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GEOGRAPHY

Variations in $\delta^{18}O$, δD, and the Concentration of Pollen and Spores in an Autochthonic Heterogeneous Massive Ice on the Erkutayaha River in the Southern Part of the Yamal Peninsula

Yu. K. Vasil'chuk, N. A. Budantseva, and A. C. Vasil'chuk

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The objective of our work is to study the new massive ice deposit in the valley of the Erkutayaha River in the southern part of the Yamal Peninsula, determine the concentration of stable oxygen and hydrogen isotopes in the ice and study the pollen and spore in the ice, to determine the conditions of ice formation based on these data, and show that massive ice in these region are of the heterogeneous autochthonic type and segregation (infiltration-segregation) and injection genesis similar to those deposits that were recently studied in the regions near Yamal, on the Bovanenkov deposit [1] close to the Harasavey [2, 3] and Marre-Sale [4] settlements.

The newly investigated outcrop of massive ice is located in the southern part of the Yamal Peninsula on the left bank of the Erkutayaha River (68°11′18″ N, 68°51′39″ E). This is the southernmost among the studied massive ice in the Yamal Peninsula. A massive ice approximately 100-m long exposes in the outcrop 15–18 m high that is embedded predominantly in the layered sand. The ice massive is most completely exposed in the cirques (figure). The massive ice is located just under the layer of the seasonal melting in the central part of the cirques. Here, it is sharply elevated and cut most likely by the postgenetic subaquatic melting. In the apical part of the cirques, the massive ice is covered by Holocene lacustrine-swamp sediments approximately 1 m thick. The ice layers sharply drop on both sides of the central part and in 15 m already the cover of the ice deposit appears at a depth of 8 m. The ice in the massive ice body has a sufficiently different cryotexture. This is predominantly the ice of four types: (1) pure ice, dull-white with a large amount of gas xenogenic inclusions; (2) crystal-clear transparent ice sometimes with ground inclusions; (3) gray layered ice with steel shimmer, the layers are parallel to the slope of the upper surface of the ice deposit; (4) gray block ice deposited as tiles.

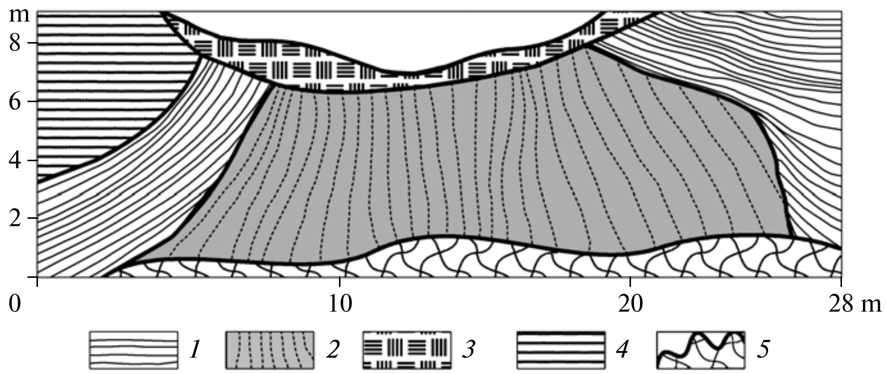
We distinguished the central dislocation part in the general structure of the deposit, a stock with vertically and subvertically located ice layers (the ice here is crystal-clear and dirty-gray with a large amount of mineral inclusions) and two peripheral parts composed of horizontally layered ice (the ice here is layered, predominantly gray with a steel shimmer, dull-white, and block gray). The horizontal layers of these two parts of the deposit change to sloping at the contact with the central stock. Such contact evidences that the ice of the central stock influences the character of the horizontally layered ice bedding.

A total of 33 samples of massive ice from different fragments of exposure and from different types of ice were selected for the isotopic and palynological determinations.

The isotopic composition of ice was determined at the Geographical Faculty of Moscow State University in the Laboratory of Stable Isotopes of the Department of Landscape Geochemistry and Soil Geography using the Delta-V mass-spectrometer with the GasBench standard option. During the measurements of $\delta^{18}O$, the analyzed samples were stabilized in CO_2 for 24 hours; stabilization for the δD measurements was performed for 40 min in the presence of a platinum stabilizer. The International Standard of Mean Ocean Water (SMOW-V), the MAGATE International laboratory standards, and the standards of the Isotope Laboratory of the Austrian Institute of Technology were used to calibrate the measurements.

The variations of stable oxygen and deuterium isotopes in the deposit are significant: in the pure dull-white ice $\delta^{18}O$ varies from −19.64 to −20.54‰, and δD varies from −152.4 to −156.9‰; in the crystal-clear transparent ice $\delta^{18}O$ varies from −19.24 to −20.24‰, and δD varies from −149.6 to −160.7‰; in the transparent gray ice with steel shimmer $\delta^{18}O$ varies from

Moscow State University,
Moscow, 119899 Russia
e-mail: vasilch@geol.msu.ru



Heterogeneous ice deposit presented by the paragenesis of the segregation and injection massive ice in the column of Kazantsev deposits in the valley of the Erkutayaha River in the southern part of the Yamal Peninsula: (*1*) segregation horizontally and subhorizontally layered ice; (*2*) injection vertically layered ice; (*3*) Holocene lacustrine-swamp loams and clay sand with peats; (*4*) sands including ice deposit; (*5*) earthflow.

–19.44 to –21.33‰, and δD varies from –150.3 to –163.8‰; in the block gray ice and in the dirty-gray ice $\delta^{18}O$ varies from –22.13 to –23.42‰, and δD varies from –165.5 to –172.7‰ (Table 1).

Estimating the entire variability range of $\delta^{18}O$ (~4‰) and δD (~20‰), we can speak about comparatively small fluctuations of the isotopic composition. Hence, the initial water for all ice types was the same or very close in its isotopic composition. In addition, the isotopic differences almost did not exceed the usual isotopic difference that appears due to the fractioning when free water freezes.

We selected samples from an ice vein and from the segregation knots of ice in the column of the bed, which was dated on the radio-carbon basis at the Geological Institute of the Russian Academy of Sciences in the range from 1000 ± 170 yr (GIN-163) to 1820 ± 80 yr (GIN-10985). Similar dates for the second sample at 1820 ± 100 yr (Hel-4492) were obtained at the Radiocarbon Laboratory of Helsinki University, which evidences the reliability of the dating.

It is worth noting that the correlation of the isotopic values obtained at different laboratories is very high. The comparatively small range of fluctuations in the values of $\delta^{18}O$ and δD evidences that the winter conditions of the vein formation were stable. In the ice vein, the values of $\delta^{18}O$ varied from –18.0 to –20.63‰ and the values of δD varied from –135.8 to –151.9‰; in the ice segregation schliers (ice inclusions in the frozen ground) and bed deposits $\delta^{18}O$ varied from –15.01 to –19.76‰ and the values of δD varied from –107.6 to –148.3‰ (Table 2).

A comparison of isotopic characteristics demonstrates that the values of $\delta^{18}O$ and δD in the massive ice are close to the isotopic characteristics of the vein ice and the most isotopically negative values obtained in the segregation ice from the bed deposit columns. This indicates the fact that the climatic conditions in the time of massive ice formation were more severe than the present ones and the annual mean air temperatures were very likely close to the modern average temperatures in winter (i.e., they varied from –17 to –20°C).

The comparatively small range of variations in the isotopic composition most likely indicates that the nature of the deposits is intra-annual, although significant differences in the structure of the ice make us think that the deformed and vertically layered ice in the central part of the deposit is most likely of the injection nature.

Horizontally layered ice is most likely segregation or infiltration–segregation ice. No significant isotopic fractioning in the formation of the layered ice was found, which indicates the fact of infiltration–segregation ice formation in the conditions of the open system.

Investigation of the pollen and spores in the ice allowed us to answer in more detail the question about the genetic relation of the studied deposit. We analyzed milky-white, crystal-clear, and gray ice with ground inclusions in the exposures open along the river. Almost the entire analyzed massive ice is characterized by a high content of redeposits of Pre-Pleistocene palynomorphs (15–35%). Such concentrations of redeposited palynomorphs are characteristic of the beach facies in the Yamal Peninsula [5, 6]. In addition, debris of sponge spicules were found in a sample of gray ice, which is also characteristic of the deposits related to the marine genesis. Fungi spores that are found in the tundra swamps and small diatoms of the *Melosira* gender were also found here. Quartz debris, generally very small and not rounded, excluding one sample of the gray ice, in which the grains were round, was found. Their dominating size is 25–30 μm. Pollen of bushes dominates (40–59%) in this part of the massive ice. Pollen of herbs dominates (39%) in the gray ice. This is generally the pollen of sedge. We analyzed the crystal-clear and gray ice in the cirques, where the massive ice was exposed. The palynospectra are characterized by the absence of redeposited Pre-Pleistocene palynomorphs, high concentration of the

Table 1. Variations in $\delta^{18}O$, δD, and d_{exc} in the samples of massive ice sampled on the left bank of the Erkutayaha River (southern part of Yamal) in July 2010 (point 10–YuV–Yerk)

Sample number	Ice type	Height over the level of the Erkutayaha River	$\delta^{18}O$, ‰	δD, ‰	d_{exc}, ‰
		Horizontally layered peripheral			
1	Crystal clear	1.0	–19.54	–156.5	–0.18
2	Crystal clear	0.7	–19.24	–149.6	4.32
3	Crystal clear	0.6	–19.44	–153.1	2.42
4	Milky white	1.0	–19.84	–154.1	4.62
5	Milky white	0.7	–19.74	–152.4	5.52
6	Milky white with sloping layers	0.6	–19.64	–155.8	1.32
7	Steel gray with ground inclusions	1.0	–19.54	–158.9	–2.58
8			–19.44	–155.5	0.02
9	Steel gray with ground inclusions	0.6	–19.44	–154.8	0.72
10	Milky white near the upper contact with transparent gray	0.7	–20.54	–156.9	7.42
11	Crystal clear	1.0	–19.64	–154.1	3.02
12		0.9	–20.24	–153.1	8.82
13		0.8	–20.04	–154.8	5.52
14		0.7	–20.14	–160.7	0.42
		Vertically layered ice of the central stock deposit			
15	Crystal clear	10.0	–19.54	–152.4	3.92
16	Crystal clear	9.5	–19.64	–155.5	1.62
17	Transparent gray	9.0	–19.64	–153.1	4.02
18		8.5	–19.84	–151.4	7.32
19		8	–19.64	–153.4	3.70
		Horizontally layered peripheral			
20	Dirty-gray with a large number of inclusions	8.2	–22.33	–170	8.64
21		8.0	–22.13	–168.6	8.44
22	Transparent gray	7.5	–20.83	–162.7	3.94
23		7.0	–21.33	–163.8	6.84
24		6.5	–19.44	–150.3	5.22
25	Block gray, deposits as tiles	1.0	–23.42	–172.7	14.66
26		1.15	–22.92	–172.4	10.96
27		1.35	–22.83	–168.6	14.04
28		1.5	–22.63	–168.2	12.84
29		1.63	–22.43	–166.2	13.24
30		1.75	–22.13	–165.5	11.54
31		2.05	–22.23	–162.7	15.04
32		2.35	–22.33	–169.6	9.04
33		2.5	–22.53	–161.7	18.54

bush pollen (57–75%), and dominating pollen of gannet (up to 41%). A large amount of green moss spores (25%) was found in the crystal-clear ice; these spores were not found in the gray ice. However, the concentration of pollen of ericales in the gray ice, which is a typical tundra component, is 10%. Downstream along the Erkutayaha River, gray ice deposited in the tile form is palynologically characterized. Its characteristic is close to palynospectra from the exposures along the river.

It is worth noting the difference between the spore-pollen spectra in the vertically layered ice from the

Table 2. Variations in $\delta^{18}O$, δD, and d_{exc} in the samples of the Holocene ice wedges sampled on the left bank of the Erkutayaha River (southern part of Yamal) (point 375–YuV)

Sample number	Depth, m	Distance from the left edge, cm	$\delta^{18}O$, ‰	δD, ‰	d_{exc}, ‰
Holocene ice wedges in floodplain sediment					
4*	1.0	10	–19.04	–140.6	11.7
7*	The same	40	–19.77	–147.7	10.5
7**	"	40	–19.0	–	–
8*	"	40	–20.03	–146.8	13.4
9*	"	40	–20.20	–150.8	10.8
9**	"	40	–19.5	–	–
10*	"	40	–20.63	–151.9	13.1
11*	"	10	–19.80	–146.2	12.2
26*	"	0–7	–18.75	–140.8	9.2
27*	"	7–14	–18.66	–137.8	11.5
27f*	"	7–14	–19.00	–139.2	12.8
27**	"	7–14	–18.0	–	–
28f*	"	14–28	–19.03	–139.0	13.2
30*	"	28–40	–19.55	–146.0	10.4
30**	"	28–40	–19.7	–	–
31f*	"	40–50	–20.37	–150.4	12.6
32f*	"	50–54	–19.91	–146.5	12.8
33f*	"	54–64	–20.30	–149.3	13.1
33**	"	54–64	–20.2		
34**	"	64–70	–19.0	–	–
35*	"	70–80	–18.31	–135.8	10.7
Modern ice vein in floodplain sediment					
36f*	0.3	–	–16.13	–114.5	14.5
Segregation ice in floodplain sediment					
2**	1.0	–	–15.4	–	–
3*	The same	–	–15.26	–109.1	13.0
3f*	»	–	–15.01	–107.6	12.5
6f*	0.3	–	–19.76	–148.3	9.8
6**	1.0	–	–19.4	–	–
Water of the Erkutayaha River					
25**	0	–	–17.9	–	–

Note: The determinations were performed by D. Rank and V. Papesh at the Scientific Research Center "arsenal" in Vienna (*); and by E. Soninnen at the Isotopic Laboratory of Helsinki University (**). Letter f denotes filtered samples.

central stock (most likely of injection genesis) and horizontally layered peripheral ice (most likely of segregation or infiltration-segregation genesis). This difference is especially noted in the analysis of redeposited pollen and spores, which are not found in the ice of the central stock deposit, and at the same time in the peripheral horizontally layered deposit, the concentration of this redeposit is high and reaches 35% (Table 3).

The same can be said about the diatomic algae, debris of sponge spicules, and remains of fungi: they were not found in the ice of the central stock and they are in abundance in the peripheral ice. Differences in the degree of roundness of the quartz particles were also found: in the ice of the stock deposit they are not rounded, and in the peripheral horizontally layered ice the roundness of the quartz particles is significant. This indicates the existence of different sources of water supply for the feeding of the vertically layered ice, central stock, and horizontally layered peripheral ice.

Palynospectra studied in different types of ice of the exposed deposit, or more exactly, the combinations of

Table 3. Palynological characteristic of the ice deposit at the left bank of the Erkutayaha River (southern part of Yamal) in % (point 10–YuV–Yerk)

Microinclusions in the ice	Vertically layered ice of the central stock deposit	Horizontally layered peripheral ice
Tree pollen	0.0	0.0–2.5
Bush pollen	35–59	36–72
Pollen of herbs and bushes	13–36	24–67
Spores	10–27	0–26
Redeposited pollen and spores	no	15–35
Pollen of Arctic dwarf birch	14–30	10–35
Pollen of gannet	21–41	2.5–42
Pollen of willow	no	2.4–7
Pollen of ericales	8–10	0–10
Pollen of graminoids	0–18	5–13
Pollen of sedge	0–7	0–24
Spores of Polypodiaceae filicales	0–7	0–1
Spores of sphagnum mosses	1–4	1–6
Spores of green mosses	0–25	1–25
Diatomic algae (*Melosira*)	no	yes
Debris of sponge spicula	no	yes
Fungi remains	no	yes
Coal microparticles	a little	a lot
Quartz microparticles	small, not rounded	small, rounded

the massive ice bodies of different textures evidence that the ice was formed in the ground. This conclusion is made on the basis of the typical tundra character of palynospectra, domination of the pollen of Arctic dwarf birch, gannet, graminoids, sedge, and spores of green mosses (14–25%), participation of ericales pollen (3–10%), almost complete absence of the tree pollen, presence of horsetail spores, pollen of aquatic plants such as *Thalictrum* and *Sparganium*, and a notable content of pre-Pleistocene palynomorphs.

Comparison of palynospectra of this complex with the previously studied spectra in the tundra zone of the Yamal–Gydansk province demonstrated a significant similarity with the palynospectra distinguished in a number of massive ice within the Bovanenkov deposit [1], in ice layers in the deposits of the first terrace in the mouth of the Gyda River [5], and in the lower reaches of the Yuribey River. The common features of the distinguished palynospectra are their tundra character: domination of the pollen of the Arctic dwarf birch, sedges, and spores of green moss with a notable content of the pollen of aquatic plants and horsetail spores, participation of the pollen of ericales, and the presence of redeposited pre-Quaternary pollen and spores (up to 17%), and the complete absence of the exotic pollen of broad-leaved trees. Remains of diatoms were found in the massive ice of the Bovanenkov deposit, the ice deposit in the lower reaches of the Yuribei River, and in the ice on the Erkutayaha River. Domination of green moss spores (22–27%) along with the pollen of the Polar willow (14%) is also characteristic of the palynospectra from the gray ice in the exposures on the Erkutayaha River and the lower ice layer in the exposure of the massive ice on the Gyda River.

If we compare palynospectra that we distinguished in the ice of the exposure on the Erkutayaha River and palynospectra from the ice and snow cover of the polar glaciers, the following differences are clear. The concentration of exotic far-transported pollen *Acer, Fraxinus, Quercus, Ulmus, Populus,* and *Abies* in the ice column of the polar glaciers fluctuates from 3 to 23%. In the investigated massive ice, pollen of species of trees exotic for the polar regions was not found. Only a single grain of pine tree pollen was found. In addition, almost no redeposited pre-Quaternary palynomorphs were found in the ice of glaciers. In the major part of samples from the massive ice, the concentration of redeposited pre-Quaternary pollen and spores was 15–35%. The pollen of pine trees easily transported in the air dominates in the ice columns of glaciers and in the snow cover [7–9]. For example, palynospectra over the Vavilov dome [10] are characterized by the domination of the pollen of wood species with the participation of the pollen of graminoids, chenopodiaces, wormwood, and Rosales. Pollen grains of pine easily transported by the wind absolutely dominate (40 pieces per liter) in the snow cover of the Akademii Nauk dome (Komsomolets Island). Their concentration reaches 97% of the total composition [9]. The pollen of pine trees *Pinus sylvestris* (26–36%) and *P. sibirica* (9–16%) also dominates in the ice and snow cover of the glaciers in the Polar Ural Mountains [11].

The age of this heterogeneous massive ice can hardly be determined now, but the OSL datings carried out in [12] from the massive ice of this massive ice (from 59 ± 4 to 72 ± 5 ka) allow us to state that this ice was formed not earlier than 60 ka.

The joint analysis of the distribution of stable isotopes and pollen-spore remains in the massive ice on the Erkutayaha River allows us to conclude that this is an intraground (autochtonous) heterogeneous massive ice [13]. The horizontal surrounding sediments was formed first as a result of infiltration–segregation ice release during the freezing of a draining beach. As a result of the further freezing, a closed talik was formed under the deposit. Its further freezing led to the upward injection of water under pressure, formation of the stock deposit of injection ice, and deformation of the overlying ice deposit formed earlier.

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