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Features of Late Pleistocene massive ice formation in the central Yamal Peninsula based on isotopic signature (^{18}O, ^{2}H) of ice

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A B S T R A C T

On Yamal Peninsula massive ice is widespread cryogenic object, lying close to the surface in different sediments, often in a combination with ice wedges. This study is dedicated to tabular massive ground ice exposed in the outcrop of the thermocirque of the third sea terrace in the Central Yamal Peninsula to establish the mechanism of ice formation and the source of water based on the isotopic signature of ice. The tabular massive ground ice body was opened with visual thickness of 2.5 m and a length of 300 m. It had formed from 43 to 37 cal ka BP according to ^{14}C AMS-data. A white ice body was found under the visible lower boundary of the studied tabular massive ground ice. Tabular massive ground ice yielded values of $\delta^{18}O$ from −19.9 to −23.1‰ and $\delta^{2}H$ from −151.8 to −164.7‰, with variations in deuterium excess from 6.5 to 20.4‰ (average d_{exc} = 13‰). The $\delta^{18}O$ and $\delta^{2}H$ values of white ice vary from −17.5 to −22.5‰, and from −132.6 to −165.3‰ respectively. The $\delta^{2}H$-$\delta^{18}O$ relationship for white ice indicating the injection of water and its freezing in a closed system condition. The study shows that the tabular massive ground ice is an intra-ground ice formed under sub-aquatic conditions from lake water. During syngenetic accumulation of segregated massive ice unstable freezing took place, widespread feature of cold regions, which led to intrusion of water under pressure and form injection ice.

1. Introduction

Large massive ice bodies are widespread on the Yamal Peninsula, while there is a great variety both in morphology, lithology of sediments and genesis of ice, as well as the conditions and mechanisms of formation and the source of water. The main hypotheses of massive ice formation identify the ice as segregated, intrusive, repeated intrusive, infiltrated and buried glacier ice (Mackay, 1971; Vtyurin, 1975; Zhestkova and Shur, 1978; Rampton, 1988; Vasil'chuk, 1992; Dubikov, 2002; Murton, 2005, 2009; French, 2007; Streletskaya et al., 2013; Vasil'chuk et al., 2012, 2014; Solomatin, 2013; Belova, 2014). Infiltration of surface water through seasonally thawed ground and the freezing of this water on the top linked to the formation of massive ice body by segregation (Zhestkova and Shur, 1978). Vtyurin (1975) favoured ice segregation near the contact between clayey sediments and water-bearing coarse-grained sediments. Gasanov (1969) hypothesized that the main factor of ice formation is water intrusion, and distinguished different types of intrusive ice: seasonal intrusive ice, multi-seasonal intrusive ice (short-term permafrost), intrusive ice, repeated intrusive ice and hydrolaccoliths. Mackay (1971, 1973) proposed that the mechanism of water injection and segregation in closed-system conditions that is widely applied to explain pingo growth can also apply to the mechanism of massive ice formation.

The discussion about the genesis of massive ice received a new round of research in connection with the use of the stable isotopes as a method to identify their atmospheric or intra-ground origin. Michel (1998) has showed the Late Pleistocene history of Yamal, summarized the established isotopic characteristics of the ice and showed that during the last more than 30 thousand years, the Yamal territory was not subject to glaciation and there was no Wisconsin ice sheet on the continental shelf of the Kara Sea. According to Michel (1998) massive ice in Bovanenkovo area was characterized by small range of $\delta^{18}O$ variation (not exceed 1‰) with average value −18‰. Vasil'chuk et al. (2009, 2011) and Vasil'chuk and Murton (2016) applied isotope studies to suggest the most probable intra-ground origin of the ice missives by segregation or segregation-injection. In area of Bovanenkovo gas field $\delta^{18}O$ values of massive ice range from −12.49 to −22.95‰ and $\delta^{2}H$ values from −91.7 to −177.1‰ (Vasil'chuk et al., 2014), earlier it has been shown similar

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values of $\delta^{18}O$ for massive ice in Yamal peninsula in range from −11.23 to −25.2‰ (Tarasov, 1990; Solomatin et al., 1993; Michel, 1998).

By themselves, $\delta^{18}O$ and $\delta^{2}H$ values of ground ice can be associated with different and any sources of moisture - both with atmospheric precipitation, a mixture with sea waters or the burial of glacial ice. Therefore, a detailed attitude to isotopic values is required in order to assess the possibility of using it as interpretation tools.

Supporters of the burial theory confirmed it by the presence of fresh ice in the enclosing sediments, which are often saline (Solomatin, 2013). The salt content is not such reliable evidence, since in saline sediments, fresh ice can form by segregation. Even if ice forms from salsuginous water, salts are squeezed out of ice crystals and concentrated in cryopegs.

Therefore, the paragenetic combination with cryopegs can be one of the signs of the intra-ground origin of the missive ice (Streletskaya and Leibman, 2002). This was described for two sites in Yamal, one near the Marre-Sale station and another near Kharasavey (Vasil'chuk, 2006, 2012; Streletskaya et al., 2013), where the cryopeg's water mineralization reaches 70 g/L or more, and sodium chlorides predominate in the ionic composition. For Marre-Sale station, formation of massive ice was established by intra-ground segregation and a source of ice was a mixture of atmospheric precipitation and sea water (Chizhova and Vasil'chuk, 2019). In addition to the combination with cryopegs, the presence of synchronous syngenetic ice wedges is an attribute of the intra-ground nature of massive ice.

One of the features of the Yamal massive ice bodies is their occurrence in strata of different ages. So, massive ice in st. The Marre-Sale (western coast of Yamal) has a two-layer structure, with the lower layer represented by ground ice of the Late Pleistocene age (Streletskaya et al., 2013). Within the Kharasavey deposits massive ice were found both in the stratum of the Late Pleistocene second terrace and in the strata of the Holocene first terrace (Vasil'chuk, 2006, 2012).

The association of massive ice both Holocene and Late Pleistocene age with coastal deposits near the coast of modern Yamal and with lacustrine sediments of inner watershed is an interesting character of Yamal Peninsula permafrost. In the Central Yamal heterogeneous autochthonous and allochthonous massive ice bodies occur as layers, laccoliths, rods and lenses, often in combination with ice of different origin, such as segregated with injection ice or segregated massive ice with ice wedges.

This work is devoted to the study of the oxygen and hydrogen isotopic composition of massive ice exposed in the outcrop of the thermocirque of the third sea terrace in the Central Yamal near the Bovanenkovo gas field. The purpose of the study is to establish the mechanism of ice formation and the source of water based on the isotopic signature of ice.

2. Material and methods

The study site is located at the watershed of Seyakha and Mordyakha rivers, in the central part of the Yamal Peninsula (Fig. 1). The Bovanenkovo oil and gas condensate field, located 30 km to the north. There are widespread massive ice bodies, exposed near the surface in thermocirques. The massive ice has been studied on the surface of the interfluve represented by outliers of the third sea terraces (70°13′57" N, 69°0′58" E), which is the surface of an older and more extensive thermokarst denudation basin, with a typical tundra and numerous modern lakes and thermocirques. In a thermocirque at a depth of 1 m from the surface, under a layer of loam, a massive ice was exposed in the form of ground ice with horizontal stratification.

The absolute height of the base of the exposed outcrop was 17 m a.s.l. (according to the GPS station Garmin Dakota 20). The tabular massive ground ice was represented by highly icy layered gray loam, the thickness of the exposed ice wall was 2.5 m in height and 300 m in length, the top of the ice was covered by 1.3 m thickness loam. The thickness seasonal thawed layer was 1.1 m. Two fragments of the tabular massive

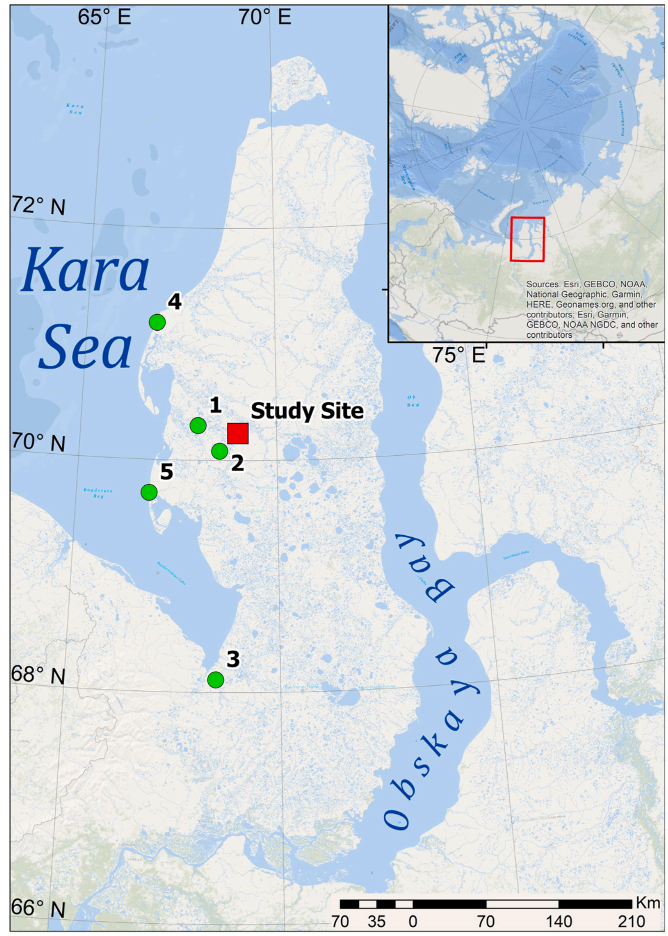

Fig. 1. Location of the study site and previously well-studied outcrops of massive ice in Yamal Peninsula: 1 – Bovanenkovo, 2 - Mordyyakha River valley, 3 – Erkutayakha River valley, 4 – Kharasavey, 5 – Marre-Sale.

ground ice were sampled - in the peripheral left section of thermocirque and in the central section, the distance between these sampling sections was 80 m. In the peripheral left section (Fig. 2), ice was sampled horizontally (samples M-55 … M-65 and M −75 … M-80) and vertically (samples M-66 … M-74).

In the central part of the thermocircque, samples were taken horizontally (samples M-92, M-93, M-104 … M-106) and vertically (samples M-94 … M-103). In addition to gray layered tabular massive ground ice,

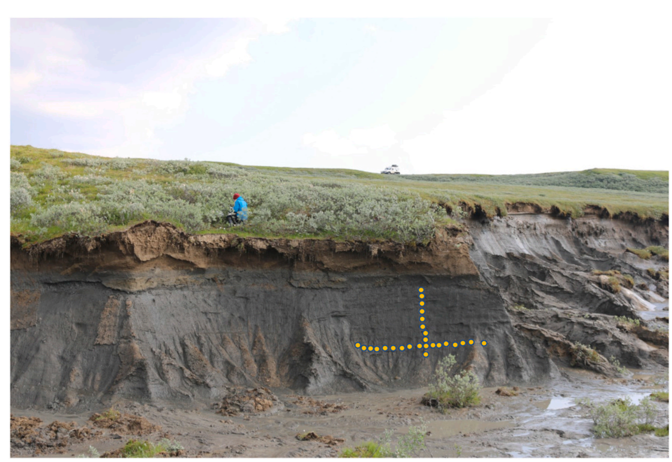

Fig. 2. The peripheral left section of thermocirque and sampling points.

clear white bubble ice was discovered, lying as a horizontal lens at the base of the exposed part of the outcrop (Fig. 3). From this white ice body 10 samples (M-81 … M-91) were taken. All samples were taken by in sub-profiles after cleaning the exposures from thawed material and debris. Ice samples were drilled with a diamond core bit using a Metabo BS 18 LTX Impuls drill, placed in plastic zip bags, melted and poured into test tubes, sealed with paraffin tape.

Above the upper boundary of the tabular massive ground ice in overlying loam (at a depth of 0.9 m from the surface), a poorly decomposed peat (with pronounced plant residues) was sampled for radiocarbon analysis.

Organic remains enclosed in ice samples from the central section at depths of 3 and 1.4 m from the surface were radiocarbon dated using the accelerator mass spectrometry (AMS). Sample preparation was done at the Institute of Geography, Russia, analysis at the University of Georgia, USA. Conventional ^{14}C ages were calculated according to Stuiver and Polach (1977). Calibrated ages were determined as years calBP using CALIB REV7.1.0 based on the IntCal13 dataset (Reimer et al., 2013).

Granulometric analysis was carried out in the laboratory of Geochemistry of Landscapes and Geography of Soils in Lomonosov Moscow State University on a Laser Particle Analyzer FRITSCH ANALYSETTE 22, MicroTec plus.

The isotope analysis was carried out in the isotope laboratory of the Russian Chemical Technology University named after D.I. Mendeleev on the Los Gatos Research Triple-Liquid Water Isotope Analyzer (LGR T-LWIA, Model 912–0050). The measured values are calibrated in V-SMOW-V-SLAP scale. The measurement accuracy was 0.1‰ for δ^{18}O and 1‰ for δ^2H.

The isotopic composition of oxygen and hydrogen is expressed in δ (‰) values relative to V-SMOW (Standard Mean Ocean Water):

$$\delta_{sample} = 1000\ ((R_{sample}/R_{SMOW})) - 1), \text{ where R is } ^{18}O/^{16}O \text{ or } ^2H/^1H. \quad (1)$$

The values of δ^2H and δ^{18}O of natural waters generally correspond to the global meteoric water line with equation:

$$\delta^2H = 8\ \delta^{18}O + 10 \text{ (Craig's line)}. \quad (2)$$

The main methodological approach to the interpretation of isotope data is linear regression of δ^{18}O - δ^2H and the establishment of an open/closed system of ice formation based on the changes of δ^{18}O, δ^2H and d_{exc} values and the slope. Changes in δ^{18}O, δ^2H and d_{exc} values of ice in a closed system occur according to equation of the Rayleigh fractionation (Souchez and Jouzel, 1984):

$$\delta_i = (\delta_0 + 1000)\ f^{(\alpha - 1)} - 1000, \quad (3)$$

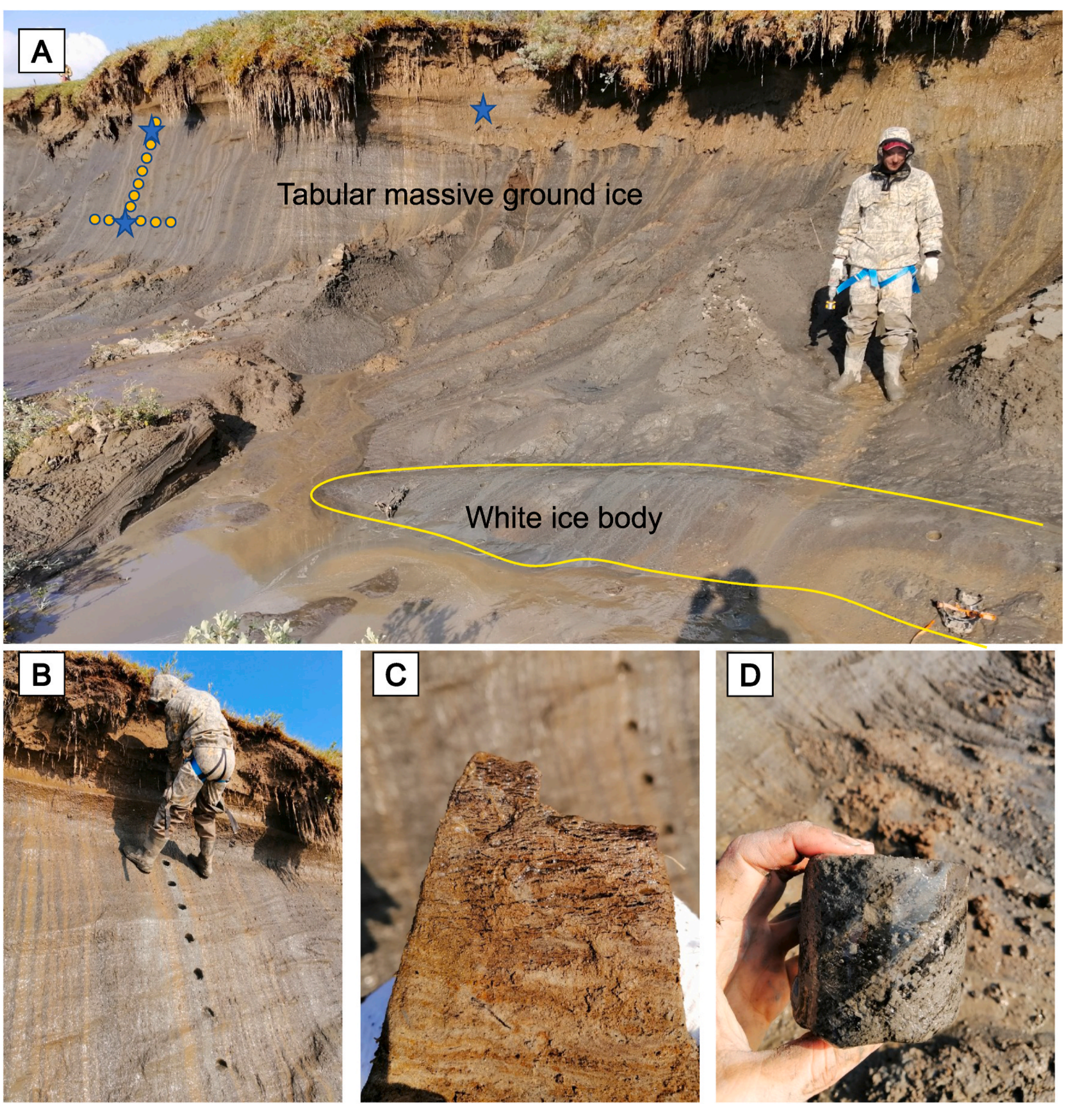

Fig. 3. The central part of the thermocirque and sampling points (A, B), cryogenic textures in the overlying loams (C) and in the tabular massive ground ice at the upper border (D). Sampling points for dating are shown as asterisks.

Where δ_i are the $\delta^{18}O$ (δ^2H) values of the formed ice, δ_0 are the $\delta^{18}O$ (δ^2H) values of the initial water, f is the fraction of the remaining water, and α is the coefficient of fractionation for the water–ice system ($\alpha^{18}O = 1.00291$ and $\alpha^2H = 1.0212$ (Lehmann and Siegenthaler, 1991). The magnitude of the slope depends on closed/open system condition and $\delta^{18}O$, δ^2H values of the initial water (Souchez and Jouzel, 1984).

3. Results

3.1. Radiocarbon dating

The dating of the tabular massive ground ice is based on two AMS dates by total organic carbon in samples from depths of 3 m and 1.4 m from the surface, and one radiocarbon date by poorly decomposed peat (hummock) at a depth of 0.9 m. A non-inversion distribution of dates in depth was obtained (Table 1), which indicates the age of massive ground ice formation from 43 197 to 37 973 cal years BP ago. Sample 102 V was taken on the upper brow of tabular massive ice, near the border with overlying loam. The date from 0.9 m depth was obtained from a buried hummock in the overlying loam layer. This date records a change in conditions from a flooded lake basin, when massive ice was accumulated, to a drained (shallow) surface, on which vegetation and peat bumps sometimes settled.

According to ^{14}C data, tabular massive ground ice had been continuously accumulated at a rate of 0.3 m per thousand years. The mineral part of massive ice, according to the granulometric analysis data, is represented by loam. The content of organic matter in ice is 4%. Excluding ice, which is from 80 to 70% of the volume, the accumulation rate of lacustrine loam was less 0.1 m per thousand years. This is a very low rate of sediment accumulation even for northern lakes.

3.2. Isotope signature

The isotopic record of the tabular massive ground ice showed small variations of $\delta^{18}O$ (from −19.9 to −23.1‰) and δ^2H (from −151.8 to −164.7‰), the same for both horizontal and vertical profiles (Fig. 4). Except for one sample on the upper edge of the massive ice in the central part (sample M-103 V) the total range of variations in $\delta^{18}O$ and δ^2H values was 3.2‰ and 12.8‰ respectively. Sample M-103 V, taken at the upper boundary of the tabular massive ground ice (brow), has a high $\delta^{18}O$ and δ^2H values up to −14.4 and −106.3‰ respectively. Similarly high values ($\delta^{18}O = -13.3$, $\delta^2H = -94.7$‰) were obtained for segregated ice from the frozen base of the seasonal thawed layer (Fig. 4D; Table 2). Percolating of modern precipitation, which may occur with an increase in the depth of the seasonal thawed layer is likely to affect the massive ice at the upper boundary.

The $\delta^{18}O$ and δ^2H values of the ice are located close to the meteoric water line (Fig. 5). For ice samples taken both vertically and horizontally from two sections of the thermocirque (left and central section), a very low slopes were established, however, the compact grouping of values does not reflect linearity well.

The $\delta^{18}O$ values of white ice (samples M-81 - M-91) vary from −17.5 to −22.5‰, the δ^2H values vary from −132.6 to −165.3‰ (Table 2). For a white ice the δ^2H-$\delta^{18}O$ relationship described by equation $\delta^2H = 6.51 \times \delta^{18}O - 16.63$ ($R^2 = 0.97$). This slope refers to the Rayleigh process during ice formation in a closed system and indicates injection nature of ice. Since the white ice body was opened naturally during thawing, its configuration was unknown. This ice body probably had the irregular morphology and there was no reason to assume that we completely sampled it. Nevertheless, the values of $\delta^{18}O$ and δ^2H are described by a linear trend and indicate the Rayleigh process. The calculation by equation (3) with initial values of $\delta^{18}O = -20.2$‰ and $\delta^2H = -148$‰ describe the values of white ice pretty well, the magnitude of the slope in the calculated model (6.25) almost correspond to that observed for ice (Fig. 6). Thus, in one section, two types of intra-ground ice were combined, the formation mechanism of which was different.

Table 1
Radiocarbon ages and calibrated ages (95.4% probability) of ice and overlaying sediments.

№	$IGAN_{AMS}$	Sample ID	Depth, m	Material	^{14}C, BP (1σ)	Calibrated age (mean) cal. years BP
1	IGAN 7680	4	0.9	Peat	10140 ± 90	11315 - 12060 (11738)
2	7699_{AMS}	102 V	1.4	TOC (ice)	33515 ± 130	37308 - 38441 (37973)
3	7700_{AMS}	104	3	TOC (ice)	39520 ± 220	42792 - 43655 (43197)

4. Discussion

4.1. The dating of ice formation

Obtained AMS-dates by total organic carbon that was stored in bottom sediments, indicates the age of accumulation of bottom sediments. In this case, bottom sediments including frozen water. The accumulation took place sequentially from bottom to top according non-inversion dates. Within continuous permafrost zone of Yamal Peninsula there might not have been a taliks under the shallow lakes. The shallow depth of the lake, which froze completely in winter, caused the upper permafrost horizons to thawed in summer and froze in winter. The accumulation of bottom sediments - mineral and biogenic – has led to an uplift of the upper surface of the permafrost. In this case, there was a sub-aquatic syngenetic build-up of the permafrost and the formation of a layered ice-ground horizon (Katasonov, 1962; Romanovsky, 1978; Zhestkova and Shur, 1982). Although the age of bottom sediments and the age of transition to the permafrost state may not coincide, i.e. the ice may be younger than the bottom sediment layer, because of seasonal thawing for some period of time. Nevertheless, we believe that even at such a low sedimentation rate (0.3 m per thousand years), the time lag between the bottom sediment accumulation and the transition to permafrost strata was quite small. Thus, the AMS dates capture the approximate age of formation of this tabular massive ground ice.

Previously, the age of massive ice was determined by radiocarbon dating the hosting sediments. For example, sediments enclosing massive ice at Tyurinto Lake outcrop have been dated at 29180 ± 2380 BP (MSU-1118) and 34030 ± 400 BP (MSU-1011) (Danilov et al., 1992). A number of radiocarbon data from the sediments hosting massive ice within third sea terrace near Bovanenkovo gasfield area were published: in outcrop on the Seyakha River 34200 ± 1000 BP (GIN-13311) at a height of 2.5 m and 31 900 ± 500 BP (GIN-13313) at a height of 2.0 m (Vasil'chuk, 2010). The age of tabular massive ground ice near Vaskiny Dachi Research station was determined based on radiocarbon dating of overlaying peat lenses, three ^{14}C dates were obtained: 30 900 ± 1300 cal yr BP, 32 200 ± 1300 cal yr BP and 37 650 ± 1950 cal yr BP (Semenov et al., 2020). These dates suggest that massive ice near Vaskiny Dachi Research station was formed not later than MIS 3 (Semenov et al., 2020). All these radiocarbon dates by hosting sediments are in good agreement with the AMS-age of studied tabular massive ice (see Table 1).

The dating of ice formation, according to the AMS data, indicates a gradual and monotonous accumulation of the massive ice, its layering - a sequential increase in the thickness. All these features are associated with sub-aquatic accumulation under conditions of the bottom of the lake. The presence of gray loams saturated with organic matter is also a feature of lake bottom sediments.

At 300 m from the studied thermocirque on a higher surface (28 m a.s.l.) ice wedges occurring in similar massive ground stratified ice, accumulated according to AMS (TOC) 13.6 cal Ky BP (Chizhova et al., 2021). Massive ice containing ice wedges were deformed between the veins, the layering of massive ground ice reflected the morphology of

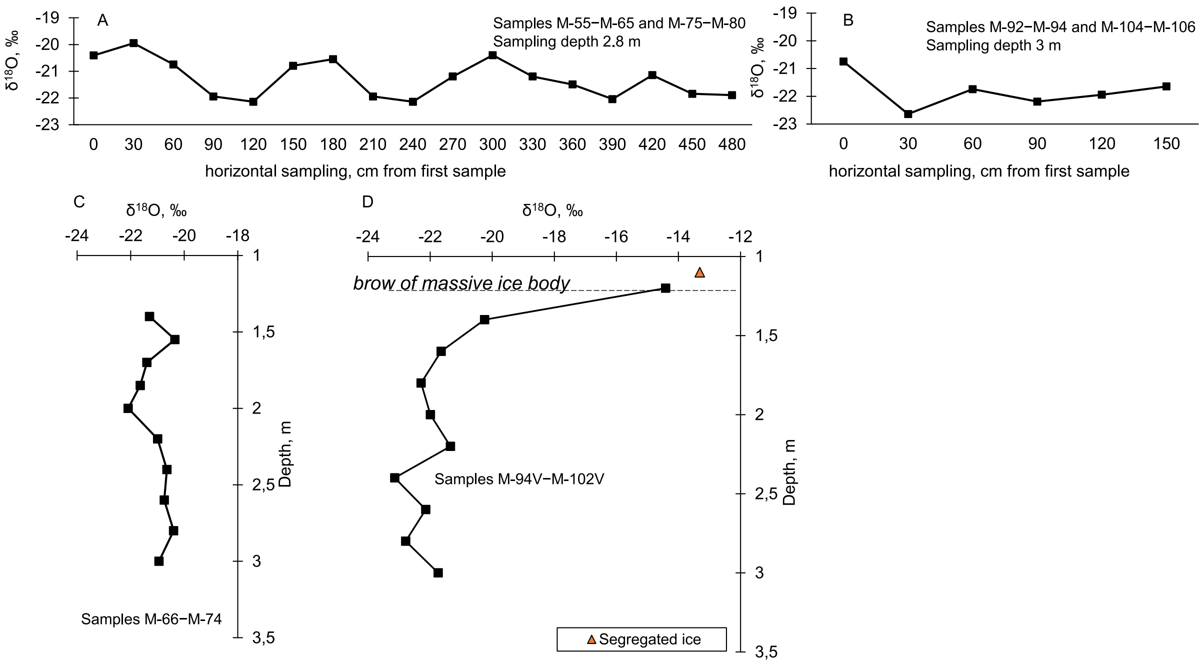

Fig. 4. The $\delta^{18}O$ values of samples of horizontally (A) and vertically (C) profiles in the left section and horizontally (B) and vertically (D) profiles in the central section of the thermocircque.

polygonal baths - polygons flooded with water. This may indicate the conditions for the formation of the massive ice as a syngenetic segregated ice of a shallow lake or a flooded area. Thereby such conditions are quite typical for massive ground ice exposed near the surface and located at the watershed within the 3rd sea terraces in Central Yamal Peninsula. The sub-aquatic conditions of ground ice accumulation and lake water as the main source of massive ice were previously reported (Danilov, 1989; Fotiev, 2011, 2012).

A similar paragenesis of horizontally layered massive ice bodies and syngenetic ice wedges was described in Mordyakha River valley. The massive ice body more than 4 m thick with normal horizontal bedding turns into vertically layered ice and is dissected by 4–5 m syngenetic ice wedges (Vasil'chuk et al., 2018). Such finding of paragenetic combinations in a single section are rare in the Permafrost zone.

4.2. Source of water and ice formation scenario

The formation of syngenetic segregated ice at the bottom of a shallow lake does not exclude the conditions of a closed system of ice formation. During injection, water freezes sequentially and isotopic depletion occurs. When lake freeze from top to the bottom, there is also a consistent top-down ice formation and isotopic depletion of residual water. At the last stage of freezing, bottom sediments saturated with residual lake water, therefore the layer of bottom sediments would be the last portion of ice in closed system.

The lake was most likely shallow, and the lacustrine sediments, as well as the sediments of seasonally thawed layer, were located very close to the surface. Therefore, the freezing rates were most likely very high and the freezing of lake water was quite fast. In addition, winter temperatures during the Late Pleistocene in Yamal were on average 7 °C colder than the present-day (Vasil'chuk et al., 2019; Chizhova et al., 2021). The equilibrium freezing according to Rayleigh process deals with a low rate and high α coefficients. In nature, on a cooling surface, freezing is usually faster, and equilibrium coefficients are not achieved. Direct observations of freezing water and congelation ice formation in Scarisoara Cave, Romania, showed that the fractionation coefficients were from 1.0018 to 1.0013 for oxygen and from 1.008 to 1.013 for hydrogen (Perşoiu et al., 2011), which is significantly lower than the equilibrium $\alpha 18 = 1.0031$ and $\alpha 2 = 1.021$ (Lehmann and Siegenthaler, 1991). When freezing going fast, α coefficients are smaller, and, therefore, a formed ice is described not only by smaller range of $\delta^{18}O$ and $\delta^{2}H$ values from the first portions of ice to the last but by extremally low slopes as well (Lacelle et al., 2009). The curtain ice (congelation ice) in Caverne de l'Ours, Que'bec, Canada plot along a regressive slope = 2.7. These unusual isotopic features can be attributed to freezing occurred under non-equilibrium conditions i.e. kinetic isotope effects during the successive freezing of thin layers of water (Lacelle et al., 2009).

Such reason of low slopes as a non-equilibrium freezing of residual water, included in bottom sediments after lake ice formation have been reported for pingo ice and cave ice blisters. The non-equilibrium type of ice formation have been described for seasonal frost mounds, pingo ice cores or injection ice of frost mounds in Bear Rock, Northwest Territories, with slopes from 3.5 to 6.5 (Michel and Fritz, 1978; Michel, 1986). For injection ice from North Fork Pass such relation have been established $\delta^{2}H = 5.1\ \delta^{18}O - 56.4$, $r = 0.99$; $n = 17$ (Michel, 1986), which indicates a closed system. The change in the $\delta^{18}O$ and $\delta^{2}H$ values of ice is described by the Rayleigh process, but does not correspond to the equilibrium one (Michel, 1986). Low slopes were described for pingo ice core Messoyakha-1 (Vasil'chuk et al., 2019).

At the bottom of a shallow Lake, when the overlying water had already frozen, the bottom sediments also were freezing very fast. It can be assumed that the lake water was the first portion of ice, remaining on the surface, the bottom sediments contained the last portions of ice (Fig. 6). Since the bottom sediments passed into the permafrost state during syngenetic accumulation, only they could be expressed on the isotope diagram - area II on Fig. 6.

The isotope composition of the source water from which the ground ice formed can be identified as the point of intersection between the $\delta^{18}O$-$\delta^{2}H$ ground ice line and the LMWL (Michel, 2011). This method is not universal, especially in the case when the source is evaporated water, however, it is most suitable in this study. Since there are no systematic data on the isotope composition of precipitation in Yamal Peninsula, calculation using the OICP calculator (https://wateriso.utah.edu) gives full coincidence LLMW with the GMWL. Therefore, the intersection with GMWL represents a possible source of water (see Fig. 6).

Table 2
Isotopic composition of oxygen ($\delta^{18}O$) and hydrogen ($\delta^{2}H$) of tabular massive ground ice in central Yamal Peninsula.

Sample ID	Depth, m	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	d_{exc} (‰)
Left Section, horizontal profile				
M-55	2.8	−20.4	−155.9	7.4
M-56	2.8	−19.9	−153.1	6.5
M-57	2.8	−20.7	−154.4	11.6
M-58	2.8	−21.9	−157.0	18.6
M-59	2.8	−22.1	−158.3	18.9
M-60	2.8	−20.8	−155.1	11.3
M-61	2.8	−20.5	−153.8	10.6
M-62	2.8	−21.9	−157.6	17.9
M-63	2.8	−22.1	−158.3	18.9
M-64	2.8	−21.2	−157.0	12.6
M-65	2.8	−20.4	−153.8	9.4
M-75	2.8	−21.2	−153.8	15.8
M-76	2.8	−21.5	−155.7	16.3
M-77	2.8	−22.0	−157.6	18.7
M-78	2.8	−21.1	−156.3	12.8
M-79	2.8	−21.8	−157.0	17.8
M-80	2.8	−21.9	−157.0	18.2
Left Section, vertical profile				
M-66	3	−20.9	−155.7	11.9
M-65	2.8	−20.4	−153.8	9.4
M-67	2.6	−20.7	−155.7	10.3
M-68	2.4	−20.6	−155.1	10.1
M-69	2.2	−21.0	−156.3	11.6
M-70	2	−22.1	−158.9	17.8
M-71	1.85	−21.6	−155.7	17.5
M-72	1.7	−21.4	−155.7	15.5
M-73	1.55	−20.3	−153.8	9.0
M-74	1.4	−21.3	−155.1	15.3
Central section, horizontal profile				
M-92	3.0	−20.7	−158.3	7.7
M-93	3.0	−22.6	−162.8	18.4
M-104	3.0	−22.2	−161.5	16.1
M-105	3.0	−21.9	−158.9	16.6
M-106	3.0	−21.6	−159.6	13.6
Central section, vertical profile				
M-94 V	3	−21.7	−160.2	13.8
M-95 V	2.8	−22.8	−162.8	19.6
M-96 V	2.6	−22.1	−161.5	15.7
M-97 V	2.4	−23.1	−164.7	20.4
M-98 V	2.2	−21.3	−161.5	9.3
M-99 V	2	−22.0	−164.0	11.9
M-100 V	1.8	−22.3	−163.4	14.9
M-101 V	1.6	−21.6	−158.9	14.2
M-102 V	1.4	−20.2	−151.8	10.1
M-103 V	1.2	−14.4	−106.3	9.0
White ice body, horizontal profile				
M-81	3.3	−19.0	−140.9	11.1
M-82	3.3	−17.8	−132.6	9.8
M-83	3.3	−19.0	−137.7	14.3
M-84	3.3	−17.5	−133.2	6.8
M-85	3.3	−19.1	−140.9	11.5
M-86	3.3	−20.8	−148.6	18.1
M-87	3.3	−21.3	−157.0	13.8
M-88	3.3	−22.5	−165.3	15.0
M-89	3.3	−21.6	−158.9	13.8
M-90	3.3	−22.2	−160.8	17.1
M-91	3.3	−20.1	−145.4	15.4
Segregated ice in bottom of seasonal thawing layer				
S 107	1.1	−13.3	−94.7	11.8

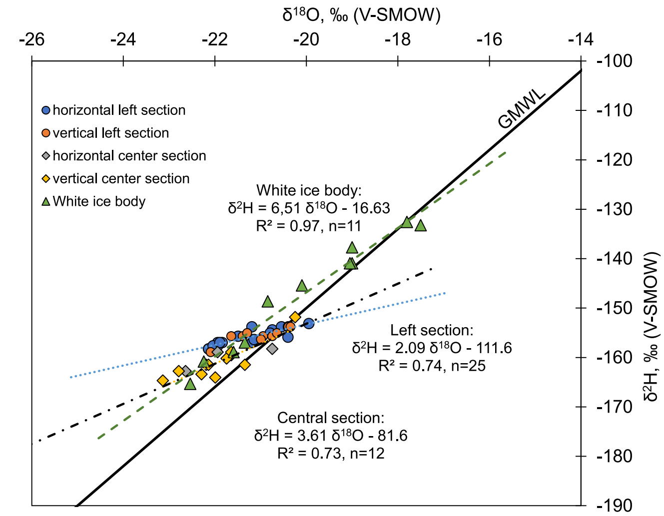

Fig. 5. The $\delta^{2}H$ vs $\delta^{18}O$ plot for all samples of massive ice.

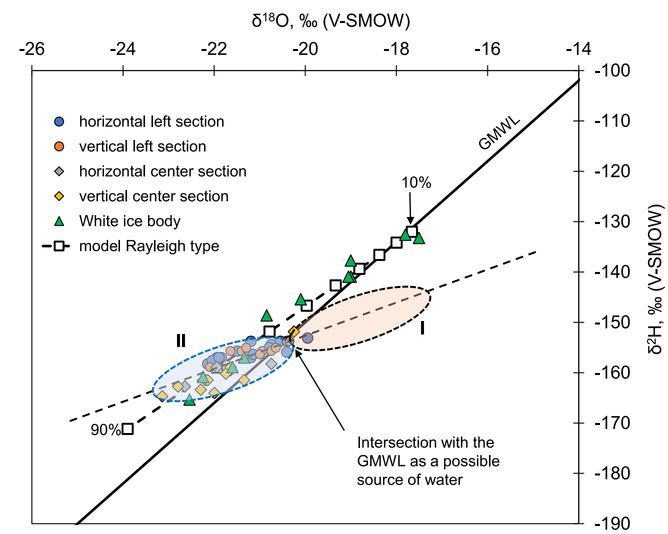

Fig. 6. Hypothetical pattern of formation isotope signature of tabular massive ground ice: area I – suppositive values of ice formed as the first portions (ice formed when the lake completely froze), area II - values of ice formed as the last portions of freezing (ice formed when water contained in bottom sediments froze). The calculated $\delta^{18}O$ and $\delta^{2}H$ values of closed system according equation (3) in comparison with values obtained in white ice body: percentages indicate how much ice has formed from the water.

The isotopic values of the initial water, which was a source for the white ice body, were established as $\delta^{18}O = -20.2$‰ and $\delta^{2}H = -148$‰. The isotopic values of the initial water, which was a source for tabular massive ground ice, were suggested as $\delta^{18}O = -20.3$ and $\delta^{2}H = -153.7$‰. Of course, this value is very approximate, generalized assumption about the possible isotopic composition of the initial water. It was not constant over the time of accumulation of the massive ice and could change slightly, as well as the freezing rate and the thickness of the freezing layer. Nevertheless, the initial water for these two different types of ice (tabular massive ground ice and intrusive white ice body) had a very close $\delta^{18}O$ and $\delta^{2}H$ values. Obviously, in both cases, it was lake water.

Lakes present in the Bovanenkovo area are characterized by a wide range of $\delta^{18}O$ and $\delta^{2}H$ values (Vasil'chuk et al., 2014) and reflect insignificant evaporation effect. Some modern lakes have a rather high values of $\delta^{18}O = -8$ … -10‰ (Romanenko et al., 2001) and $\delta^{18}O = -13$‰, $\delta^{2}H = -102$‰ (Vasil'chuk et al., 2014), which is associated with summer precipitation. Others have a very low values ($\delta^{18}O$ −18.6 and −21.9‰ and $\delta^{2}H = -143$ and −166‰), which may indicate thermokarst nature and the flow of water from thawing of underground ice, or input of snow melt water into the lake in the spring season. The ice-wedge ice of the Late Pleistocene age in the neighboring thermocirque, which keeps the mark of winter precipitation, has values of $\delta^{18}O$ lower by 5‰ (Chizhova et al., 2021). Most likely, the water balance of the lake included melted snow water as well as summer precipitation. Perhaps the catchment area of the lake was quite large.

The Lake water as a source of massive ice was considered in the previous works Vasil'chuk (2012) and Fotiev (2015). The authors proposed the schematic diagrams of the stages of massive ice formation (Vasil'chuk, 2012, p. 62 - seasonal differences in the isotopic composition of waters supplied the lake basins of Yamal and Chukotka Peninsulas in the Late Pleistocene, which could be as a source for the formation of thick massive ice; Fotiev, 2015, p. 34 - formation of thermokarst lakes and sub-lake taliks, stages of development of the marine plain and formation of massive ice layer).

The good linearity in $\delta^{18}O$ - $\delta^{2}H$ relationship for white body ice and compliance with the Rayleigh process suggests that the white ice body was formed as a result of water injection under pressure and its successive freezing.

This injection could have occurred during the freezing of a local talik, which was subsequently blocked from above by a freezing front. The tabular massive ground ice is attributed to Lake sedimentation. Most likely, there was a small talik under the Lake, then the lake was drained or some processes on the surface led to its shallowing. It began to freeze downward and some layer of permafrost formed, separating the seasonally thawed layer and unfrozen talik. The permafrost layer began to increase, i.e. syngenetic accumulation took place on the one side, and the talik froze downward on the other side. The water contained in the talik was pressurized, which led to the injection. Moreover, it was an underground injection, overlapped frozen deposits (tabular massive ground ice). Due to the injection was underground, deeper from the surface than the boundary of the seasonally thawed layer, the freezing rate was slower, which allowed ice to freeze according to the Rayleigh process. In general, there are a lot of frozen sediments in Yamal Peninsula with is characterized by very pronounced processes of unstable freezing, leading to a whole complex of deformations and combination of different type of ice in one outcrop.

The gorgeous example of a combination of segregation and injection ice within one outcrop is a massive ice body located on the left bank of the Erkutayakha River (68°11′N, 68°51′E) (Vasil'chuk and Murton, 2016). A massive-ice body approximately 100 m long is embedded predominantly in stratified sand. The ice layers sharply drop on both sides of the central part, and just 15 m from the center of the cover of the massive ice appears at a depth of 8 m. The central part of the massive-ice body takes a form similar to a stock (a type of igneous intrusion), with vertical and subvertical ice layers, whereas the peripheral parts comprise horizontally layered ice. The range of $\delta^{18}O$ (∼4) and $\delta^{2}H$ (∼20) values indicates comparatively small fluctuations of the $\delta^{18}O$ and $\delta^{2}H$ values of different types of ice: in pure white ice $\delta^{18}O$ values varies from −19.6 to −20.5‰, $\delta^{2}H$ from −152.4 to −156.9‰; in clear transparent ice $\delta^{18}O$ values varies from −19.2 to −20.3‰, $\delta^{2}H$ from −149.6 to −160.7‰; in transparent gray ice with a steely shimmer $\delta^{18}O$ values from −19.4 to −21.3, $\delta^{2}H$ from −150.3 to −163.8‰; in gray ice and in the dirty gray ice $\delta^{18}O$ values varies from −22.1 to −23.4, $\delta^{2}H$ from −165.5 to −172.7‰ (Vasil'chuk and Murton, 2016). Probably, the difference between the isotope signal of the initial water and the different type of ice was comparatively small. Thus, different mechanisms of ice formation - both segregation and injection can participate simultaneously in one section and ice may formed from one source of water. These findings obtained previously for the central Yamal are in good agreement with our results and indicate a significant role of lakes and taliks as a source for massive ice as well as a platform for a combination of different mechanisms of ice formation.

4.3. Variety of isotope signature of massive ice bodies in Yamal Peninsula

The massive ice bodies have different morphology, layering and depth from the surface. The diversity of the features of the formation and morphology of underground ice is also expressed in the isotopic parameters of ice – massive ground ice with $\delta^{18}O$ values from −16.9 to −23.13‰ have been described in the Bovanenkovo area (Michel, 1998; Vasil'chuk et al., 2014). This variety of isotope signature indicates ice heterogeneity. In the Bovanenkovo area of Yamal Peninsula, the massive ice layers are predominantly segregated and syngenetic; the idea of possible congelation ice at the bottom of the lake was also declared (Vasil'chuk et al., 2014).

Despite the individual characters, a good congruence with isotope data of previously studied massive ice bodies of interior regions of Yamal Peninsula indicates the general pattern of the formation of segregated ground ice in the Late Pleistocene (Fig. 7). For massive ice bodies lying close to the surface within alluvial or lacustrine-alluvial sediments in Central Yamal Peninsula, surface water was a source for ice, as was described for Late Pleistocene massive ice in Mordyyakha and Erkutayakha valleys.

The massive ice described near the sea coasts - at st. Marre-Salle (Streletskaya et al., 2013) and Kharasavey (Kritsuk, 2010) have higher values of $\delta^{18}O$ and $\delta^{2}H$ (see Fig. 7). For the coastal locations, the partial participation of sea water in the formation of massive ground ice was established. Comparison with isotope parameters of freshened waters of the Barents Sea (Dubinina et al., 2017) made it possible to prove the process of mixing sea water with isotopically light atmospheric precipitation (Chizhova and Vasil'chuk, 2019).

Numerous lenses of massive ice were described at the Bovanenkovo gas condensate field, most often within sediments of the third and second terraces (with absolute marks from 15-20 to 40 m), as well as the alluvial and lacustrine-alluvial floodplain. For ice bodies with different morphology, sampled at different depths, $\delta^{18}O$ values from −16.9 to −23.13‰ were obtained (Vasil'chuk et al., 2014). These ice deposits were classified as intra-ground segregated, which accumulated during the freezing of waterlogged sediments.

An intriguing distribution of $\delta^{18}O$ and $\delta^{2}H$ values was obtained for massive ice in a deep bore (P-34) at depths from 28 to 32 m from the surface and for water from cryopeg at depth of 120 m. The $\delta^{18}O$ values of massive ice varied from −16.95 to −18.89‰, cryopeg water had $\delta^{18}O$ value −22.36‰ (Vasil'chuk et al., 2014). All these values form one line with slope = 7.5 on $\delta^{18}O$-$\delta^{2}H$ plot (Fig. 8) indicating an open system condition.

The isotopic fractionation during ice formation in open system always leads to higher values in ice compared to water due to the preferential partitioning of the ^{18}O and ^{2}H isotope in the ice. So, the water from which the ice was formed should have $\delta^{18}O$ values from −20 to −21.7‰, which is close to cryopeg's $\delta^{18}O$ value. The $\delta^{18}O$ value of cryopeg water may indicate a cryogenic concentration of salts contained in sediments and dissolved in a small amount of water that did not pass into ice (see Fig. 8).

Moreover, all these values lie on the line of mixing with the freshened water of the Kara Sea. This is surprising because we saw this earlier for the Marre-Sale coastal sediments (Chizhova and Vasil'chuk, 2019). But there we suspected the direct input of sea water to the source, from which ground ice was formed. In the central regions of Yamal Peninsula, especially near the surface, the participation of sea water is impossible, but at a depth, within older sediments, we see the same mixing processes

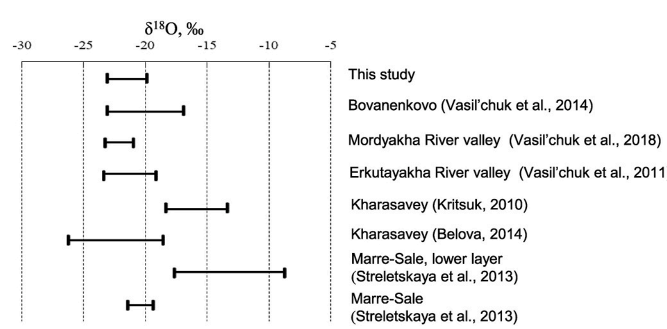

Fig. 7. The range of $\delta^{18}O$ values (from minimum to maximum) of Late Pleistocene massive ice in Yamal Peninsula.

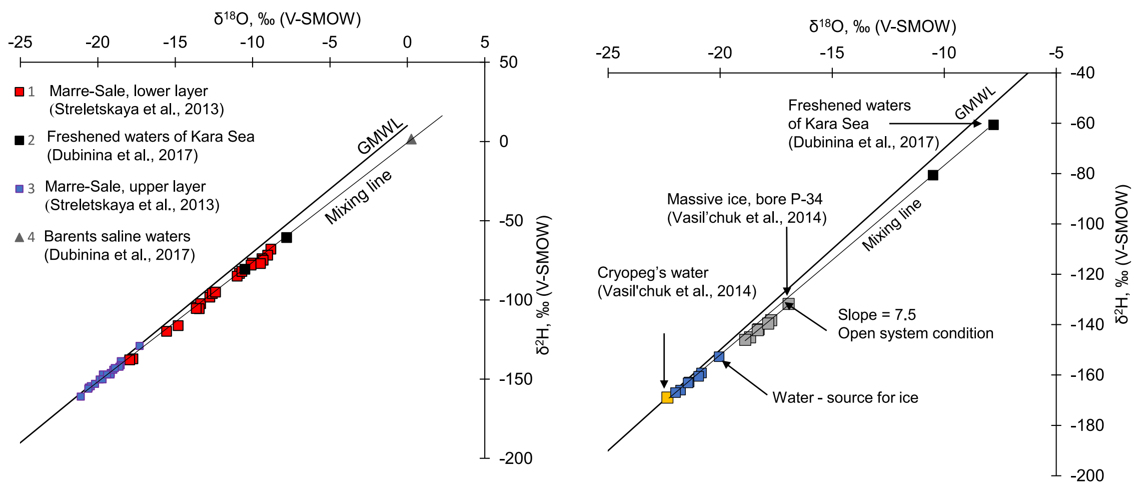

Fig. 8. Participation of strongly freshened sea water in ice formation near Marre-Sale station (A) and Bovanenkovo gas field (B).

with the water of the Kara Sea reflected by the isotopic signature of ground ice (see Fig. 8).

In the Pleistocene, marine transgressions were deep and long-term, resulting in the accumulation of thick strata of marine sediments (Danilov, 1982). The marine sediments of the sea terraces of Central Yamal Peninsula contained salts and possibly trace amounts of sea water. These salts were dissolved in water when a large amount of fresh water was supplied. Part of this water froze and formed fresh massive ice, and part of the water was squeezed out in a liquid state due to cryogenic concentration of salts. This is one of the possible ways of cryopeg formation with low $\delta^{18}O$ values, which are associated with meteoric water.

The $\delta^{18}O$ values of massive ground ice do not reflect a direct climate signal, as occurs when glacial ice or ice wedges form, but the signal of surface conditions and type of freezing. The difference in formation mechanism of massive ice leads to $\delta^{18}O$ values of ice can be either higher or lower relative to the initial water. If ice formation occurs in an open system, the $\delta^{18}O$ value of ice will be higher than initial water by ε (ε = 1000 (α – 1), where α is the coefficient of fractionation for the water–ice system $\alpha_{18O} = 1.00291$ (Lehmann and Siegenthaler, 1991) when freezing is slow, and $\alpha_{18O} = 1.0018$ when the freezing is fast (Perşoiu et al., 2011). If ice formation occurs in a closed system, the $\delta^{18}O$ value of first portions of ice will be higher, and the $\delta^{18}O$ value of last ones are much lower than the initial water. Thus, in each specific case of studying massive ice, it is necessary to determine the conditions (open or close system) and the isotope signature of initial water. Michel (1998) reports the mean values of $\delta^{18}O = -18‰$ for detailed sampled 2.5 m thick massive ice segregational origin exposed at site on the Seyacha River bank. If we accept the hypothesis of an open system condition for the formation of ice, then average $\delta^{18}O$ value of ice −18‰ originated from $\delta^{18}O$ value of water around −21 … −19.8‰ depending on which α_{18O} was used. It is practically coinciding with the $\delta^{18}O$ value of the source of water for massive stratified ice in this study.

Segregated massive ice are often penetrated by injection veins, stocks and lenses, forming paragenetic complexes of different morphologies and deformations. The establishment of the paragenetic combination of different type of ice previously carried out usually on the basis of the morphology and dislocations, the chemical composition of ice and sediments (Fotiev, 2011). Now the study of the formation of ground ice by different mechanisms in one outcrop is gaining an advantage in the use of stable isotopes.

5. Conclusions

The studied tabular massive ground ice located near Bovanenkovo oil and gas condensate field in the central part of the Yamal Peninsula was formed from 43 to 37 cal Ka BP. The massive ice accumulated simultaneously with the accumulation of lacustrine loams saturated with dissolved organic matter, i.e. syngenetically. Tabular massive ground ice yielded values of $\delta^{18}O$ from −19.9 to −23.1‰ and δ^2H from −151.8 to −164.7‰, with variations in deuterium excess from 6.5 to 20.4‰ (average $d_{exc} = 13‰$), both within vertically and horizontally sampling profiles. A white ice body was found under the visible lower boundary of the studied massive stratified ice. The $\delta^{18}O$ values of white ice vary from −17.5 to −22.5‰, the δ^2H values vary from −132.6 to −165.3‰. The δ^2H-$\delta^{18}O$ relationship of white ice indicate the injection of water and its freezing in a closed system condition. The injection could have occurred during the freezing of a local talik, which was subsequently blocked from above by a freezing front. A similar combination of segregated and injection ice was previously described in Yamal Peninsula in the Mordyakha river valley. The source of water for the studied tabular massive ground ice was lake water with values of $\delta^{18}O = -20.3‰$, $\delta^2H = -153.7‰$. Tabular massive ground ice was formed at the bottom of the lake as the last portions of ice in a closed system after the freezing of the lake. The isotopic parameters of initial water - source for white ice body, were similar to water, from which tabular massive ground ice formed. The massive ground ice near Bovanenkovo gas field is a syngenetic intra-ground ice formed under sub-aquatic conditions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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