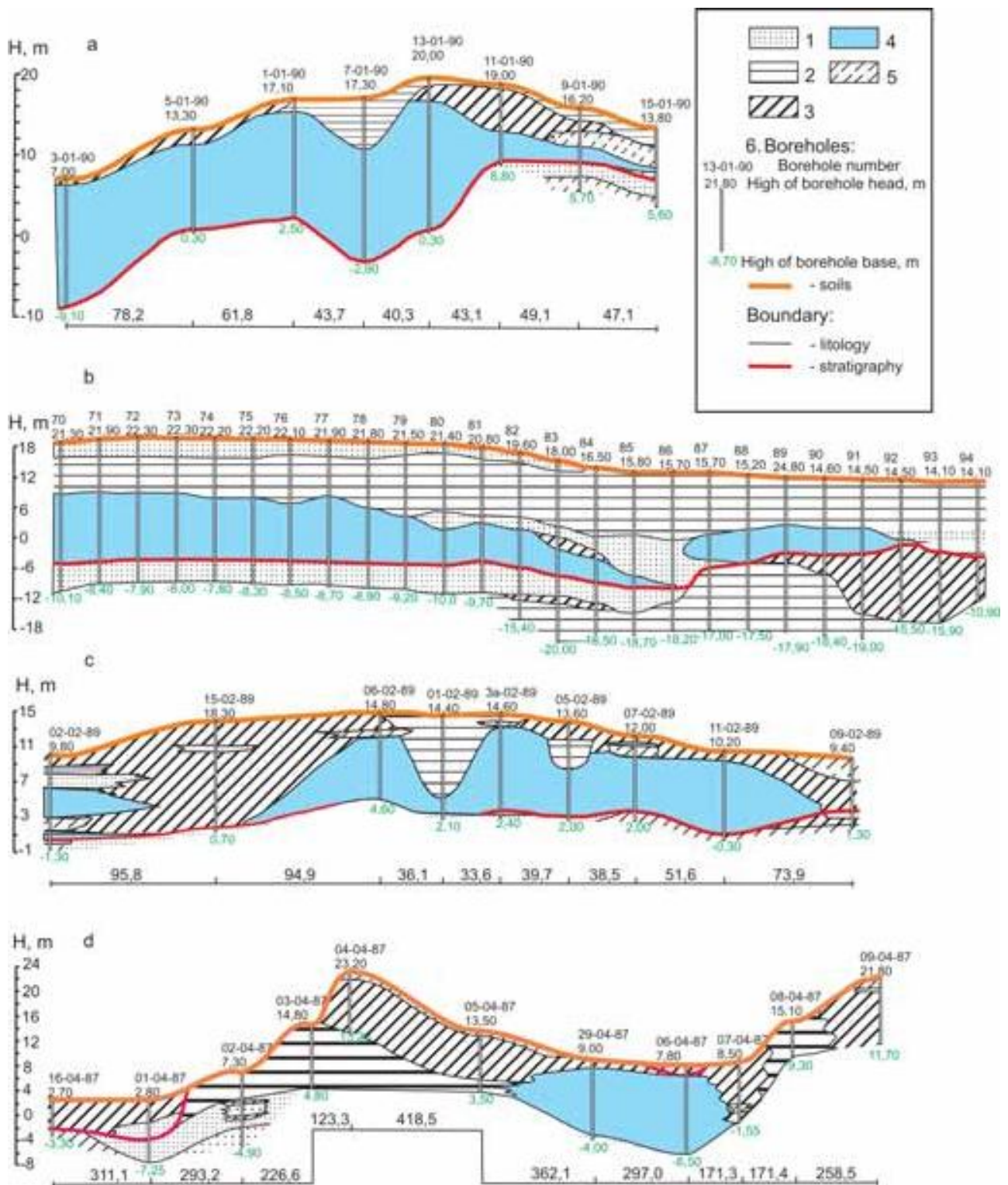
Fig. 2. Massive ice bodies at the third terrace Bovanenkovo gas field:

1. sand; 2. clay; 3. loam; 4. massive ice; 5. clay sand; 6. location and characteristics of boreholes.

The roof of the massive ice is located both at the base of the active layer and at a depth of 52 m. The base of the massive ice occurred at a depth of 1–57 m, but the massive ice base is not located below –21, 5 m of absolute elevation. The roof of the massive ice is relatively uneven, and the roof and the base of the ice are not parallel in many cases (Fig. 2, *c*). Maximum thickness of the ice in borehole is 28, 5 m, and the mean value is

8 m (as a result of 260 measurements). The lateral extent of massive ice bodies is more than 200 m, and the area often is more than 10 km^2. There are two main types of massive ice: pure layered ice (Fig. 3, *a*); and layered ice with a band of ground between white and grey layers (Fig. 3, *b*).

There are primary and secondary contacts between the ice and host sediments. As has

Fig. 3. (a) Stratified massive ice body, and (b) band of ground between layers of white and gray clear (overhead) and clear (below) ice, at the third terrace of the Bovanenkovo gas field. Thickness of single layer is about 25–35 cm. Photo by Ye.Ye. Podborny.

been shown by the investigation, primary contacts are typical for localities where erosion of host Late Pleistocene sediments didn't affect the surface of the massive ice. Clay and loam are characterized by a great number of ice lenses, which form reticulate structures at the contact with massive ice. The height of separate vertical lenses is about 10–20 cm, while the width of horizontal lenses is smaller. Volumetric ice content of sediments covering massive ices is more than 50–60%. Upwards the ice content decreased to 25–30% and the cryogenic structure became quasi-reticulate. A large number of clay particles of 2–3 cm in size often occurred at the contact zones in the massive ice. The amount of clay inclusions decreased with distance from the contact zone [Parmuzin, Sukhodol'sky, 1982].

More than half of the boreholes revealed secondary contact. These boreholes were drilled mainly on the slopes of terraces. Ice bodies here formed near the surface and were covered only by a thin layer of slope deposits. According to Parmuzin and Sukhodol'sky [1982], secondary contacts are peculiar to the majority of massive ice exposed within watersheds. Only in two cases has the ice body been covered by Late Pleistocene sediments. As a rule, primary contacts are observed deeper than secondary ones. The thickness of Late Pleistocene sediments above the massive

ice is about 10–15 m. The revealed primary contacts found at the top parts of slopes and horizontal surfaces of a terraces are without thermo-denudation signs.

Within the remaining terraces only one borehole number 27–28 at 6 m abowe see lewel has revealed the contact of fine-grained sand with underlying massive ice. However, the thickness of massive ice is unknown owing to the partial thawing of ice during slope development, and it is obvious that the thickness of ice at some localities is not less than 25 m [Parmuzin, Sukhodol'sky, 1982]. Massive ice bodies are covered by Pleistocene-Holocene delluvial-solifluction clay or loam. The former lies in the terrace pedestal and is covered by the horizontal layer of Late Pleistocene sandy loam and sand. The latter covers the slopes of terraces like a blanket at a thickness of 1–6 m.

According to Parmuzin and Sukhodol'sky [1982], secondary contacts had been formed at the sites where ice bodies partially thawed and were covered by younger sediments, owing to thermo-denudation. These contacts are more contrasting than the primary ones. The cryogenic structure of cover sediments at the contact zone is constant, and ice content is also constant. Massive ice at the contact zone is either clean or has an admixture of mineral particles. The secondary contacts at some

Fig. 4. Secondary downhill contact of massive ice with slope sediment. Photo by G.A. Rzhanitsyn.

cross-sections are formed by the ice layer up to 1 m, with a high concentration of mineral admixture, about half of the bulk volume of the ice [Parmuzin, Sukhodol'sky, 1982]. This formation is a result of the fast freezing of water-saturated ground mass flowing on the surface of the ice body, which is exposed as a result of the thawing of overlapping icy sediments. It was a mixture of thawed soil, water and peaty material, flowing down the headwall of massive ice, exposed in retrogressive thaw slumps and refreezing in the autumn. The mineral inclusions are syngenetic to the ice, and were formed as a result of the segregation of saturated water. Such flows of icy ground slowly moving down from the ledge of thawing ice had been observed at many localities of the watershed. Secondary downhill contact of massive ice with slope sediment is observed at the slopes of the third terrace (Fig. 4; 5, *a*).

Secondary gently sloping contact of massive ice with lacustrine sediment (Fig. 5, *a*) may

**Fig. 5. (a) Secondary downhill contact of massive ice with slope sediments;
and (b) feather-like secondary contact as a result of lake abrasion.
Photos by Ye.Ye. Podborny and F.A. Romanenko.**

be a result of surface thermokarst and the formation of a small lake (hasyrey or alas), immediately above the roof of the tabular ice.

Mackay [1989] and Mackay and Dallimore's [1992] called such secondary contacts 'thaw unconformities'. Feather-like secondary contact formed as a result of lake abrasion and the partial melting of the side of the tabular ice (Fig. 5, *b*).

Some data show great sizes, and accordingly, great volumes of ice bodies. In the northern part of the profile near the Nguriyaha River valley, three boreholes revealed massive ice approximately at the same depths. The distance between boreholes was about 1 km, which was too large to assume the existence of single ice body with confidence, with a length of up to 2 km. At the same time, detailed studies of massive ice within the terrace at the right bank of the Seyaha River suggest the existence of ice bodies with a lateral extent of 1–2 km or more [Parmuzin, Sukhodol'sky, 1982].

MATERIALS AND METHODS

Analysis of boreholes and exposures with massive ice allowed us to define some features of massive ice distribution and occurrence in the Middle Yamal Peninsula.

In order to specify formation conditions and the age of massive ice around the Bovanenkovo gas field ^{14}C dating, stable isotope analysis and palynologic studies were carried out.

Over forty samples of massive ice, ice-wedge ice and water (lake, river and cryopeg) were brought to the isotope laboratory of the Austrian Research Center (ARC), in Seibersdorf. Stable isotope measurements were performed using isotope mass spectrometers (Finnigan MAT 251 and Delta Plus XL), equipped with automatic equilibration lines. All results were reported as relative abundance (δD and δ^{18}O, respectively) of the isotopes D and ^{18}O in permil (‰), with respect to the international standard VSMOW (Vienna Standard Mean Ocean Water). The accuracy of δD and δ^{18}O measurements is better than ± 1, 0‰ and ±0,1‰, respectively.

SOME FEATURES OF GLACIATION OF YAMAL PENINSULA IN THE LATE QUATERNARY

According to reconstructions [Svendsen et al., 2004] from the vast lowland areas between Taimyr and the Pechora River, there are no convincing geological data to suggest any Middle Weichselian ice sheet advance (Fig. 6).
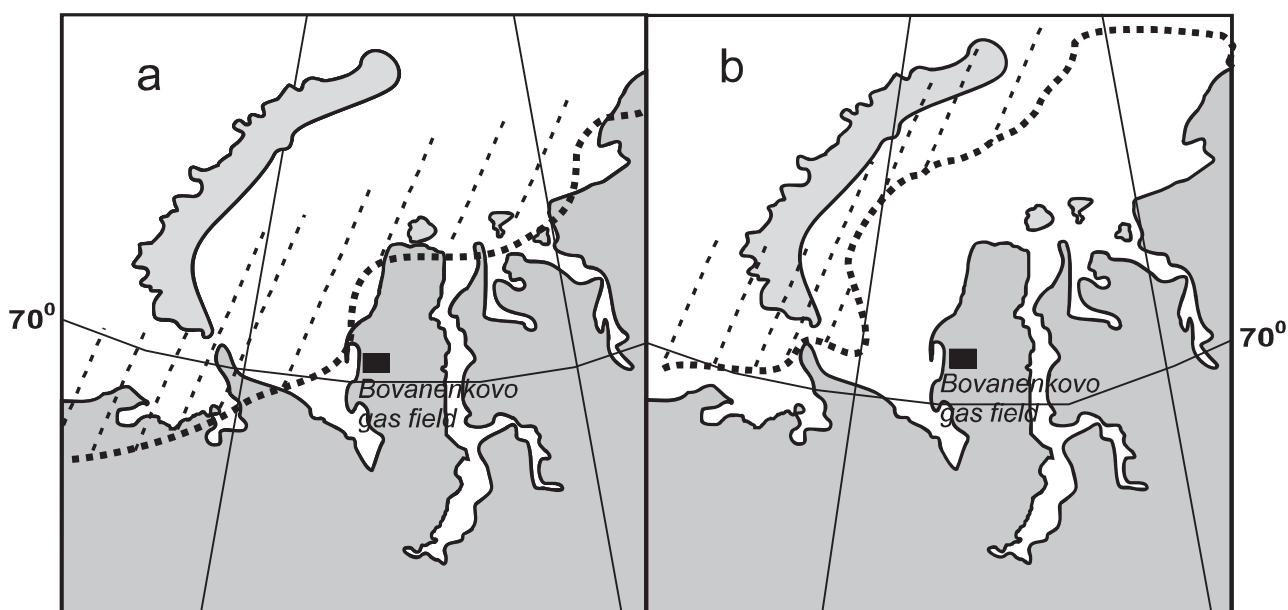

Fig. 6. (a) Location of the Eurasian ice sheet extent (dotted line) during the Middle Weichselian glacial maximum, 60–50 ka BP and (b) at the Late Weichselian glacial maximum (LGM), about 20 ka BP, according to Svendsen et al. [2004].

During the Late Weichselian, the southern ice sheet limit was evidently located on the sea floor, off the Siberian mainland. In the southern Kara Sea, the LGM ice sheet most likely corresponded to a well-defined morainic ridge, SE of Novaya Zemlya. Further north, the ice limit was probably localized along the eastern margin of the Yamal Peninsula, located many kilometers to the east of the LGM ice limit [Svendsen et al., 2004]. Surging from the higher parts of the ice sheet at its Barents-Kara Sea interfluve, north of Novaya Zemlya, could have been very short-lived, and the ice masses may have blocked the northward flow of water from the Yenisei and Ob Rivers for only a brief interval.

Concerning the correlation between the Late Quaternary transgression of the sea and glaciations in the Yamal Peninsula, the majority of scientists marked out the complex of marine terraces on the western coast, and lagoon marine terraces on the eastern coast [Saks, 1953; Danilov & Yershov, 1989; Baulin et al., 1989, 1996; Vasil'chuk, 1992], which accumulated in last 40–50 kyr. However, some investigators believe that dislocated sediments that are usually found on the west coast have a glacial origin [Kaplyanskaya, Tarnogradsky, 1986; Forman et al., 2002]. We have yielded many ^{14}C dates in syngenetic sediments with ice wedges as evidence that, during the last 40–50 kyr, large ice wedges had accumulated both at the west and eastern areas of the Yamal Peninsula [Vasil'chuk, 1992, 2006a]. Such ice wedges have not been found in the glaciated area.

The polar Ural Mountains are supposed to be one of the main regions of glaciation source. However, Mangerud et al. [2008] concluded, on the basis of a 10-year investigation, that glaciers in the Polar Urals were not much larger than at present. A combination of local factors and especially the very low LGM winter precipitation explains the surprisingly small Ural glaciers during the Last Glacial Maximum. A similar situation is described at the middle-high northern latitudes of

Severnaya Zemlya [Raab et al., 2003]. Both the Polar Urals and Severnaya Zemlya are located to the east of the Scandinavian-Barents ice sheets, but Severnaya Zemlya is located at 79 °N; i.e. more than 12° further north than the Polar Urals. To our knowledge, the only place with glacier relief is located to the south-west of the Yamal Peninsula, near Bolshoi Sopkai, which sides with the Polar Urals. In the other territory of Yamal, there are three levels of marine accumulative terraces, and Kazantsev (Eem) and Salekhard (Sangamon) coastal lowlands occur within the Central Yamal Peninsula.

RESULTS

The ^{14}C age of sediments containing massive ice bodies

The time of massive-ice formation depends on the age of hosting sediments and the time of their freezing. The thermoluminescence dating (TL) of 6 samples from 300 m borehole reveal an age from 22 ± 7 ka BP (of the sandy horizon directly beneath a massive ice body) to 197 ± 25 ka BP at a depth of 300 m. The upper part of marine sand accumulated at a rate of 5–8 m/kyr, and the lower part at 2–3 m/kyr [Solomatin et al., 1993]. According to these data, the age of perennially frozen marine sand and sandy loam, underlying the massive ices within the third terrace, can be from 22 to 30 ka BP. This is in agreement with our radiocarbon dating of plant residues from sediments containing massive ice within the third terrace (Table 1).

However as thermoluminescence (TL) dating and ^{14}C dating were carried out within a 30-year interval, the location of the radiocarbon and TL-dates is indeterminate. There are also 31 and 34 ka BP dates which can be a result of the active redeposition of organic material in fluvial conditions [Yu. Vasil'chuk, A. Vasil'chuk, 2010]. The dates of 25 and 26 ka BP are closest to the age of loamy sediments of the third terrace. Therefore, the sandy loam containing the massive ice was deposited from 25 to 20 ka BP, or a little later. According to the stable isotope

Table 1. Radiocarbon dates of organic material from sediments including massive ice body (body 1) in the third terrace of the Seyaha River, Bovanenkovo

Depth, m	Dated material	Laboratory number	14C-age, kyr BP
Seyaha River, site GS-1, 2.5 m above river level	Peat	GIN-13311	34200 ± 1000
Seyaha River, site GS-1, 2.0 m above river level	Peat	GIN-13312	26100 ± 150
Seyaha River, site GS-1, 2.0 m above massive ice roof	Peat	GIN-13313	31900 ± 500
Thermo-abrasion circus, 1.1 m above massive ice roof	Peaty loam	GIN-13314	28900 ± 1000
Thermo-abrasion circus, depth 10.3 m	Peaty loam	GIN-13326	25600 ± 700
Thermo-abrasion circus, depth 1.3–1.4 m	Peaty loam	GIN-13327	25100 ± 500

composition of synchronous ice wedges [Vasil'chuk, 2006], this was the period of the most severe climatic conditions of the final stage of the Late Pleistocene cryochrone [Vasil'chuk, 1992]. Winter temperatures were colder than present by 6–8 °C [Vasil'chuk, 1992; Vasil'chuk, 2006a; Vasil'chuk et al., 2000].

The abundance of organic matter in sediments overlying and underlying the massive ice suggests that peaty loams containing massive ice have been deposited either in shallow coastal conditions, or from periodically drained beaches or low coastal floodplains. There, organic material has accumulated as a result of washout and redeposition, as well as during the period of drainage and overgrowing of these areas. As has been established, the modern coastal area of the Yamal Peninsula, are located below the Kara Sea and Ob bay level; 22–11 kyr BP [Vasil'chuk, 1992]. Marine forms are found in the sediments of the third terrace accumulated 22–11 kyr BP [Vasil'chuk et al., 2000].

In the contemporary climate, the beach and low coastal flood plain sediment of the Kara Sea and Baidarata Bay are frozen perennially 25–20 ka BP, and in more severe conditions these sediments froze just after accumulation, and a massive ice body formed during the freezing of water-saturated sediments (mainly sand horizons underlying loam with massive ice). This type of massive ice can be considered as syngenetic bottom-segregated ice [Shpolianskaya, 1989, 1999, 2003; Shpolianskaya et al., 2006]. It was formed most likely about 25–20 ka.

Stable oxygen and hydrogen isotopes

Oxygen-isotope values ($\delta^{18}O$) of massive ices range from −12, 49‰ (standard SMOW) up to −22, 95‰. Deuterium (δD) values vary from −91, 7‰ up to −177, 1‰. Deuterium excess (d_{exc}) changes from 3, 4 up to 10, 6‰ (Table 2).

Earlier it has been shown that $\delta^{18}O$ values in massive ice range from −11, 23‰ up to −25, 2‰ [Tarasov, 1990; Solomatin et al., 1993; Michel, 1998]. According to 142 measurements of stable isotopes [Solomatin et al., 1993], more than 60% of $\delta^{18}O$ values vary in a rather narrow range from −16 up to −20‰. Sampling with 10 cm vertical intervals from 2,5 m massive ice in the Bovanenkovo area shows that variations of $\delta^{18}O$ do not exceed 1‰, and the average value is −18‰ [Michel, 1998].

The similarly homogeneous isotope signal we obtained from the massive ice of bodies 2 and 3 (Fig. 7, 8, *a*, *b*), where $\delta^{18}O$ variations do not exceed 1‰, and δD variations are less than 4‰. Comparatively small $\delta^{18}O$ variations not exceed 2‰, and δD variations less than 8‰ are observed in deep (about 30 m) occurring massive ice bodies, as revealed by Borehole 34-P (Fig. 10, *a*).

We also studied a massive ice body 4 (Fig. 9) with noticeable variations in the stable isotope composition, where even in the upper layer 0.6 m of the ice $\delta^{18}O$ varies more than 10‰, from −12, 49 up to −22, 75‰, and δD from −91, 7 to −171, 9‰ (Fig. 10, *b*). The sufficient variations we explain [Vasil'chuk,

**Table 2. Stable isotopes of oxygen (δ18O), deuterium (δD) and deuterium excess (dexc)
in massive ice at the third terrace of the Seyaha River, and also ice wedge, cryopeg samples
and water of river and lake in the Bovanenkovo Gas field area**

Sample no.	Depth, m	Material	δ18O, ‰	δD, ‰	d_{exc}, ‰
Borehole 34 – P					
YuV-34P-1/0	28.5–32.4	Massive ice	−18.29	−141.8	4.5
YuV-34P-1/1	28.5–29.1		−17.73	−138.2	3.6
YuV-34P-1/2	29.1–29.7		−18.67	−145.0	4.4
YuV-34P-1/4	30.2–30.7		−18.89	−146.0	5.1
YuV-34P-1/5	30.7–31.4		−16.95	−131.7	3.9
YuV-34P-1/6	31.4–31.9		−18.33	−142.1	4.5
YuV-34P-1/7	31.9–32.4		−17.86	−139.5	3.4
Massive ice body 1. Seyaha River near site Gas stations (GS)-1, depth from massive ice roof					
YuV05-Bov/24	0.1	Massive ice	−21.69	−163.4	10.1
YuV05-Bov/25	0.45		−22.74	−171.3	10.6
YuV05-Bov/16	2.25		−21.55	−163.1	9.3
YuV05-Bov/27	3.15		−22.12	−167.2	9.8
YuV05-Bov/28	5.7		−22.62	−170.7	10.3
Massive ice body 2. Lake in 1300 m from site Gas compressor stations (GCS), depth from massive ice roof					
YuV05-Bov/17	0	Massive ice	−22.54	−170.0	10.3
YuV05-Bov/18	0.4		−22.11	−167.6	9.3
YuV05-Bov/19	0.8		−22.75	−171.9	10.1
Massive ice body 3. Thermo-abrasion circus east from site K–64, depth from massive ice roof					
YuV05-Bov/11	0	Massive ice	−22.79	−175.9	6.4
YuV05-Bov/14	0.5		−22.95	−176.4	7.2
YuV05-Bov/15	1.0		−23.13	−177.1	7.9
YuV05-Bov/12	1.5		−22.44	−173.1	6.4
YuV05-Bov/9	2.0		−22.61	−173.5	7.4
Massive ice body 4 near Thermo-abrasion circus , depth from massive ice roof					
YuV05-Bov/54	0–0.2	Massive ice	−12.49	−91.7	8.2
YuV05-Bov/44	0.35–0.5		−18.47	−142.9	4.9
YuV05-Bov/51	0.5–0.85		−21.42	−162.6	8.8
YuV05-Bov/49	0.85–0.95		−22.75	−171.9	10.1
YuV05-Bov/43	0.95–1.05		−18.80	−144.4	6.0
YuV05-Bov/46	1.05–1.15		−19.11	−147.6	5.3
YuV05-Bov/45	1.5–1.7		−18.32	−142.2	4.4
YuV05-Bov/55	1.75–1.8		−19.24	−147.6	6.3
YuV05-Bov/50	1.8–1.95		−22.39	−169.6	9.5
YuV05-Bov/53	2.46–2.63		−16.85	−129.6	5.2
YuV05-Bov/48	2.63–2.87		−20.65	−159.4	5.8
Ice-wedges					
YuV05-Bov/65	1	Ice-wedge Ice	−13.54	−101.2	7.1
YuV05-Bov/3	2		−17.35	−135.5	3.3
YuV05-Bov/70	3		−13.65	−105.7	3.5
Cryopegs					
YuV05-Bov/32	120	Water	−22.36	168.9	10.0

Sample no.	Material	δ18O, ‰	δD, ‰	d_{exc}, ‰
Lake				
YuV05-Bov/30	Water	−21.92	−165.9	9.8
YuV05-Bov/60		−13.03	−98.8	5.4
YuV05-Bov/62		−18.58	−143.3	5.3
YuV05-Bov/67		−13.88	−97.3	13.7
YuV05-Bov/72		−13.57	−103.2	5.4
YuV05-Bov/74		−13.01	−102.8	1.3
Rivers				
YuV05-Bov/66	Seyaha River water	−14.16	−106.6	6.7
YuV05-Bov/69	Seyaha River water	−13.65	−104.5	4.7
YuV05-Bov/59	Seyaha River water	−18.66	−143.1	6.2
YuV05-Bov/68	Mordiyaha River water	−13.78	−103.5	6.7

2006b, 2010] by the formation of ice during freezing water-saturated ground in closed-system conditions [Vasil'chuk, 2011b].

A similar situation has been described in the mouth of the Gyda River, where lenses of syngenetic segregated ice were characterized by $\delta^{18}O$ variations, from −16 up to −34‰ [Vasil'chuk, 1992]. The variations are the result of isotope fractionation in the closed system. Similar variations are found in the intrasedimental ice in the Mackenzie Delta [Fujino et al., 1983, 1988].

Isotope values of cryopeg water, from a depth of 120 m, are of $\delta^{18}O$ −22, 36‰ and δD −168, 9‰. They are close to the isotope composition of massive ice, but contrast

Fig. 7. Sampling of massive ice body 3. Photo by Ye.Ye. Podborny.
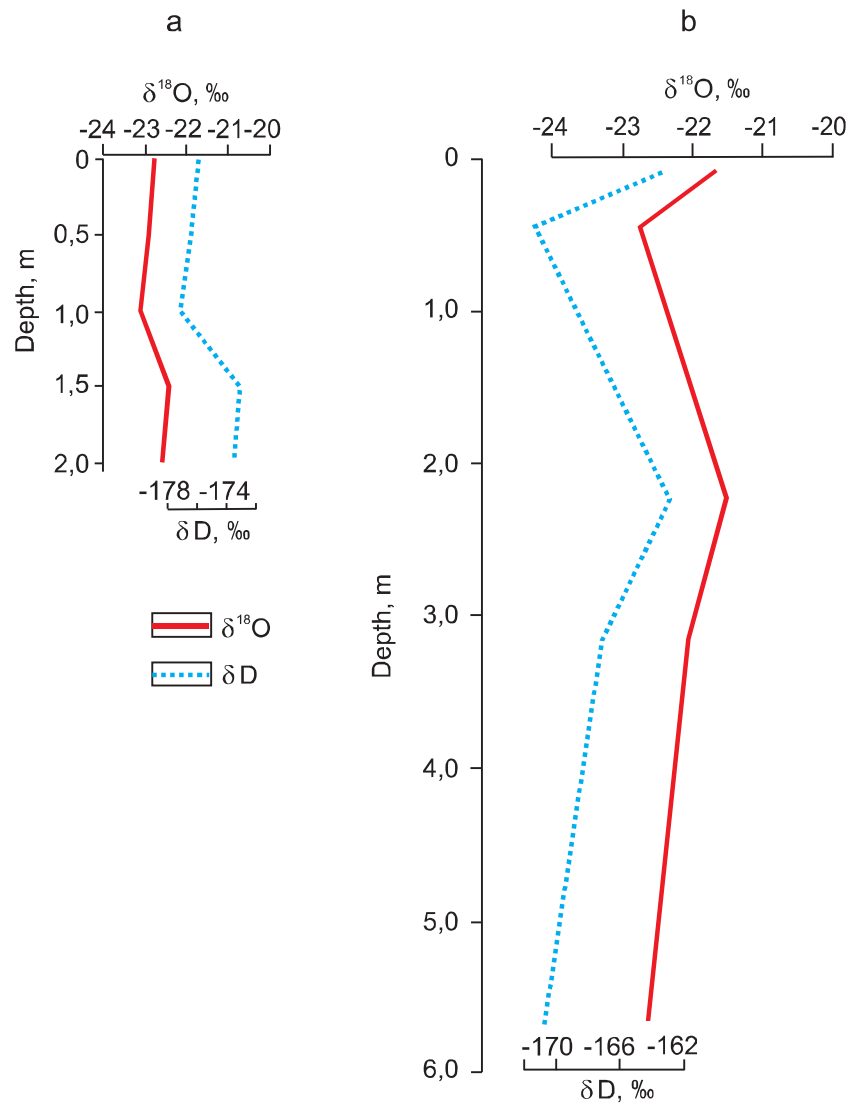
Figure 8. (a) Oxygen isotope and deuterium diagram for massive ice body 3; and (b) massive ice body 1 on Bovanenkovo gas field.

Fig. 9. Sampling from massive ice body 4. Photo by Ye.Ye. Podborny.

with published data value $\delta^{18}O$ of −16, 2‰ in cryopeg water near the Voynungto Lake in the same area [Tarasov, 1990]. The ratio of $\delta^{18}O$ and δD of all the samples of ice in body 4 are close to global meteoric water line (Fig. 11), which indicates rather slow freezing of a water-saturated horizon, which has been uniformly "depleted" both by ^{18}O and ^2H, in the final stages of formation.

For comparison, the isotope composition of ice wedges, cryopegs, and lake and river water of the Bovanenkovo gas field area was analysed. It was demonstrated that the main part of massive ice is isotopically more positive than Holocene ice wedge ice, as the isotope composition of massive ice and cryopegs is similar, so massive ice and cryopegs are formed from the same lenses of ground water. Lake and river water, as a rule, is isotopically more positive than
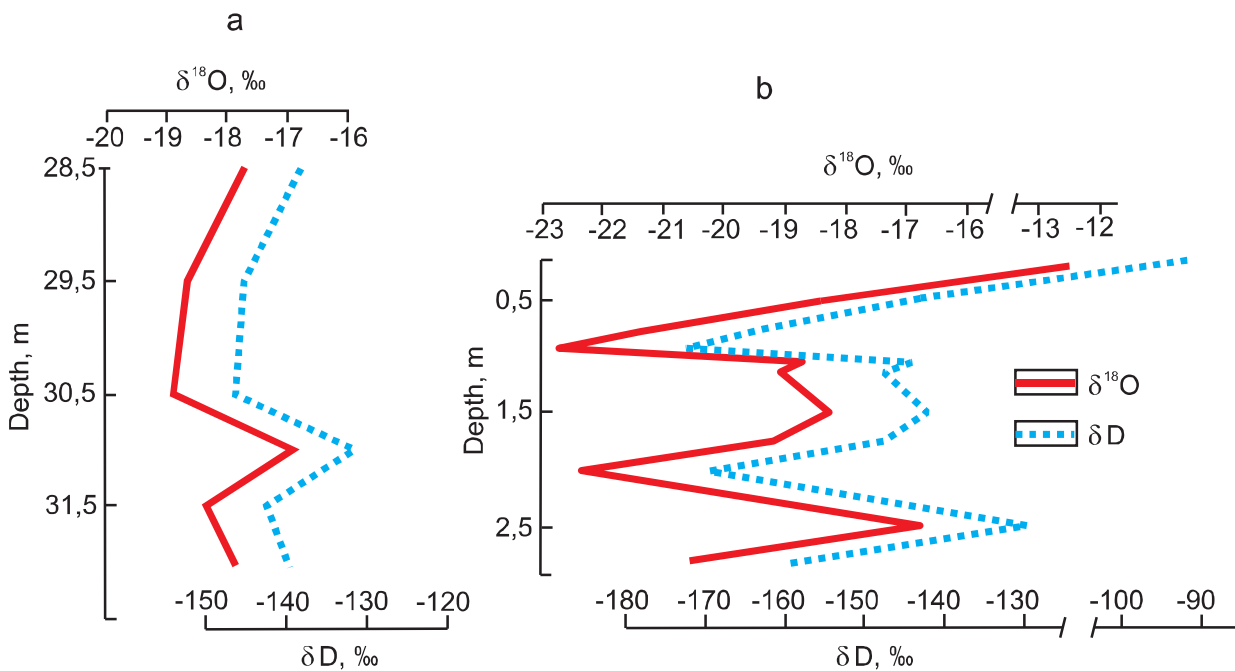
Fig. 10. (a) Oxygen isotope and deuterium plot for massive ice in borehole P-34; and (b) body 4.
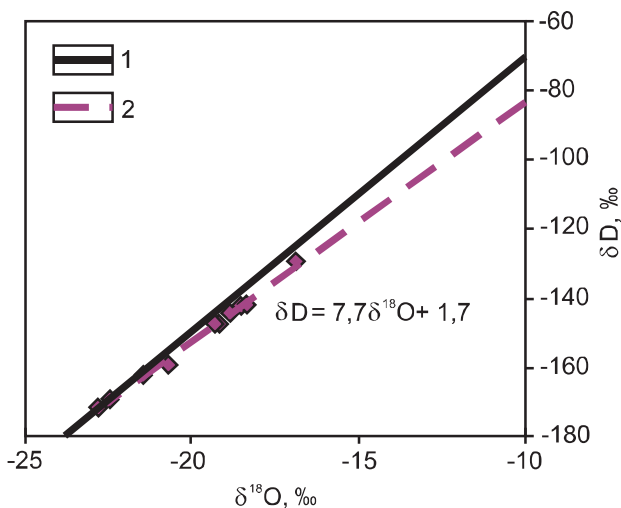

Fig. 11. Comparison of Global Meteoric Water Line (GMWL; 1) with local meteoric water line (2) of massive ice (body 4) at the third terrace of the Bovanenkovo gas field.

massive ice. This indicates that massive ice bodies originated from Late Pleistocene ground water, with a more negative isotope composition than modern river and lake water.

Pollen spectra IN massive ice

In studied massive ice in Bovanenkovo area far-transported pollen of *Pinus* is practically absent, while regional pollen, such as *Betula* sect. *Nanae, Alnaster, Salix, Cyperaceae,* and local pollen, *Ranunculaceae, Polygonaceae, Fabaceae,* are the main components of the pollen spectra [A. Vasil'chuk, Yu. Vasil'chuk,

2010a, b, c]. In the ice of body 4 (Fig. 12) a maximal observed concentration of pollen is 1300 piece/l (sample YuV05-Bov/49). Local pollen prevails (*Cyperaceae, Polygonum sp., Polemoniaceae, Liliaceae, Sparganium*) in the pollen spectrum.

The content of redeposited Pre-Quaternary components does not exceed 9%. Minimal concentration is 5 piece/l (sample YuV05-Bov/46, fine pollen *Cyperaceae* and *Salix* only).

Pollen concentration does not depend on the concentration of clay particles. A high concentration was found with the presence of clay particles (YuV05-Bov/49), as well as without (sample YuV05-Bov/53). In massive ice body 4 the content of redeposited pollen and spores varies from 2 to 9%. This is close to pollen characteristics of modern lacustrine and coastal floodplain sediments in the area. Numerous remains of monocelled green and diatom algae were also found in the ice.

This probably specifies the existence of a fresh-water reservoir, most likely as benthonic silt waters of a large lake or a fresh bay frozen through, or at the bottom.

The general pollen characteristic of massive ice layers of non-glacier origin is the presence
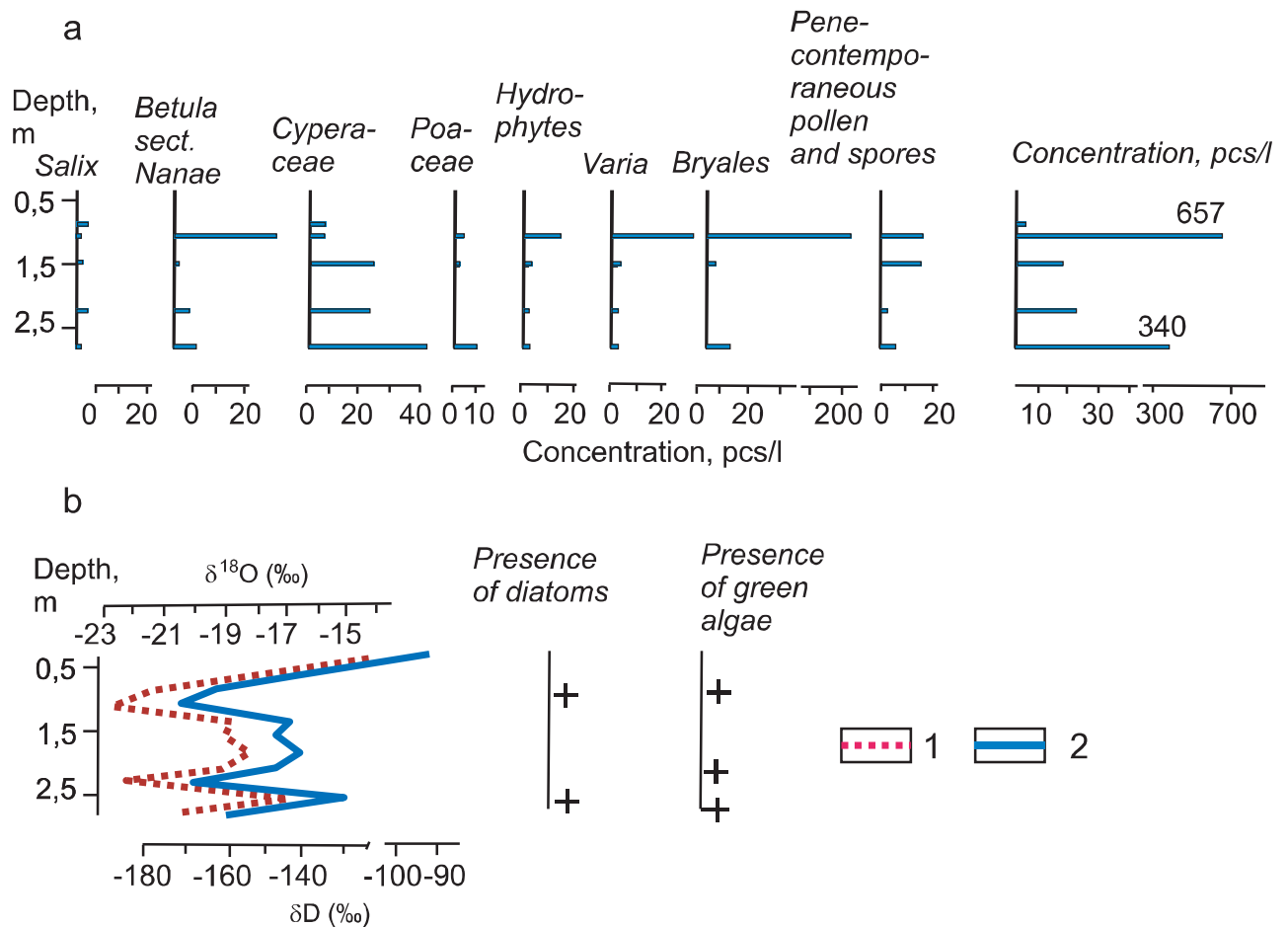
Fig. 12. Pollen diagram of massive ice body 4 at: (a) the third terrace, Bovanenkovo gas field; and (b) isotope plot in the same samples: 1 – $\delta^{18}O$, 2 – δD [A. Vasil'chuk, Yu. Vasil'chuk, 2010a].

of green moss, and often horsetail spores, which are present in buried deposits of pack or ground ice.

DISCUSSION

The massive ices of the Bovanenkovo gas-condensate field are syngenetic and genetically heterogeneous, such as: segregated, any infiltrated-segregated, any lake bottom congelation ice etc. [Vasil'chuk, 2011a]. A possible cause of the horizontal structure of ground ice lenses is burial at the bottom of lake ice. As example is the tabular ice exposure at the bank of the Nedarmato Lake [Parmuzin, Sukhodol'sky, 1982]. The layers of massive ice occur in accordance with host sediments. The thickness of ice layers of various colours and their bedding are similar to the lamination of the overlapping sediments. These facts, together with the shape of the ice lens and thin peaty laminas at the contacts of ice layers, led us to conclude that ice is made up of separate facies of lagoon sediments, which are composed on

the third terrace in the region. In coastal areas, as a result of draining, the sea beach began freezing with the active segregation of the ice. Under the cliffs at that time floating sea ice could be buried. Segregation processes in contact with buried tabular ice could be formed in direct contact segregation ice. So paragenesis of buried and segregated massive ice could be formed. Relatively thin layers of segregated ice formed on braids and shallow beaches. However, freezing was differentiated along the coast: some massifs froze quickly; others over a long time; while some thawed. This led to the formation of closed talik, water-saturated areas, typical of injection ice. Paragenesis of injection and segregation ice could be formed along the periphery of the injection massive ice.

However, we suppose that the formation of horizontally stratified ice bodies took place by the interment of bottom ice. This phenomenon could be widespread in shallow lagoons (with a depth of 1–2 m), or deltas in the period from 30–35 ka BP to 10–15 ka BP. The modern

analogue is the left coast of Ob Bay, where we observed bottom ice in the shallow lakes in the Northern Yamal Peninsula in a cold summer (in August–September), and also a modern polygonal network in the banks and bottom of the lakes. This revealed that underlake talik is absent or depthless in some lakes. More severe summer conditions, with average annual temperatures of 5–6 °C lower than the present-day, are distinctive for LGM in Yamal [A. Vasil'chuk, 2007], so segregation ice formed beneath shallow lake bottoms in winter do not keep pace to thaw in the sub-lake active layer during the following summer. Another hydrologic feature of Yamal is common aufeis fields along river valleys. Aufeis is a sheet-like mass of layered ice that forms by the upwelling of river water behind ice dams, or by ground-water discharge. Successive ice layers can lead to aufeis accumulations that are several metres thick. In LGM conditions aufeis could also be buried. Waller et al. [2009] show areas that include dykes and sills of intrusive ice, massive segregated intrusive ice, ice wedges and composite wedges, segregated ice, pool ice.

Pollen and spores in massive ice were studied in the Mackenzie River Delta [Fujino et al., 1988], and a high concentration of cretaceous pollen and spores was found in silty layers in the ice. Quaternary pollen in the silty layers showed sporadic far-transported pollen of a pine and a fir tree. In the pure ice, pollen spectra consisted of regional components. We suppose that the origin of the massive ice is similar to the origin of massive ice in Bovanenkovo [A. Vasil'chuk, Yu. Vasil'chuk, 2010 a, b, c]. The difference between pollen spectra is possibly caused by a variation in seawater participation in the case of the Mackenzie River Delta. The application of palynologic methods, together with isotope analysis, could be relevant to the study of genesis of massive ice and water sources for ice formation.

Two new categories could be entered into the systematization of massive ice, such as: homogeneous and heterogeneous ice deposits. The structure and particular properties of homogeneous massive ice are similar to all parts of tabular ice complex. Heterogeneous massive ice complexes consist of two or more homogeneous massive ice bodies, or combinations of homogeneous massive ice bodies, whose structure and properties are different [Vasil'chuk, 2011a, 2012, 2014].

CONCLUSIONS

1. Stable isotope data show that massive ice in the permafrost sediment of the Bovanenkovo gas field is heterogeneous, and has been formed syngenetically as segregated or segregated-infiltrated ice in freezing, water-saturated, unconsolidated deposits (possibly in an underlake talik) about 25–20 ka BP.

2. The massive ice of the Bovanenkovo gas-condensate field is syngenetic and genetically heterogeneous, such as: segregated, any infiltrated-segregated, any lake bottom congelation ice etc. Some massive ice could also be formed in underwater conditions in the zone of fresh and supercooled saline waters. These three mechanisms of ice formation occurred at different stages in massive ice formation. Significant volumetric pressure led to local injections, forming vertical ice veins above massive ice or small rods and dykes, penetrating horizontal bodies of massive ice.

3. One of the factors of massive ice formation under the bottom of lakes or lake-bog complexes could be the ingression of cold (with the temperature essentially lower than –2 °C) seawater on a surface of coastal flood plain with numerous lakes (present third terrace), that led to the sharp cooling of water and ground suspension, freezing and intensive ice segregation, with the formation of extensive ice layers under the large but shallow lakes. As a result, syngenetic segregated (infiltrated-segregated) massive ice was formed.

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