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GEOGRAPHY

Oxygen Isotope and Deuterium Indication of the Origin and ^{14}C Age of the Massive Ice, Bovanenkovo, Central Yamal Peninsula

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Abstract—The conditions and forming time of massive ice were specified (Bovanenkovo gas condensate field, Central Yamal). Here, massive ice lies as stratums, laccoliths, stocks, and lenses. Three thousand boreholes 10–100 m in depth were analyzed. In 260 of them massive ice was broached. The ice foot is situated from 1 to 57 m deep. The maximal thickness of ice broached with boreholes came to 28.5 m; on average, it was about 8 m. The extension of massive ice is sometimes more than 2000 m, and its area is quite often more than 10 km^2. According to the radiocarbon method, loams of the third terrace, containing and overlapping ice deposits, were formed from 25 000 to 20 000 years ago or somewhat later. These strongly peat loams containing massive ice formed either in shallow sea conditions or during periodical draining conditions of beaches or low laida, where organic matter appeared due to erosion and deposition and accumulated during draining and overgrowing of drains. In more inclement conditions than at present, loam deposits were frozen immediately, forming massive ice, which occupied the barely water-saturated layers. The oxygen isotope composition (δ^{18}O) of massive ice samples varied from –12.49‰ (here and further, relative to SMOW) to –22.95‰. The deuterium concentration (δD) varied from –91.7 to –177.1‰. Deuterium kurtosis (d_{exc}) varied from 3.4 to 10.6‰. In one seam outcrop, the content of stable isotopes varied significantly. Here, at a depth of 0.2–0.8 m, the δ^{18}O content varied by more than 10‰ (from –12.49 to –22.75), and the δD content, from –91.7 to –171.9‰. Such variations testify about ice extraction upon freezing of water-saturated grounds in a closed system. According to palynological analysis of ice stratums, numerous remains of unicellular green algae and diatoms were revealed. It is possible that this is evidence of the existence of a fresh well, which was a source of water, feeding the layer. Most probably these were near-bottom silt waters of a large lake or desalted bay, which were frozen syngenetically. This accentuates the new type of massive ice, syncriogenic segregative ice, which probably formed 25 000–20 000 yr BP.

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The purpose of this study is to specify the conditions and forming time of massive ice near Bovanenkovo gas condensate field (GCF) (Central Yamal Peninsula) and demonstrate that here massive ice had predominantly autochthonal, segregative (segregative-infiltrative and even segregative-congelation) genesis and formed syngenetically due to freezing of the water-saturated ground.

The territory of Bovanenkovo GCF is unique. There is a lot of underground ice, occurring as stratums, laccoliths, stocks, and lenses. By now, we have analyzed about 3000 boreholes from 10 to 100 m in depth drilled within Bovanenkovo in the interfluve of the Naduyakhi and Nguriyakhi rivers. In 260 holes, massive ice was broached. Most of the ice is attached to late Pleistocene rocks of coastal genesis, and rarely, to alluvial slopes and lacustrine-marsh deposits.

In boreholes massive ice occurs under the outliers of the third and second terraces (absolutely benchmarks are from 15–20 m to 40 m) and also within the alluvial and lacustrine-alluvial floodplain [1–6]. Even under the bed of the Seyakha River, massive ice of 7–9 m in thickness was noted [1].

Massive ice most often has a lens formed of different thicknesses, blowing out along the strike of the seam. Well-boring showed (Fig. 1) that the ice roof was located both directly near the foot of the seasonally melted layer and at depths down to 52 m below the surface. The ice foot is situated at a depth from 1 to 57 m,

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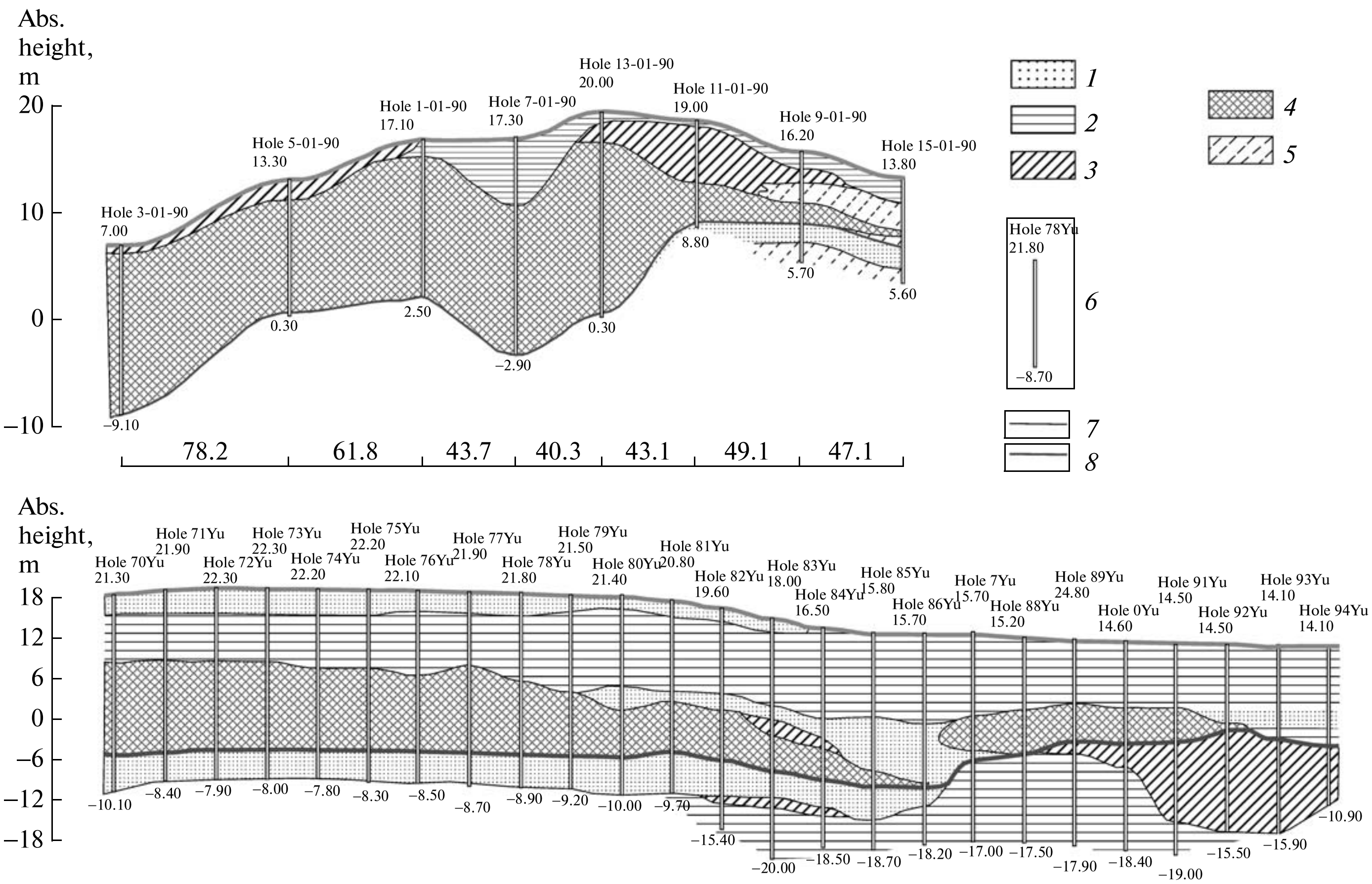

Fig. 1. Massive ice deposits in the thickness of the third terrace (Bovanenkovo, GCA) on the basis of exploratory drilling (materials of TyumenNIIGIPROGAZ): (*1*) sand; (*2*) clay; (*3*) loam; (*4*) massive ice; (*5*) sandy loam; (*6*) location and parameters of boreholes (boreholes number, upper figures—absolute benchmarks of wellhead (m), lower figures—absolute benchmarks of bottom hole (m); (*7*) lithologic and (*8*) stratigraphic boundaries.

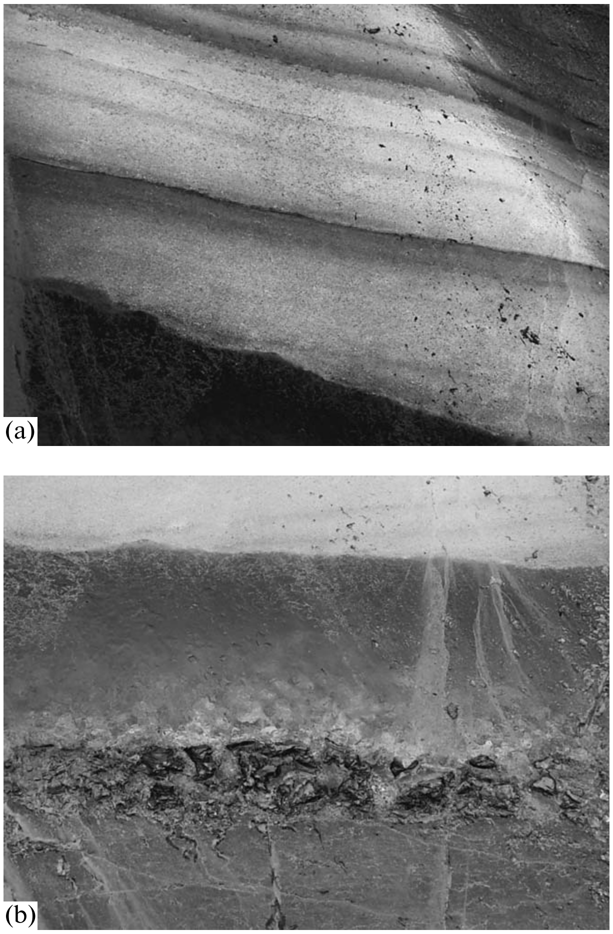

Fig. 2. Stratified massive ice deposit (a) and sublayers between layers of white and grey limpid (above) and limpid (below) ice (b) in the thickness of the third terrace (Bovanenkovo, GCA). Photo by Ye.Ye. Podborny.

and it does not occur below –21.5 m (absolute benchmark). The ice roof is more uneven than the ice foot. The roof and foot of the ice are not always parallel. The maximal thickness of the ice broached with boreholes came to 28.5 m and the mean thickness was about 8 m (according to measurements of 260 samples). Sometimes, two or three ice layers occurred in a log. The length of massive ice is sometimes more than 2000 m and its area is quite often more than 10 km^2.

The structure of the studied massive ice is horizontally laminated (Fig. 2a) with a thickness of layers of 5–50 cm and more. Ice lamination in the upper site has inclusions of sandy loams, loams, and laminated clays no more than 1–10 mm in thickness. Ice is clean, limpid, with scattered gas bubbles of rounded form (2–5 mm in diameter). Sometimes, layers of bladdery ice thickness up to 5 cm occur. In some stratums exclusively clean, "crystal-clear" ice can be found. Quite often laminated ice with horizontally oriented ground layers between ice layers of different textures can be found (Fig. 2b). In some samples we found small sharp xenolith of ground, "floating" within the ice, which was so devitrified that it looked like a single huge crystal. In addition, we found an ice-ground with schlieres and ice lenses, introduced in loam, forming a thick schlier and mesh texture. Along the strike of steam, ice-ground changes into clean ice. Such textures of ice probably support the mechanisms of ice formation as segregative or infiltrative-segregative [7].

The time of massive ice formation. To date the studied ice stratums, it is necessary to answer two questions: When did the deposits containing ice form? When did the ice formation start?

Some time ago, V.I. Solomatin et al. by means of radiothermo-luminescence (RTL) dated six soil samples taken from 300 m depth in the range from 22 000 ± 7000 years (from the sand layer underlaying massive ice) to 197 000 ± 25 000 yr. Judge by RTL-dating, the forming of frozen bedrock on the third terrace could have occurred 22 000–30 000 yr BP [1]. This data firmly conforms to radionuclide investigations of plant material from massive ice of the third terrace (Table 1).

Undoubtedly, among all cited dates, too many are ancient. This is explained by active reaccumulation of third terrace material within the subaqual environment. These dates are 31 000 and 34 000 yr BP. Dates of 25 000 and 26 000 yr BP are closest to the time of loam accumulation on the third terrace. This suggests that loams of third terrace, containing and overlapping ice deposits, were formed from 25 000 to 20 000 yr BP or somewhat later. This was the period of the final cycle of the late Pleistocene cryochron [8], when climatic conditions, according to isotope composition of repeated-vein ice formed in this period [9], were most inclement. Winters were cooler, on average, by 6–8°C [8, 9]. Carbon-14 dating provides evidence of ice saturation by organic matter. It follows that strongly peat loams, containing massive ice, formed either in shallow sea conditions or periodical draining conditions of beaches or low laida, where organic matter came due to erosion and deposition and accumulated during draining and overgrowth of drains. At the present time, all drains both on the floodplain, towing-path, and on the beach, low laida of the Kara Sea, Baidaratskaya Bay, are in long-term congelation. Thus, we have every reason to be sure that 25 000–20 000 yr BP, in more inclement conditions than now, loam deposits were frozen immediately, forming massive ice, which occupied barely water-saturated layers (usually, these are sand layers, underlaying loams, which contain massive ice). This affords ground to accentuate the new type of massive ice, syncriogenic segregative ice, which probably formed 25 000–20 000 yr BP.

Table 1. Identification of organic plant matter by means of the radiocarbon method from deposits, containing massive ice (the thickness of the third coastal terrace of Seyakha (Mutnaya) River, Bovanenkovo)

Sampling location	Dated material	Laboratory number	^{14}C-radiocarbon age
Exposure of Seyakha River opposite *GP*-1, 2.5 m above the shore line	Peat	GIN-13311	34200 ± 1000
Exposure of Seyakha River opposite *GP*-1, 2.0 m above the shore line	The same	GIN-13312	26100 ± 150
Exposure of Seyakha River opposite *GP*-1, 2.0 m above the roof of massive ice	“	GIN-13313	31900 ± 500
Exposure near thermo-abrasive kar, with depth of 1.1 m above the roof of massive ice	Hard peat loam	GIN-13314	28900 ± 1000
Exposure near thermo-abrasive kar, with depth of 10.3 m	Peaty loam	GIN-13326	25600 ± 700
Exposure near thermo-abrasive kar, with depth of 1.3–1.4 m	Hard peat loam	GIN-13327	25100 ± 500

Variations of stable isotopes. The oxygen isotope composition (δ^{18}O) of massive ice samples varied from –12.49‰ (here and further, relative to SMOW) to –22.95‰. The deuterium concentration (δD) varied from –91.7 to –177.1‰. Deuterium kurtosis (d_{exc}) varied from 3.4 to 10.6‰ (Table 2). In earlier published works [1, 2, 10, 11], it was shown that δ^{18}O in massive ice varied from –11.23 to –25.2‰. According to 142 measurements, more than 60% of δ^{18}O values were in the range from –16 to –20‰ [1].

The values of δ^{18}O in whitish bladdery ice varied from –18.4 to –22.4‰ (mean –20.4‰), in “crystal-clear,” from –17.4 to –25.4‰ (mean –22.7‰), and in ice-ground, –12.5‰.

In Michel’s work [10], the isotope profile of massive ice (2.5 m in thickness) on the third terrace of the Seikha River is presented. There, the variations of δ^{18}O in 28 samples, taken with an interval of less than 10 cm, did not exceed 1‰ and came to about 18‰ on average. A uniform isotope profile of massive ice broached at a depth of 28–32 m (borehole 34-P) was received (Fig. 3a). The δ^{18}O varied from –16.95 to –18.29‰, and δD ranged from –131.7 to –146‰. The same uniform isotope profiles were received according to stratums 2 and 3, where δ^{18}O variations did not exceed 1‰, and the δD variation was less than 4‰.

At the same time, in one seam outcrop, the content of stable isotopes varied essentially (Fig. 3b). Here, at a depth of 0.2–0.8 m, the δ^{18}O content varied more than 10‰ (from –12.49 to –22.75), and the δD content ranged from –91.7 to –171.9‰. Such variations, as it shown earlier [8], testify about ice extraction under freezing of water-saturated grounds in a closed system—lenses of syngenetic segregative ice in the mouth of the Gyda River were characterized by variations of δ^{18}O from –16 to –34‰.

The distribution of stable isotopes in stratum 4 suggests that heavy (isotopically) ice formed primarily in the uppermost and lowest parts of the stratum, where the values of δD are above 130‰, and at the final stage of the central layer formation, when δD is lower –140‰.

According to palynological analysis of ice stratum 4, numerous remains of unicellular green algae and diatoms were revealed. Possibly, this is evidence of the existence of a fresh well, which was a source of water feeding the layer.

Most probably these were near-bottom silt waters of a large lake or desalted bay, which were frozen on the bottom or in shallow water in decompressed silts. The pollen spectra of massive ice differ from those of superficial glaciers of the Arctic [12, 13]. In superficial glaciers long-drifted pollen of pines is absent, whereas regional pollen (*Betula* sect. Nanae, *Alnaster* sp., *Salix*, *Cyperaceae*) and local (*Ranunculaceae*, *Polygonaceae*, *Fabaceae*) vegetation [14] is presented widely. Concentration of spores and pollen varies from 1300 pieces/l (sample YuV05-Bov/49 with domination of local components *Cyperaceae, Polygonum* sp., *Polemoniaceae, Liliaceae, Sparganium* sp., and redeposited components content not exceeding 8%) to 5 pieces/l (sample YuV05-Bov/46-fine pollen *Cyperaceae* and *Salix*). The concentration of pollen and spores does not depend on the concentration of loamy particles. The highest concentration of them is observed both in the presence of loamy particles (sample YuV05-Bov/49) and in their absence (YuV05-Bov/53). The content of reworked pollen grains and spores fluctuates from 2 to 9%, which is very typical of modern lacustrine and laida waters and for deposits in this region [15].

At the same time isotope variations in cryopag, starting with the depth of 120 m, where δ^{18}O comes to –22.36‰ and δD comes to –168.9‰ are surprising. However, A.M. Tarasov [11] found earlier that isotopic values in cryopag near Voynungto Lake are also quite low (δ^{18}O = –16.2‰). These values are close to those of massive ice in this region: from –16 to –17‰. This suggests that in this case cryopags are isotopically close to massive ice. The ratio of δ^{18}O and δD in ice of stra-

Table 2. Content of stable oxygen isotopes (δ^{18}O), deuterium (δD), and values of deuterium excess (d_{exc}) in massive ice (third terrace of Seyakha River (Mutnaya), Bovanenkovo)

Field number	Depth, m	δ^{18}O, ‰	δD, ‰	d_{exc}, ‰
Borehole 34-P*				
YuV–34P–1/0	28.5–32.4	–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	30.25–30.75	–18.89	–146.0	5.1
YuV–34P–1/5	30.75–31.4	–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
Stratum 1. Seyakha River opposite *GP*-1**				
YuV05-Bov/24	0.1	–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
Stratum 2. The lake 1300 m from PPG**				
YuV05-Bov/17	0	–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
Stratum 3. Thermo-abrasive kar to the east of K-64**				
YuV05-Bov/11	0	–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
Stratum 4. Exposure near thermo-abrasive kar**				
YuV05-Bov/54	0–0.2	–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
Repeated-vein ice				
YuV05-Bov/65	2 m	–13.54	–101.2	7.1
YuV05-Bov/3		–17.35	–135.5	3.3
YuV05-Bov/70		–13.65	–105.7	3.5
Cryopag's water				
YuV05-Bov/32	120 m	–22.36	–168.9	10.0
Lake water				
YuV05-Bov/30		–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
River water				
YuV05-Bov/66	Seyakha River	–14.16	–106.6	6.7
YuV05-Bov/68	Mordyyakha River	–13.78	–103.5	6.7
YuV05-Bov/69	Seyakha River	–13.65	–104.5	4.7
YuV05-Bov/59	Seyakha River	–18.66	–143.1	6.2

* Ice type – massive ice.

** Depth from the roof of massive ice, ice type – massive ice.

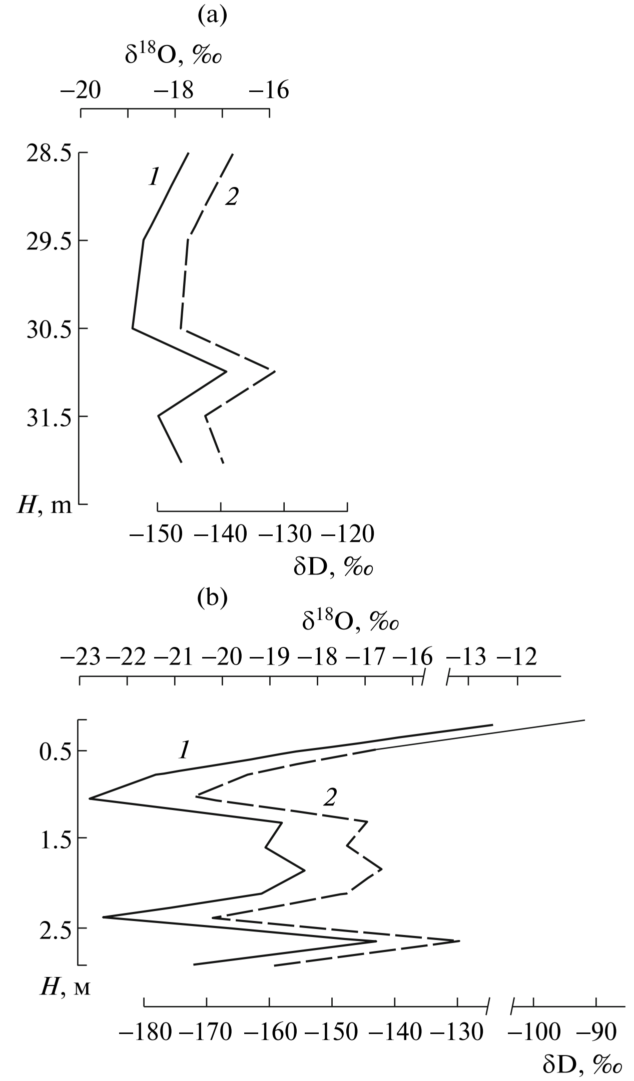

Fig. 3. Oxygen-isotope (*1*) and deuterium (*2*) diagrams of massive ices broached in borehole P = 34 (a) and stratum 4 (b). *H* is depth.

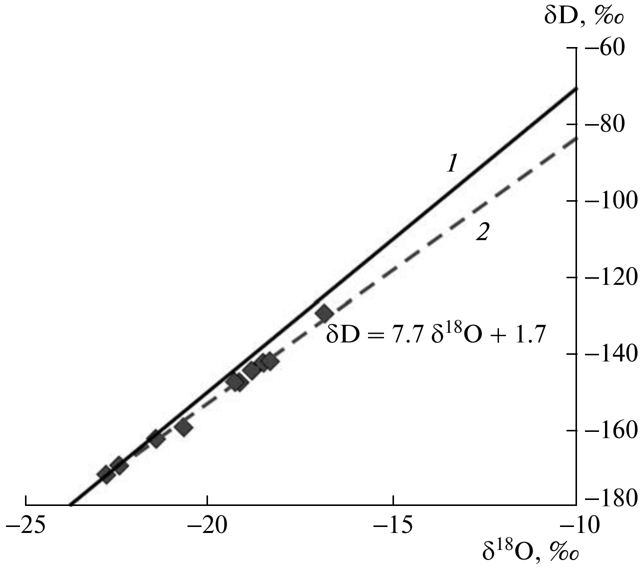

Fig. 4. Comparison of global meteoric water line (*1*) with local meteoric water (*2*) line of massive ice no. 4 in the thickness of the third terrace (Bovanenkovo, GCF).

tum 4 is indicative. Here, all points in samples of massive ice are located near the global line of meteoric (atmospheric) waters (Fig. 4). This suggests that water-saturated layers froze slowly. Isotope exhaustion of water-saturated layers occurred at the final stages of their formation, but it occurred evenly for both ^{18}O and ^{2}H. The data indicate that massive ice of Bovanenkovo is primarily from intraground ice forms, syngenetically formed due to segregative, segregative-infiltrative, or segregative-congelation ice forming upon freezing of water-saturated decompressed layers (possible in underlacustrine taliks) 25 000–20 000 yr BP. Single layers may have been formed interwater in the mixing zone of fresh and super cool salt waters. Obviously, all three mechanisms of ice forming occurred at different stages of stratum formation. In single fragments significant pressures occurred. This led to local injections, appearing in the formation of vertical schlieres above layers or small stocks and dikes, penetrating horizontal ice bodies.

Ingression of cool (temperature below –2°C) seawaters on the surface of lake-rich laida (third terrace now) could be one reason for ice forming under the bottom of lakes or lake-bog pools. In our opinion, this leads to sharp cooling of water and bottom suspension, freezing, and active ice forming under large, but shallow lakes.

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