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ISOTOPE-GEOCHEMICAL COMPOSITION OF THE ICE WEDGES IN THE SLOPE YEDOMA ON THE KULAR RIDGE AND RECONSTRUCTION OF THE MEAN JANUARY AIR PALAEOTEMPERATURE DURING 47,000–25,000 BP

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The isotope composition and hydrochemical properties of the Late Pleistocene ice wedges in the outcrop of flat side of Kular Ridge located in the western part of Yana-Indigirka Lowland have been analyzed. It has been established that variations of the $\delta^{18}O$ values in the ice wedges (varying –32.6 ‰ to –31.0 ‰) do not exceed 1.6 ‰. The mean winter and mean January temperature reconstructions have been carried out by means of the palaeogeocryologyical studies of the oxygen stable isotopes contained in ice wedges. In the Kular Ridge area, the mean January air temperature in Late Pleistocene was by 7 °C lower than the current. Besides, the lowest mean winter temperature referred to the 37–32 ka BP.

Ice wedges, Late Pleistocene, palaeotemperature, permafrost, yedoma, oxygen isotopes, hydrochemistry, trace elements, Kular, Northern Yakutia

INTRODUCTION

The purpose of this study is to reconstruct the mean January and mean winter air palaeotemperatures in the Late Pleistocene (47,000 to 32,000 yr BP) on the basis of data obtained by studying yedoma on the gentle slope of Kular Ridge nearby the abandoned Kular Settlement, as well as to identify the geochemical features which are characteristic for the ice wedges and yedoma sediments containing them. For a study, aimed at air palaeotemperature reconstructions, it has been necessary to analyze the isotopic and geochemical composition of syngenetic ice in order to establish the basic conditions for the formation of the yedoma strata and ice wedges. The formation of the Kular yedoma dates from 47,000 to 25,000 yr BP [*Vasil'chuk, Vasil'chuk, 2020*].

Location and physical-geographical features of the studied area

The studied section of the yedoma strata (70°38′32″ N, 134°18′78″ E) has been exposed in an outcrop of the slope sediments on a gentle slope in the foothills of Kular Ridge, nearby Kular Settlement, on the right bank of the Burguat River, 0.5 km from the mouth of the Emis Creek (Fig. 1). A detailed description of the section is given in the previous paper [*Vasil'chuk, Vasil'chuk, 2020*].

The Arctic climate dominates in the studied area, the mean January air temperatures range from –30 to –39 °C, and the minimal ones vary from –47 to –54 °C (Kazach Settlement). The mean July air temperatures range from +4 to +5 °C [*Reference book..., 1966;* http://ru.climate-data.org/2019].

The local relief has been formed mainly by the slope, lacustrine-alluvial and alluvial processes. The alimentation of the Kular region watercourses is provided by precipitation and water of active layer. According to available data [*Soloviev et al., 2003*], the chemical composition of surface waters is represented by two types, either water of the sodium-calcium chloride-hydrocarbonate type, or the magnesium-calcium hydrocarbonate one. Less common are waters of mixed cationic composition. Small streams, as a rule, are characterized by the chloride-hydrocarbonate sodium-calcium composition.

The depth of seasonal thawing, as a rule, does not exceed 50 cm, but on the slopes of the southern exposure it can reach 1 meter. The mean annual temperature of perennially frozen ground varies from –6 to –8 °C. The active layer water are mainly descending, soil-porous ones. According to the degree of mineralization, they are fresh and ultra-fresh (mineralization up to 0.1 g/L). According to the hydrogen-ion exponent, the water is classified as neutral (pH 6.0–7.0), in terms of hardness the water is soft (total hardness does not exceed 1.0 mmol/L). Water supply of the active layer occurs due to the infiltration of precipitation and partly due to the melting of ice, as well as the condensation of the porous air vapor. The chemical characteristic of the active layer water is very close to that of small streams: it is of chloride-bicarbonate sodium-calcium type with a salinity of 0.02 to 0.10 g/L (ultra-fresh to fresh). According to the hydrogen-ion exponent, water is classified as neutral (pH 6.0), and by hardness (total hardness from 0.3 to 0.1 mmol/L) it refers to soft one [*Soloviev et al., 2003*].

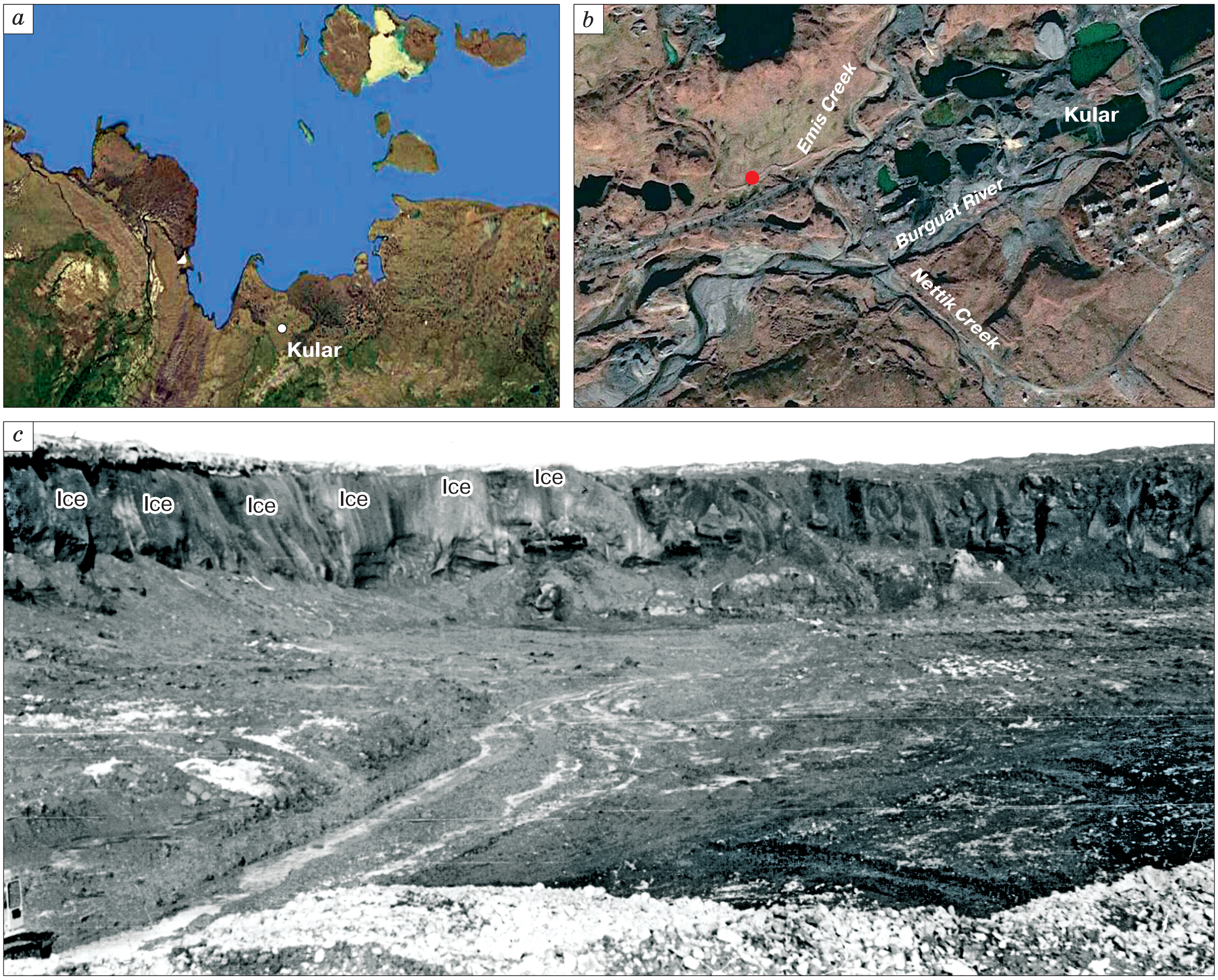

Fig. 1. Location of reference section (marked with a red circle) nearby Kular Settlement (*a*, *b*) and general view of the section (*c*).

THE RESEARCH METHODS

In the field, the samples of ice wedges for isotope and chemical analysis were sampled out of the axial parts of the wedges from the main outcrop wall with an interval of 0.2 to 0.5 m using the sampling method elaborated by Yu.K. Vasil'chuk [*1992*]. The samples of yedoma sediment were taken from the frozen outcrop wall, packed into the double plastic bags, and delivered in the melt state (with the preservation of natural water content) to the laboratory for geochemical measurements. The segregated ice from ice lenses and structure-forming ice were taken separately. The samples of ice wedges and segregated ice were melted in plastic bags at a temperature of no higher than 15 °C, poured into chemically inert plastic bottles of the volume of 20 to 500 mL. Analytical measurements of the trace element composition (Sr, Mn, Zn, Cu, Fe, Co) have been performed on the samples by the method of atomic-absorption spectroscopy at the Dokuchaev Soil Institute. The isotopic composition of ice wedges has been determined at the Tallinn Institute of Geology. The chemical composition of water-soluble salts in the Late Pleistocene yedoma deposits and ice wedges has been determined by titration in the chemical laboratory of the PNIIIS.

RESULTS OF A STUDY OF THE ICE WEDGES AND ENCLOSING DEPOSITS

Structure of yedoma strata

The outcrop of the yedoma strata is exposed on a gentle slope (slope angle is 4 to 5°) of the southern exposure of the Burguat River valley. The yedoma base is located at altitude of 95 to 120 m a.s.l., and its roof is situated at those of 105 to 140 m a.s.l. The thickness of these deposits ranges from 20 to 28 m. At the base of yedoma, firm bedrock lies, which is over-

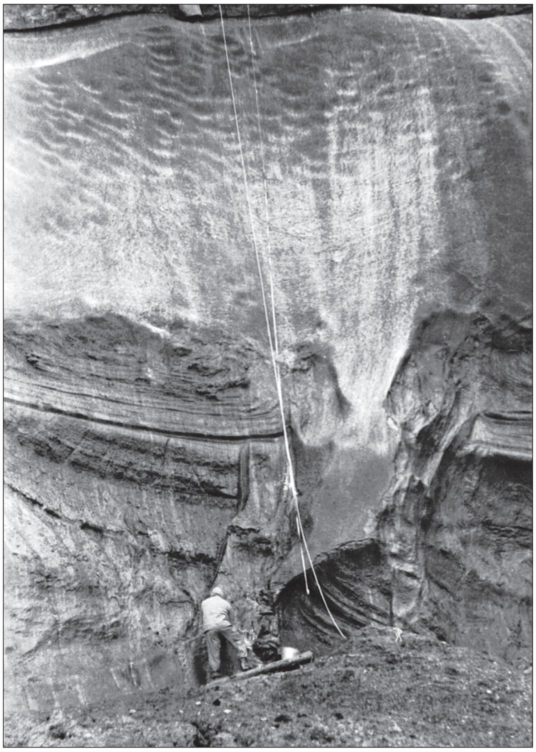

Fig. 2. Ice wedges in slope yedoma strata nearby Kular Settlement.
Photo by Yu. Vasil'chuk.

lain by the rubble eluvium; black sand lies above with the inclusion of gravel and slightly rounded pebbles. Even higher, including lenses of loam and peat, the strata of the gray sandy loam is disposed. Between the black sand and gray sandy loam, there is a layer of segregated ice with a thickness of up to 1.5 m. In the sandy loam, three lenses of pure peat are noted at depths of 4, 8 and 18 m. Multi-tiered and merging ice wedges (Fig. 2) cut through the entire sandy loam strata; their width is not less than 3 m, and the distance between them is 10 to 15 m. The heads of individual wedges are located at different heights, and the lower tier of ice wedges penetrates into bedrock [*Vasil'chuk, Vasil'chuk, 2020*].

Sampling for the isotopic and hydrochemical analyses has been performed at the merging of two ice wedges along their axes. To characterize the lower part of the section, samples were taken from the left ice wedge (wedge No. 1), and to characterize the upper part of that, samples were taken from the right ice wedge (Fig. 3, wedge No. 2). The segregated ice lenses have been also sampled.

Isotopic and chemical composition

Exhaustive isotope information has been obtained from samples of the Kular yedoma: ice wedges, as well as the segregated ice lenses have been studied (Table 1). The content of alkaline-earth metals (cal-

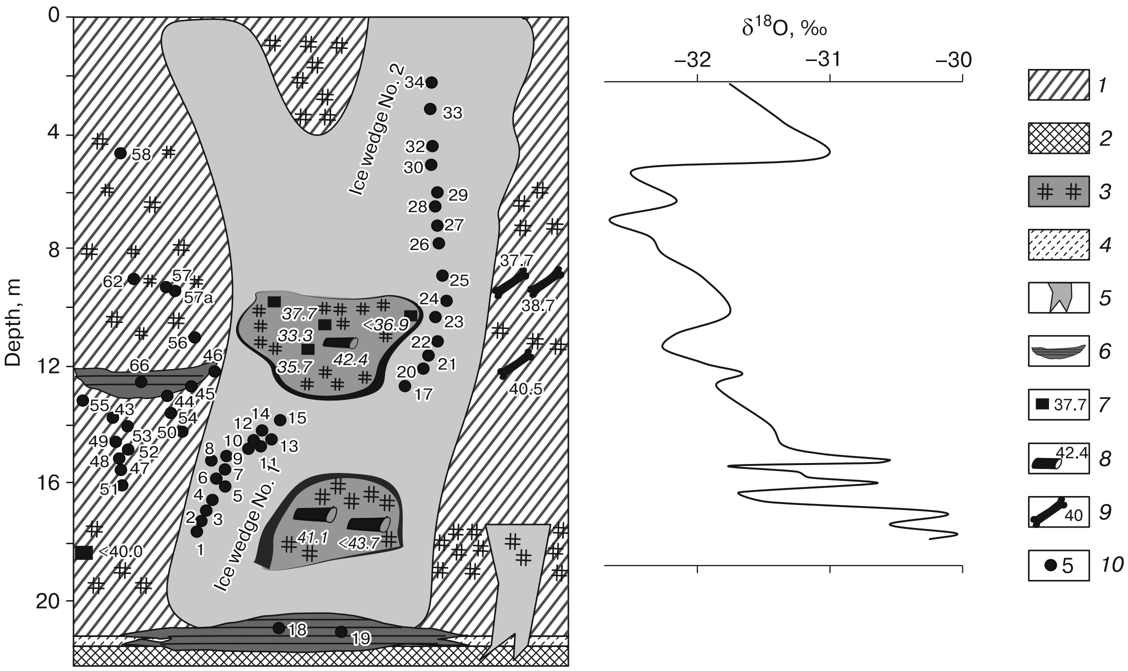

Fig. 3. Scheme of sampling for isotope-oxygen analysis of ice wedges in slope yedoma strata nearby Kular Settlement:

1 – frozen grey loamy sand of the medium-layered, lenticular cryostructures; *2* – grus and rubble deposits; *3* – frozen peat of the cross-layered, irregular reticulate cryostructures; *4* – frozen black fine sand; *5* – ice wedges; *6* – thick massive segregated ice lenses; radiocarbon dating of: *7* – peat; *8* – wood; *9* – bones; *10* – sampling sites for oxygen-isotope and chemical analysis; figures correspond to sample's numbers given in Tables 1–4.

Table 1. **Variations of $\delta^{18}O$ in Late Pleistocene ice wedges, in structure-forming ice and segregated ice lenses, as well as in snow and water of Burguat River**

Sample ID	Depth, m	$\delta^{18}O$, ‰	Sample ID	Depth, m	$\delta^{18}O$, ‰
Syngenetic Late Pleistocene ice wedges in yedoma strata					
34	2.0	–31.7	15	13.6	–31.4
33	3.3	–31.3	14	14.3	–31.3
32	4.5	–31.0	13	14.6	–31.0
30	5.0	–32.4	12	14.8	–30.5
29	6.0	–32.1	11	14.9	–30.6
28	6.6	–32.6	10	15.0	–31.7
27	7.2	–32.3	9	15.2	–31.2
26	7.8	–32.2	8	15.4	–31.1
25	8.6	–31.9	7	15.6	–30.6
24	9.8	–31.7	6	15.8	–31.6
23	10.5	–32.1	5	16.1	–31.4
22	11.0	–32.2	4	16.5	–30.1
21	11.5	–31.9	3	17.0	–30.5
20	12.0	–31.6	2	17.3	–30.0
17	12.3	–31.8	1	17.5	–30.2
Syngenetic Late Pleistocene structure-forming ice lenses in yedoma strata					
62	9.0	–35.6	55	13.0	–25.3
56	11.0	–25.2	54	13,5	–23.8
46	12.0	–22.1	43	13.5	–25.2
45	12.5	–23.7	53	14.0	–24.2
44	13.0	–23.3			
Segregated thick ice lenses in yedoma strata					
65	12.5	–24.4			
Segregated thick ice lenses at the bottom contact of yedoma strata					
18	21.0	–23.5	19	21.5	–23.5
Water of Burguat River			*Snow of September 16*		
63f	0	–21.4	67	0	–25.8

Table 2. **Content of trace elements and alkaline-earth metals in Late Pleistocene syngenetic ice wedges**

Sample ID	Sampling depth, m	Co	Cu	Mn	Zn	Ca	Mg
		μg/L				mg/L	
Ice wedge No.1							
15	13.6	6.2	24.22	22.94	1.8	6.74	3.25
14	14.3	10.23	20.34	11.47	2.4	10.48	5.56
13	14.6	6.7	35.43	8.57	125.5	9.86	4.14
11	14.9	6.0	28.62	20.64	291.6	10.21	3.66
10	15.0	5.6	26.41	98.97	332.2	4.1	2.42
9	15.2	22.1	26.62	15.36	65.58	9.7	5.38
7	15.6	5.1	20.92	63.83	391.6	9.0	4.34
3	17.0	20.68	23.31	67.46	29.61	**13.8**	6.16
1	17.5	12.3	36.67	6.9	10.83	9.85	5.32
Ice wedge No. 2							
34	2.0	6.6	31.86	254.4	262.5	6.75	2.76
32	4.5	19.69	36.54	187.4	123.5	5.38	2.78
30	5.0	9.77	32.15	126.5	742.8	9.0	3.76
29	6.0	4.64	30.57	224.2	35.61	9.0	3.94
28	6.6	2.2	30.19	0.63	74.09	9.1	4.51
27	7.2	1.6	35.02	11.34	17.74	8.7	4.09
26	7.8	10.04	24.52	110.7	141.1	12.2	4.73
25	8.6	21.41	60.88	142.3	93.05	9.67	3.71
24	9.8	9.8	30.52	189.6	406.6	10.78	4.29
23	10.5	21.97	39.11	172.0	**1764**	10.93	4.27
22	11.0	0.62	31.28	9.14	349.5	8.15	2.87
21	11.5	14.36	40.86	8.8	394.6	10.04	4.35
20	12.0	4.7	38.85	2.4	33.82	7.32	3.44
Segregated thick ice lenses							
18	21.0	6.9	28.99	10.49	565.6	4.0	1.95
19	21.5	4.2	0.65	25.27	102	1.04	0.38
Structure-forming segregated ice							
43	13.5	5.3	2.88	3304	68.70	39.48	25.34
44`	13.5	4.6	22.85	3119	17.51	–	–
44	13.0	32.05	27.57	597.7	100	69.53	56.74
54	13.5	184.6	28.73	716.6	5.8	75.28	27.01
56	11.0	49.26	44.27	2956	**1802**	18.10	11.68
58	4.5	7.85	28.94	2681	1.4	208.0	–
58f	4.5	5.435	32.72	**3850**	32.66	–	–
66	12.5	20.05	27.09	31.23	**1193**	3.518	0.46
Burguat River							
63 (water)	0.0	13.42	39.55	98.66	2.5	70.66	39.19
67 (snow)	0.0	14.16	23.77	15.57	30.60	0.6591	0.8174

Note: the maximum values are marked in bold; ‘f’ stands for filtered samples.

cium and magnesium), as well as trace elements (cobalt, copper, manganese, zinc) in ice wedges of the Kular section has been analyzed (Table 2). The content of trace elements in natural waters (Table 3) along with that of water-soluble salts in the yedoma deposits (Table 4) has been also analyzed.

The isotopic composition of cryostructure-segregated ice, which differs from that of other yedoma sections, is noteworthy. The general range of variations in the values of $\delta^{18}O$ has exceeded 13 ‰, although more often the values of $\delta^{18}O$ in ice lenses of the yedoma sections vary from 3 ‰ to 4 ‰ [*Vasil'chuk Yu., Vasil'chuk A., 2018*]. The values of $\delta^{18}O$ in the cryostructure-ice of the peat lens in the central part of the outcrop range from –25.3 ‰ to –22.1 ‰, which is exactly 3.2 ‰. However, in the lateral part of the section, in the sections of sandy loam of peat formation with osseous remains, the value of $\delta^{18}O$ was –35.6 ‰ (Table 1). That is one of the lowest values of $\delta^{18}O$ obtained from the cryostructure ice lenses in the yedoma strata of Siberia. Most likely, that indicated the process of fractionation in a closed system, for example, as noted by the authors in

Table 3. **Composition and content of water-soluble salts in syngenetic ice wedges**

Sample ID	Sampling depth, m	Solid content, mg/L	Major ions, mg/L						pH
			HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	$Na^+ + K^+$	
27	7.2	76.0	41.5	6.7	19.8	11.6	2.2	**12.0**	7.27
26	7.8	88.0	**68.3**	6.7	13.2	**16.8**	4.9	7.8	7.15
25	8.6	62.0	42.7	5.4	10.7	12.0	1.5	8.0	7.22
24	9.8	68.0	43.9	6.1	13.2	11.2	2.2	9.7	7.07
22	11.0	76.0	65.9	4.7	10.7	14.4	3.6	9.4	7.08
21	11.5	70.0	48.8	5.4	14.8	7.2	5.8	9.7	7.08
17	12.3	60.0	26.8	7.4	18.1	12.8	1.0	7.1	7.13
15f	13.6	56.0	30.5	4.7	14.0	6.4	2.9	8.3	7.27
15	13.6	58.0	29.3	5.4	18.1	6.4	4.9	6.7	7.23
13	14.6	60.0	30.5	5.4	17.3	3.6	2.2	15.0	7.24
12	14.8	44.0	24.4	**8.1**	5.8	4.0	2.9	7.1	7.05
10	15.0	58.0	31.7	6.7	14.0	9.2	2.2	8.3	7.37
9	15.2	58.0	34.2	6.7	14.8	11.6	3.4	4.6	6.97
8	15.4	56.0	36.6	6.7	9.1	12.0	1.9	5.1	7.07
7	15.6	86.0	57.4	6.7	18.1	12.8	5.1	10.4	7.60
6	15.8	68.0	43.9	5.4	15.6	11.2	2.9	9.2	7.14
5	16.1	72.0	57.4	5.4	11.5	12.8	5.4	5.8	7.16
4	16.5	**92.0**	46.4	5.4	**33.7**	11.2	**6.8**	11.3	7.25
2	17.3	70.0	46.4	6.7	15.6	10.4	5.1	7.8	7.38
1	17.5	62.0	46.4	6.1	10.7	10.0	6.1	3.5	7.11

Note: the maximum values are marked in bold.

Table 4. **Composition and content of water-soluble salts in yedoma Late Pleistocene deposits**

Sample ID	Sampling depth, m	Solid content, %	Major ions, %						pH
			HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	$Na^+ + K^+$	
58	4.5	0.135	**0.044**	0.011	0.007	**0.012**	**0.006**	0.001	8.15
57	9.6	0.138	0.017	0.005	0.005	0.004	0.002	0.004	6.55
57a	9.8	**0.142**	0.022	0.005	0.007	0.006	0.002	0.004	6.60
56	11.0	0.124	0.016	0.005	0.005	0.003	0.001	0.005	6.10
45	12.5	0.107	0.015	0.005	0.004	0.004	0.002	0.002	6.56
44	13.0	0.113	0.021	0.007	0.005	0.005	0.003	0.002	6.97
55	13.0	0.092	0.028	0.004	0.011	0.007	0.003	0.005	7.74
50	13.4	0.096	0.027	0.013	0.017	0.008	0.003	**0.011**	7.98
43	13.5	0.082	0.016	0.007	0.007	0.004	0.002	0.005	7.10
53	14.0	0.078	0.034	0.003	0.019	0.010	0.002	0.008	7.96
49	14.3	0.109	0.028	**0.014**	0.021	0.010	0.004	**0.011**	7.89
52	14.6	0.090	0.028	0.004	0.024	0.011	0.002	0.008	8.00
48	15.1	0.096	0.026	0.012	0.013	0.006	0.003	**0.011**	7.75
47	15.7	0.094	0.035	0.008	0.007	0.008	0.003	0.007	7.90
51	16.0	0.092	0.028	0.003	**0.026**	0.010	0.003	0.008	7.86

Note: the maximum values are marked in bold.

the massive ice on the first terrace at the mouth of Gyda River (West Siberia), where the value of $\delta^{18}O$ in the most isotopically negative ice layer was −34.3 ‰ [*Vasil'chuk A., Vasil'chuk Yu., 2018*].

The value of $\delta^{18}O$ in the lenticular segregated ice bodies underlying yedoma is −23.5 ‰, and it is equal to −24.4 ‰ in the lens of segregation ice lying in the middle part of the yedoma, that is close to the isotopic composition of cryostructure ice lenses. For comparison, the values of $\delta^{18}O$ in the water of Burguat River and in the fresh snow which fell in September are adduced in Table 1.

In ice wedges, the values of $\delta^{18}O$ are significantly lower than in segregated ice, and they vary in the range of –32.6 ‰ to –30.0 ‰ (Table 1, Fig. 3). All the obtained values of $\delta^{18}O$ in ice wedges are lighter (more negative) than the current ones by 5 ‰ to 7 ‰ (the average value of $\delta^{18}O$ in the present-day veinlets of the region is equal to –25 ‰). There is a trend of lightening the isotopic composition from the bottom up from –30 ‰ to –32 ‰ or less. Local isotopic maxima are distinguished in the intervals of depths of 16 to 17 m, 9 to 10 m, and 2 to 5 m, which obviously reflects the cyclical nature of the formation of ice wedges [*Vasil'chuk, 1990*]. The heavier isotopic values are probably partially related to those moments of the development of the ice wedge complex, when its formation resumed after a break caused by strong watering of the massif, when the lake and swamp water could pour into the cracks. The authors have managed to trace a similar process of the laterally varying mineralization of ice wedges on the first terrace of Bely Island [*Vasil'chuk, Vasil'chuk, 2015*]. At these moments, the underlying sandy loam accumulated on the frozen substrate and peat overlaying them of 2 to 2.5 m thick was subjected to the freezing process.

The general trend is consistent with changes in winter air temperatures, demonstrating a transition to colder conditions in the winter season. That is evidenced by the similarity of the isotope curve from the samples taken from ice wedges with variations in the values of $\delta^{18}O$ in the Greenland ice core NGRIP (North Greenland Ice Core Project) (Fig. 4). According to the obtained radiocarbon dating and calculations of the accumulation rate of yedoma deposits and syngenetic ice wedges, taking into account the assumed depth of frost cracking of 2 to 3 m, we attribute the accumulation time of ice wedges to a time interval of 49,000 to 25,000 yr BP [*Vasil'chuk, Vasil'chuk, 2020*].

The isotopic curve of variations in the values of $\delta^{18}O$ in the Greenland ice core NGRIP (age referencing of the core has been produced by using the results of the Oxcal 4.2 calibration program [*Bronk, 2009*]) is shown on the right in Fig. 4 for comparison. The symbol "H" denotes a cold stage of Heinrich's events [*Vasil'chuk, 2003*]. The similarity of the variations in the values of $\delta^{18}O$ in ice wedges with the NGRIP isotope curve is emphasized primarily by the fact that in the interval from 47,000 to 44,000 cal yr BP, both plots fix a stable negative isotope trend, although its value on the Kular isotope curve is about 1.5 ‰, and that on the NGRIP curve is 2.5 ‰. Most likely, the isotopic values which are less than –32 ‰ on the Kular curve in the depth interval of 12.0–10.05 m (related approximately to the period of 38,000 to 37,000 cal yr BP) correspond to the fourth Heinrich's event, and those in the depth interval of 7.2 to 5.0 m (dated about 31,000 cal yr BP) correspond to the third Heinrich's event [*Vasil'chuk, 2003*]. Earlier cooling due to global climate changes has not been recorded on the isotope curve of the Kular yedoma, what can be attributed to the participation of other water sources besides atmospheric one.

Being based on the close positive correlation between the content of calcium ions and the concentration of dust particles, the content of calcium ions in

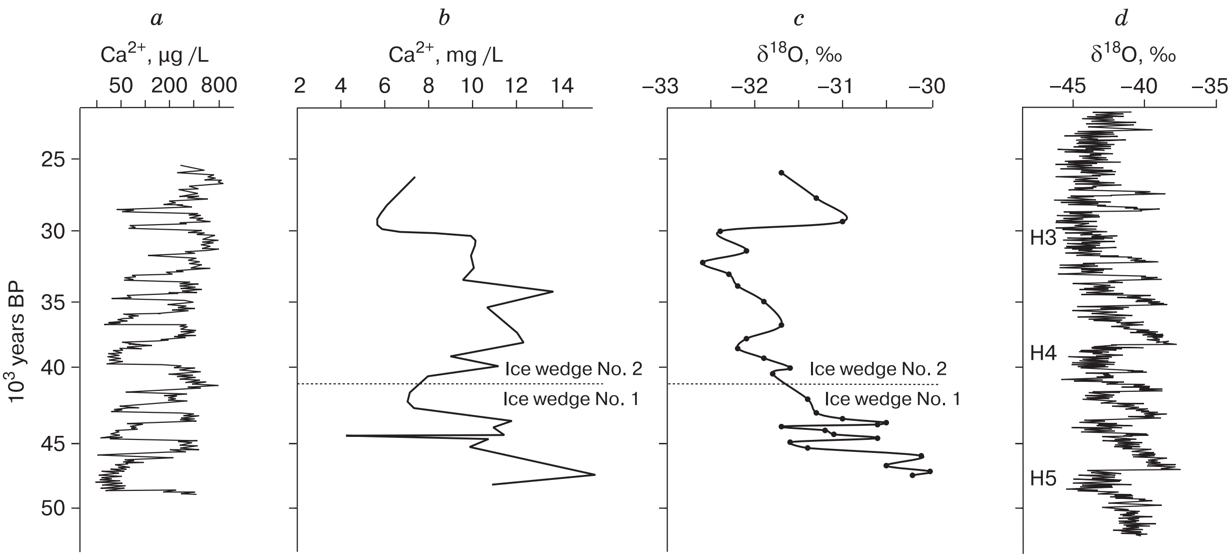

Fig. 4. Variations of $\delta^{18}O$ values and concentrations of calcium ions in ice wedges (*b*, *c*) (according to data of Tables 1 and 2), and comparison with hydrochemical curve of GISP ice core (*a*) and isotope curve of NGRIP ice core (*d*) (Greenland).

Letter H marks a cold stage of Heinrich event.

the ice of ice cores is most often interpreted as a change in the content of dusty particles in atmospheric air [*Hansson, 1994*]. It is also assumed that the isotopic composition of glacial ice can be more accurately estimated taking into account the concentration of calcium ions, which is an indicator of dustiness [*Rasmussen et al., 2013*]. To compare the content of calcium ions in the ice wedges of the Kular yedoma with that in the GISP (Greenland Ice Sheet Project) ice core (Greenland), the values of the content of calcium ions determined by atomic-absorption spectroscopy have been used (Table 2), since the same method had been used to determine the calcium content in the ice core [*Mayewski, 1999*]. A comparison of the content of calcium ions in the ice of the GISP (Greenland) ice core (age referencing is according to Mayewsky and Rasmussen [*Mayewski, 1999; Rasmussen et al., 2013*]) and in the ice of the ice wedges of the Kular section (Fig. 4) allows us to interpret the relatively high content of calcium ions as a reflection of the degree of dustiness of the Earth's atmosphere during the formation of ice wedges within the temporary range of 40,000 to 30,000 yr BP. The peak content of calcium ions in the lower part of the section (Fig. 4) is local in nature, not expressed in the diagram of the ice core of the GISP, and most likely corresponds to the maximum dustiness in the region. Increased dust content in the atmosphere in the north of Yakutia has been observed for that period in the Lower Kolyma River on the basis of a study of the yedoma deposits of Duvanny Yar [*Murton et al., 2015*].

The zinc content in the Kular ice varies over a wide range of 1.4 to 1802 μg/L (Fig. 5) with a median value of 93 μg/L. The maximum zinc content has

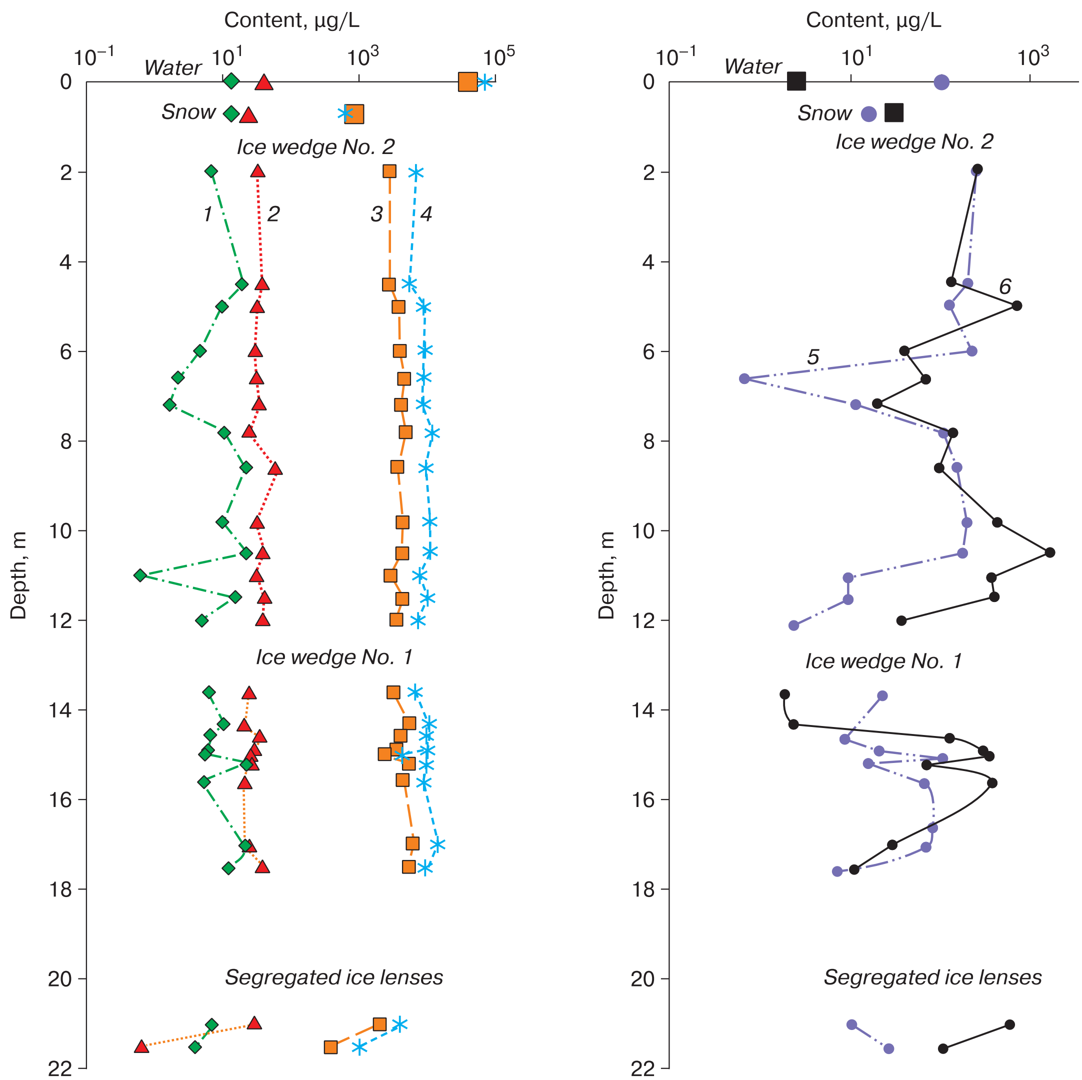

Fig. 5. Content of trace elements and alkaline-earth metals in syngenetic ice wedges and lenses of segregated ice.

1 – Co; *2* – Cu; *3* – Ca; *4* – Mg; *5* – Mn; *6* – Zn.

been noted in cryostructure-forming-ice and amounts to 1802 μg/L (Fig. 6), the maximum zinc content of ice wedges of the same order is 1764 μg/L. The average zinc content in ice wedges is 506.93 μg/L. Least of all zinc is contained in the segregated ice of ice lenses, varying from 102 to 565.6 μg/L. In the water of Burguat River, the zinc content is very small and does not exceed 2.5 μg/L. According to the data given by S.L. Shvartsev, the waters of the hypergenesis zone contain zinc on average 34 μg/L. According to Moor and Ramamurthy, 0.5 to 15 μg/L of zinc are dissolved in unpolluted fresh waters of the world's rivers [*Shvartsev, 1978*]. The zinc content in the Kular section is much higher. The high zinc content in cryostructure-ice within the depth interval of 11 to 12.5 m (Fig. 6) is probably due to the ingression of zinc-containing weathering products into the lake-bog basin, where peat has accumulated against the background of increased runoff. The probable source of zinc supply (according to the data of the group geological survey of a scale of 1:50 000, carried out by the State Unitary Enterprise "Yangeology"), is the outcrops of the Lower Tarbaganakh subformation in the valley of Nettik Creek, represented by quartz veins with phenocrysts of pyrrhotite and sphalerite (zinc-containing minerals). The zinc content in them is 0.1 % [*Soloviev et al., 2003*].

The maximum of manganese content has been registered in the segregated cryostructure-ice lenses, varying from 597 to 3850 μg/L (Fig. 6), and the minimum of that has been recorded in the segregated ice of lenses, ranging from 10.4 to 25.2 μg/L (Table 2). The manganese content in ice wedges varies over a wide range of 0.6348 to 254.4 μg/L, with an its average value of 79.7 μg/L and a median one of 16.1 μg/L [*Vasil'chuk et al., 2017*]. For comparison, the manganese content in the water of the Burguat River is 98.6 μg/L, and that in a snow sample taken in the immediate vicinity of the section is 15.57 μg/L, i.e. the manganese content in ice wedges is closer in magnitude to its content in snow. According to G.N. Baturin [*Yudovich, Ketris, 2013*], in rainwater, the manganese is contained in a concentration of 0.14 to 94 μg/L, with its average content of 0.2 μg/L. In general, the content of manganese in ice wedges of the Kular yedoma is closer to the obtained values of the manganese content in the snow and in the water of Burguat River. The high content of manganese in the cryostructure ice is probably due to the fact that manganese enters the cryostructure ice from solutions which are filtered through the mineral (gleyed) and organic (peaty) horizons, since gley soil and peaty-gley soil are typical types of soils in the region. It is exactly in soils of that type takes place a significant accumulation of manganese [*Lapteva et al., 2015*], because in the process of gleization the bio-

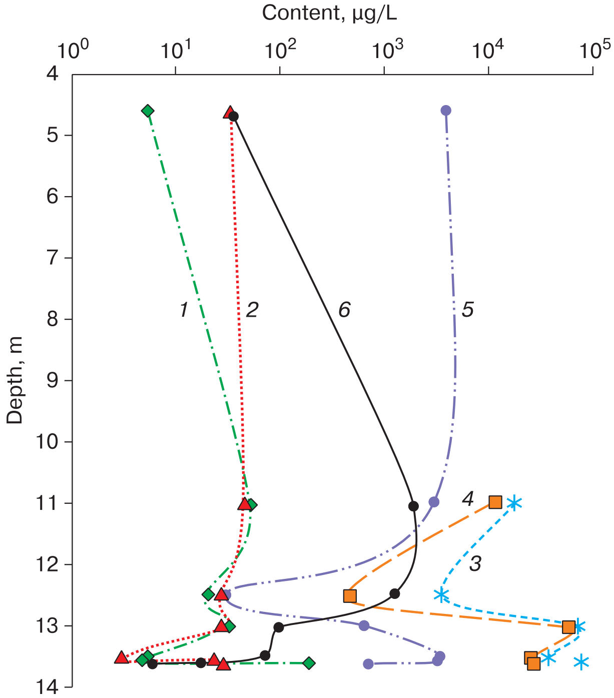

Fig. 6. Content of trace elements and alkaline-earth metals in cryostructure-segregated ice.

1 – Co; *2* – Cu; *3* – Ca; *4* – Mg; *5* – Mn; *6* – Zn.

chemical restoration of elements with variable valence (primarily iron and manganese) occurs. The high manganese content in the yedoma deposits allow us to suggest that gleization has played a significant role in the accumulation of yedoma deposits on the slope of Kular Ridge.

The copper content in the ice wedges varies from 20.3 to 60.8 μg/L, with an average copper content of 32.0 μg/L and a median one of 30.9 μg/L. The copper content in river water (39.55 μg/L) and snow (23.77 μg/L) corresponds to the range of copper content in ice wedges.

The cobalt content varies from 0.6 to 22.1 μg/L (Fig. 5), while its average content is 10.1 μg/L and the median one is 8.2 μg/L. The cobalt content in the river water and snow is approximately the same, amounting to 13.42 and 14.16 μg/L correspondingly.

The ice wedges of the Kular yedoma are characterized by the increased content of copper, zinc and cobalt, which is higher than the world average one (i.e. clarke) for surface natural waters [*Shvartsev, 1978*]. The sources of heavy metals in all probability are dolerites of the Derbeke complex of Late Jurassic intrusions, characterized by a high content of copper and cobalt, outcrops of which are often found in the valleys of the Burguat and Kuchchuguy-Kuegyulyur Rivers [*Soloviev et al., 2003*]. Zinc, copper and cobalt

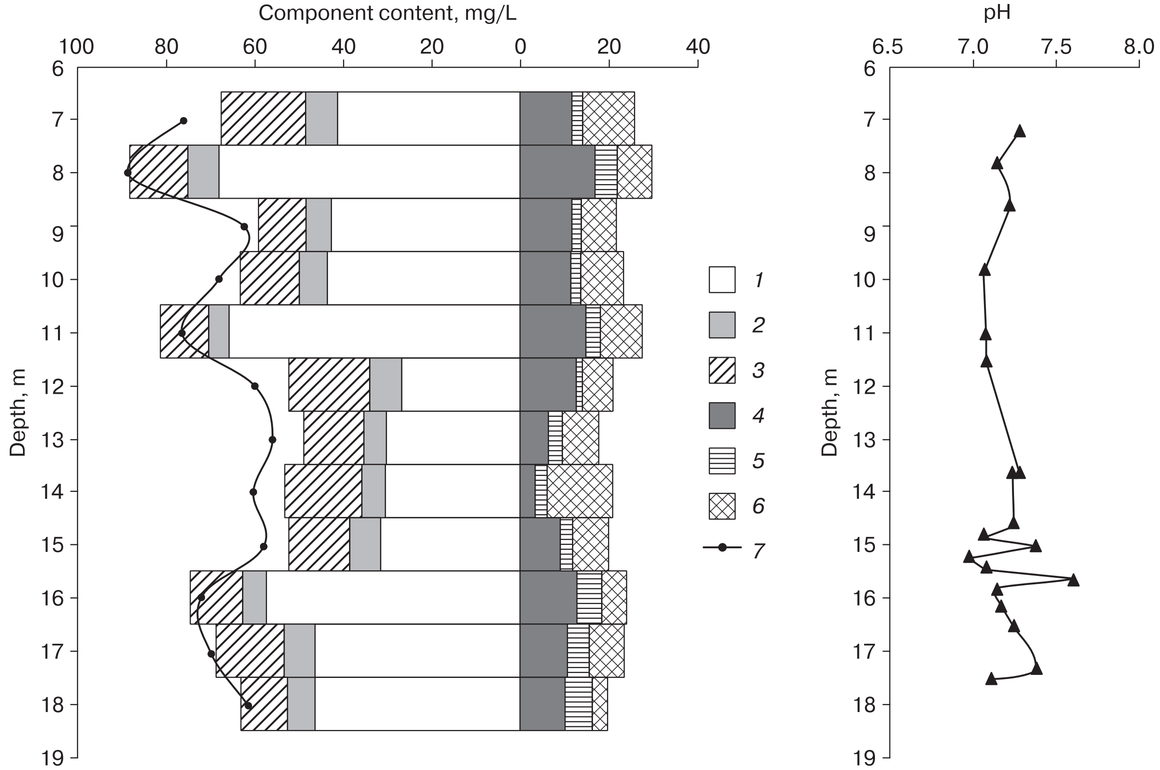

Fig. 7. Composition of water-soluble salts in syngenetic ice wedges.
1 – HCO_3^-; *2* – Cl^-; *3* – SO_4^{2-}; *4* – Mg^{2+}; *5* – Ca^{2+}; *6* – $Na^+ + K^+$; *7* – solid content.

are also included in the geochemical association of elements which are typical for gold deposits and their dispersion halos. In the immediate vicinity of the studied section, the Emis gold deposit is located. Among the main concomitant elements in that deposit, copper and zinc are noted [*Soloviev et al., 2003*], and cobalt is found here in a smaller amount. For the accumulation of copper, zinc and manganese in the yedoma deposits and ice wedges, a gleization situation is favorable. It could arise in the absence of aeration and with excessive moisturizing during the formation of ice wedges.

According to the data of the geological survey of a scale of 1:50 000 [*Soloviev et al., 2003*], abnormal concentrations of manganese, iron, beryllium, fluorine, aluminum, and tungsten reaching 8 MAC (maximum allowable concentrations for 4th climatic region [*Health standard 2.1.5.1315-03, 2003*]) have been found in ice wedges in the vicinity of Kular. Increased concentrations of beryllium, tungsten, aluminum, titanium, manganese and iron in the same range of 1 to 8 MAC have been also found in the icing fields in the vicinity of Kular.

Ice-wedges ice is generally characterized as fresh one, mainly of hydrocarbonate sodium-potassium-calcium type with an average salinity of 67 mg/L. The calcium content in the ice wedges varies from 4 to 13.8 mg/L (Fig. 7), averaging 10.38 mg/L, and the magnesium content varies in the range of 2.4 to 6.1 mg/L (Table 2). In the ice wedges of the Lena River valley, with an equally low salinity (0.05 to 0.08 g/L), the content of calcium varies from 2.8 to 15.6 mg/L, and that of magnesium ranges from 1.3 to 9.5 mg/L [*Anisimova, 1981*]. Consequently, the content of calcium and magnesium ions is determined to a greater extent (as in the case of the ice wedges of the Lena River valley [*Anisimova, 1981*]) by the chemical composition of precipitation.

The content of water-soluble salts in the yedoma deposits, represented by non-saline soils, does not exceed 0.142 %. The entire section is characterized by a predominance of calcium ion and hydrocarbonate ion. The average contents of bicarbonate ion, chlorine ion and sulfate ion are 0.026, 0.070 and 0.0119 %, correspondingly (Fig. 8), and those of calcium ion, magnesium ion, sodium and potassium ions are 0.0072, 0.0027 and 0.0061 %, respectively. According to the value of solids content, the strata can be divided into two portions: the lower portion, located in the depth interval of 13 to 16 m, where solid content is 0.092 %, and the upper one, disposed in the depth interval of 4.5 to 13 m, where solid content is 0.127 %.

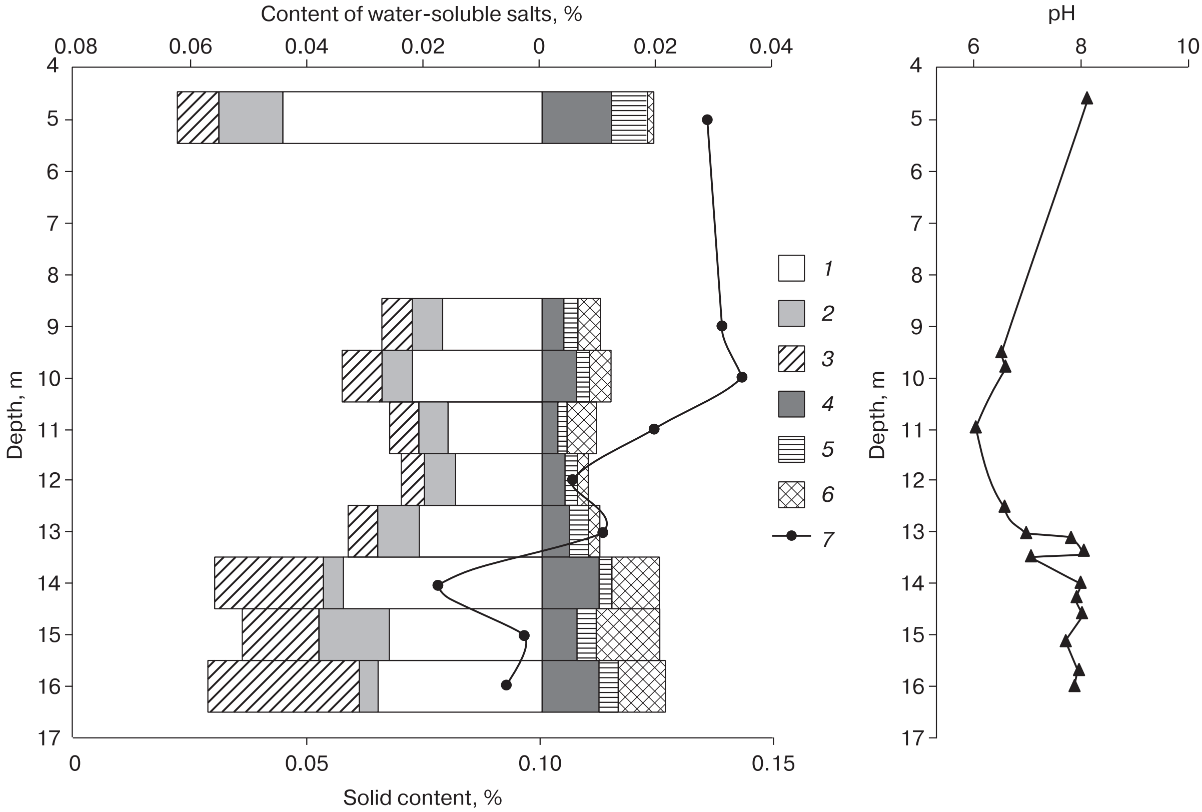

Fig. 8. Composition of water-soluble salts in syngenetic ice wedges.

1 – HCO_3^-; *2* – Cl^-; *3* – SO_4^{2-}; *4* – Mg^{2+}; *5* – Ca^{2+}; *6* – $Na^+ + K^+$; *7* – solid content.

RECONSTRUCTIONS OF THE MEAN JANUARY AND MEAN WINTER AIR TEMPERATURES BY ISOTOPE DATA

Reconstructions of the mean January (t_{mJ}) and mean winter (t_{mw}) air temperatures have been performed on the basis of a comparison of the isotopic composition of the present-day veinlets ($\delta^{18}O_{vs}$) and the present-day winter air temperatures for the period of formation of veinlets, i.e. for the last 60 to 100 years [*Vasil'chuk, 1991, 1992*]. As a result of that comparison, the following two equations have been obtained:

$$t_{mJ} = 1.5 \cdot \delta^{18}O_{vs}\ (\pm 3\ ^\circ C) \text{ and } t_{mw} = \delta^{18}O_{vs}\ (\pm 2\ ^\circ C).$$

Using these equations, t_{mJ} and t_{mw} have been calculated for different time intervals of the Kular yedoma, and a number of neighboring yedomas of northwestern Yakutia (Table 5).

If we compare the isotopic data on two periods of Late Pleistocene (47,000 to 42,000 cal yr BP and 37,000 to 32,000 cal yr BP, characterized by the $\delta^{18}O$ values of –31 ‰ and –32.5 ‰, respectively) with the data on such sections of the yedoma deposits of northwestern Yakutia as the Mamontovy Khayata and Oyogos Yar (with the values of $\delta^{18}O$ which are –30.2 ‰ to –31 ‰ and –29.5 ‰ to –31.4 ‰ for the above-mentioned periods, respectively), we can see that the older ice, which formed 47,000 to 42,000 cal yr BP, is noticeably (by 1 ‰ to 2 ‰) heavier than the ice wedges being formed during the period of 37,000 to 32,000 cal yr BP (Table 5). The foregoing indicates that the mean January air temperature between 47,000 to 42,000 cal yr BP was higher than between 37,000 to 32,000 cal yr BP by 1.0 to 3.8 °C. The time intervals of 47,000 to 42,000 cal yr BP and 37,000 to 32,000 cal yr BP are characterized by average January air temperature (t_{mJ}) of –46 and –49 °C in Kular, –45 and –46 °C in the north of Bykovsky Peninsula (Mamontovy Khayata), –44 and –47.8 °C in the Oyogos Yar region, respectively.

The yedoma deposits accumulated in the lower reaches of Yana River [*Pitulko et al., 2004; Pavlova et al., 2015*] are approximately age-appropriate for the Kular yedoma. The deposits are represented by syncryogenic sediments of the riverbed and floodplain alluvial facies with a developed network of ice wedges of two generations with total thickness of 14 m to 16 m. An ice wedge, the age of which is attributed to

Table 5. **The $\delta^{18}O$ values in Late Pleistocene and present-days syngenetic ice wedges of Kular and surrounding yedpomas of Northern Yakutia**

The name of reference section	Paleoreconstruction					Current values					Source of data
	$\delta^{18}O_w$	Σt_w	t_{mw}	t_{mJ}	$t_{pal.s}$	$\delta^{18}O_w$	Σt_w	t_{mw}	t_{mJ}	$t_{cur.s}$	
47–42 cal kyr BP											
Kular	–31.0	–7750	–31.0	–46.0	–20	–25.0	–5920	–25.0	–37.0	–14	[*Vasil'chuk, 1992, with additions*]
Mamontovy Khayata	–30.2	–7550	–30.0	–45.0	–19	–23.0	–5382	–21.5	–31.0	–14	[*Meyer et al., 2002*]
Kurungnakh Island	–31.8	–7900	–32.0	–48.0	–21	–24.6	–5540	–22.0	–34.3	–15	[*Wetterich et al., 2008*]
Oyogos Yar	–29.5	–7375	–29.5	–44.0	–19	–24.4	–5230	–21.0	–30.4	–14	[*Opel et al., 2017*]
37–32 cal kyr BP											
Kular	–32.5	–8000	–32.5	–49.0	–22	–25.0	–5920	–25.0	–37.0	–14	[*Vasil'chuk, 1992, with additions*]
Mamontovy Khayata	–31.0	–7750	–31.0	–46.0	–20	–23.0	–5382	–21.5	–31.0	–14	[*Meyer et al., 2002*]
Lower reaches of Yana River	–31.4	–7800	–31.4	–47.8	–19	–21.0	–6006	–24.0	–38.0	–14	[*Pavlova et al., 2015*]
Oyogos Yar	–31.4	–7800	–31.4	–47.8	–19	–24.4	–5230	–21.0	–30.4	–13	[*Opel et al., 2017*]

Note: $\delta^{18}O_w$ – isotopic composition of ice wedges, %; Σt_w – sum of negative temperatures, °C; t_{mw} – mean temperature of the winter season, °C; t_J – mean January temperature, °C; $t_{pal.s}$ – mean annual soil surface paleotemperature, °C; $t_{cur.s}$ – current mean annual soil surface temperature, °C.

the 3rd marine isotope stage (MIS 3), has been sampled in a transverse horizontal profile at the level of the cultural layer, whose age is dated from 28,500 to 27,000 yr BP. The values of $\delta^{18}O$ in the ice wedges are close to those obtained by the authors in the ice wedges of the Kular yedoma. The value of $\delta^{18}O$ in the ice wedges of the Yana archeological site varies in the range of –32.7 ‰ to –29.4 ‰ averaging –31.4 ‰. The value of δ^2H varies from –260.8 ‰ to –230.6 ‰ with an average value of –250.9 ‰. The value of deuterium excess (d_{exc}) is within the range of –7.6 ‰ to –5.3 ‰ [*Pavlova et al., 2015*]. The ratio of $\delta^{18}O$ and δ^2H is approximated by a straight line according to the equation $\delta^2H = 7.3 \cdot \delta^{18}O - 20$.

Wetterich with co-authors [*Wetterich et al., 2008*] have obtained close values of the isotopic composition of ice wedges on the Kurungnakh Island located in the delta of Lena River. The syngenetic ice wedges, assigned in accordance with the obtained dating to a time interval of 50,000 to 31,000 yr BP ago, are characterized by the following average values: $\delta^{18}O$ = –32 ‰, δ^2H = –248 ‰ and d_{exc} = 6 ‰. As for the growing season, the most favorable conditions for it according to pollen data have been temporarily related to 42,000 yr BP and between 40,000 and 32,000 yr BP [*Wetterich et al., 2014*].

The adduced data confirm the intensive formation of the yedoma complex over the entire Late Pleistocene cryochron. The simultaneous accumulation of ice wedges and organic material in the yedoma strata indicates the possibility of the synchronous increase in the severity of winters and some improvement in conditions of vegetation in certain periods of the Late Pleistocene cryochron.

CONCLUSIONS

The values of $\delta^{18}O$ vary from –32.6 ‰ to –30.0 ‰ in ice wedges of the Kular Ridge slope yedoma. The values of $\delta^{18}O$ vary within the range of –35.6 ‰ to –22.1 ‰ in cryostructure-segregated ices of the yedoma strata, and those in segregated ice lenses range from –24.4 ‰ to –21.5 ‰.

The values of $\delta^{18}O_{vs}$ (in the area of Kular Ridge) for two periods of Late Pleistocene, from 47,000 to 42,000 cal yr BP and from 37,000 to 32,000 cal yr BP, are –31.0 ‰ and –32.5 ‰, respectively.

The mean January air temperature in the region of Kular Ridge 47,000 to 42,000 cal yr BP was higher by 1 to 3.8 °C than 37,000 to 32,000 cal yr BP amounting to –46 and –49 °C, respectively, for the indicated periods.

The lowest mean January air temperature (about 10 °C lower than the current one) in the Kular Range area refers to the time period of 37,000 to 32,000 yr BP.

The chemical composition of ground ice reflects the geochemical features of the region and is characterized by an increased content of manganese, zinc, copper and cobalt, which is associated with the Emis ore occurence and Late Jurassic dolerite intrusions, from where an intensive outflow of dispersed elements occurs.

The relatively high content of calcium ion probably reflects the increased dustiness of Earth's atmosphere during the formation of ice wedges which occurred between 40,000 and 30,000 yr BP.

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