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DISCUSSION

AIR JANUARY PALEOTEMPERATURE RECONSTRUCTION 48–15 CALIBRATED KA BP USING OXYGEN ISOTOPE RATIOS FROM ZELYONY MYS YEDOMA

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The features of the Late Pleistocene ice wedges in the outcrop of the Zelyony Mys Yedoma located on the right bank of the Lower Kolyma River are considered. The oxygen isotope composition of ice wedges, radiocarbon age, and hydrochemical characteristics have been studied. Stable oxygen isotopes provide the main basis for reconstructing the mean January air temperature history of a site from ice wedges. Detailed quantitative assessments of paleogeocryological and paleoclimatic changes of the region in the Late Pleistocene 48–15 cal ka BP were performed.

Key words: *ice wedge, Late Pleistocene, permafrost, yedoma, oxygen isotopes, radiocarbon age, pollen and spores, hydrochemistry, Zelyony Mys exposure, Lower Kolyma River, north-eastern Yakutia.*

INTRODUCTION

Syngenetic ice wedges were actively accumulated in maritime lowlands during the Late Pleistocene. The yedoma section of Zelyony Mys is located in the boundary between tundra and forest-tundra, i.e. in the area sensitive to climatic and landscape changes. Main purposes of this article are: 1) Study of syngenetic Late Pleistocene ice wedges and host yedoma deposits located on the right bank of the Kolyma River near Zelyony Mys settlement; 2) Study of the oxygen isotope composition in ice wedges; 3) Radiocarbon and hydrochemical analysis of ice wedges and host sediments, generalization of all radiocarbon data available for the section; 4) Air paleotemperature reconstruction for the Late Pleistocene 48–15 thousand calibrated years BP in this region.

ENVIRONMENTAL CONDITIONS OF THE STUDY AREA

Zelyony Mys Yedoma section is located 3 km away from Chersky on the right bank of the Kolyma River, 130 km from its mouth, in the continental region of Northeastern Russian Arctic. The mean air temperature in January is –32.3 °C, that in July is +15.5 °C, in winter is –31 °C, in summer is +15 °C; the mean annual temperature is –10.8 °C. The average annual precipitation is 197 mm; stable snow cover forms from September to mid-May [*Davydov et al., 2008*]. According to Chersky weather station data, in 1940–2020 the lowest January air temperature was observed in 1964 (–41.7 °C), the highest one – in 1969 (–24.4 °C). The lowest mean annual air temperature was observed in 1940 (–14.5 °C), and the highest one in 2003 (–7.4 °C); the maximum July air temperature was observed in 1960 (17.7 °C), and the minimum one – in 1948 (8.6 °C). The maximum annual amount of precipitation was observed in 1968 (439 mm), the minimum one – in 1978 (102 mm) (www.pogoda.klimat.ru). Permafrost thickness reaches 500–600 m; the mean annual ground temperature at the depth of zero annual amplitude varies mostly within the range of –9 to –11 °C [*Fyodorov-Davydov et al., 2004*]. Permafrost distribution is continuous except of taliks under large rivers. During 1970–2009 observation period, the mean annual ground temperature at the depth of zero annual amplitude changed from –12 to –9 °C in the boreholes in Chersky area [*Romanovsky et al., 2010*].

The yedoma deposits exposed in Zelyony Mys outcrop on the right bank of the Kolyma River near the port of Zelyony Mys (Fig. 1), are arguably among the most representative yedoma outcrops. The outcrop vertical wall reached 36 m in its most complete form. At present, the outcrop is covered by landslides.

In 1983, Yu.A. Murzin and Ya.I. Torgovkin [*1984*], simultaneously with the authors, described the outcrop of that Ice Complex and noted that the outcrop had been formed at the spot of a small lake which was drained in 1981. The drained lake basin was about 200 m wide and 400 m long. A deep ravine with several outcrops on its sides has formed after lake drainage. The study of the Zelyony Mys yedoma has a short history, since the outcrop itself did not ex-

Article by Yu.K. Vasil'chuk and A.C. Vasil'chuk is published contrary to the decision of the editorial group, as it contains a significant amount of self-plagiarism and has no scientific novelty. The authors of the article contacted the editor-in-chief of the journal, Academician V.P. Melnikov, who made the decision to publish this article in the "Discussion" section, simultaneously conducting its independent review. In the same issue, an open review by A.A. Galanin for this article has been published.

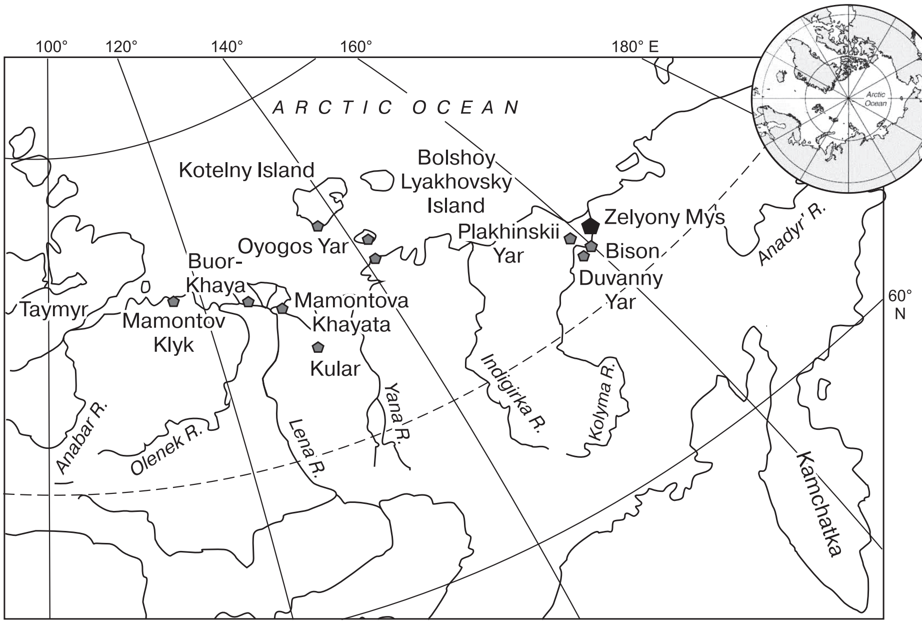

Fig. 1. Location of the Zelyony Mys section and the yedoma sections synchronous to it in the northeast of Yakutia.

ist long [*Vasil'chuk et al., 1985; Vasi'lchuk, 1992; Zanina, 2005; Gubin, Lupachev, 2008; Mikhalev et al., 2012; Gubin, Zanina, 2013*].

Vegetation of the area described, is represented by pre-tundra larch forests. According to Yu.P. Kozhevnikov, the forest-forming specie here is *Larix cajanderi* Mayr. The shrubs understorey is composed of *Betula exilis* Sukacz., *Salix glauca* L., *Rosa acicularis* Lindl., as well as *Vaccinium uliginosum* L., *Arctous erytrocarpa* Small., *A. alpina* (L.) Niedenzu [*Kozhevnikov, 1981*]. According to O.G. Zanina and D.A. Lopatina [*2017*], the vegetation at the drained lake bottom near the Zelyony Mys is characterized by pioneer communities with predominance of *Chamaenerion angustifolium* (L.) Scop., *Tanacetum vulgare* L., *Erigeron acris* L., *Poa pratensis* L., *Hordeum jubatum* (L.) Nevski, *Salix glauca* L.

YEDOMA STRUCTURE AND COMPOSITION

Zelyony Mys yedoma had been studied in 1983 in a ravine 2 km to the north of the Zelyony Mys on the right bank of the Kolyma River (Fig. 1). Ice-rich yedoma has been exposed in the middle part of the ravine (68.7875° N, 161.3806° E) in the outcrop high wall (up to 35–36 m high). The outcrop was subject to annual studies, from 1983 to 1988. At the beginning of 2000s it had been completely covered by landslide deposits.

Stratigraphy and cryolithological features of the yedoma deposits. The 36-meter-high outcrop consists of two parts. The upper gray portion, about 12–13 m thick, is almost free of organic material. The lower brownish gray one, 24 m thick, consists of three peat layers with plant detritus and three layers without visual organic remains. It is these organic-reach layers (Fig. 2, *a*) which studying lead to formulation of the hypothesis of the cyclical development of the yedoma [*Vasil'chuk, 1992, 1999*].

The upper horizon of the outcrop, less than 0.5 m thick, is represented by banded lacustrine loams. The deposits of an Ice Complex 11–12 m thick represented by the dark gray sandy loams with thin or medium ice lenses, rarely with ice belts lie below. The total water content is 75–100 %. Within the interval of 12.5–16.3 m, the upper layer of peaty loam has been exposed. In the middle part, almost pure dark brown peat with reticulate cryostructure is exposed, *in situ* roots have been sampled for ^{14}C dating. At 16.3–18.6 m depth brownish-gray sandy loam with layered cryostructure (thin to medium layers) is exposed. At a depth of 18.6–20.1 m, brown peat with roots and sandy loam with reticulate cryostructure is found. At 20.1–24.2 m, the brownish-gray sandy loam is exposed; cryostructure is reticulate with thin ice layers. At a depth of 24.2–25.4 m lays brown sandy peat with roots, cryostructure is cross-layered and reticulate. Below, up to a depth of 36 m, dark gray sandy loam with horizontal-layered, cross-layered cryostructure with thin ice lenses. In the distribution of ice content and cryostructures through the section, as in the lithological structure, a trinomial mesocyclicity is noted: an increase in ice content, a decrease in the thickness of ice lenses and the distance between them from less peaty horizons up to the base of more peaty ones.

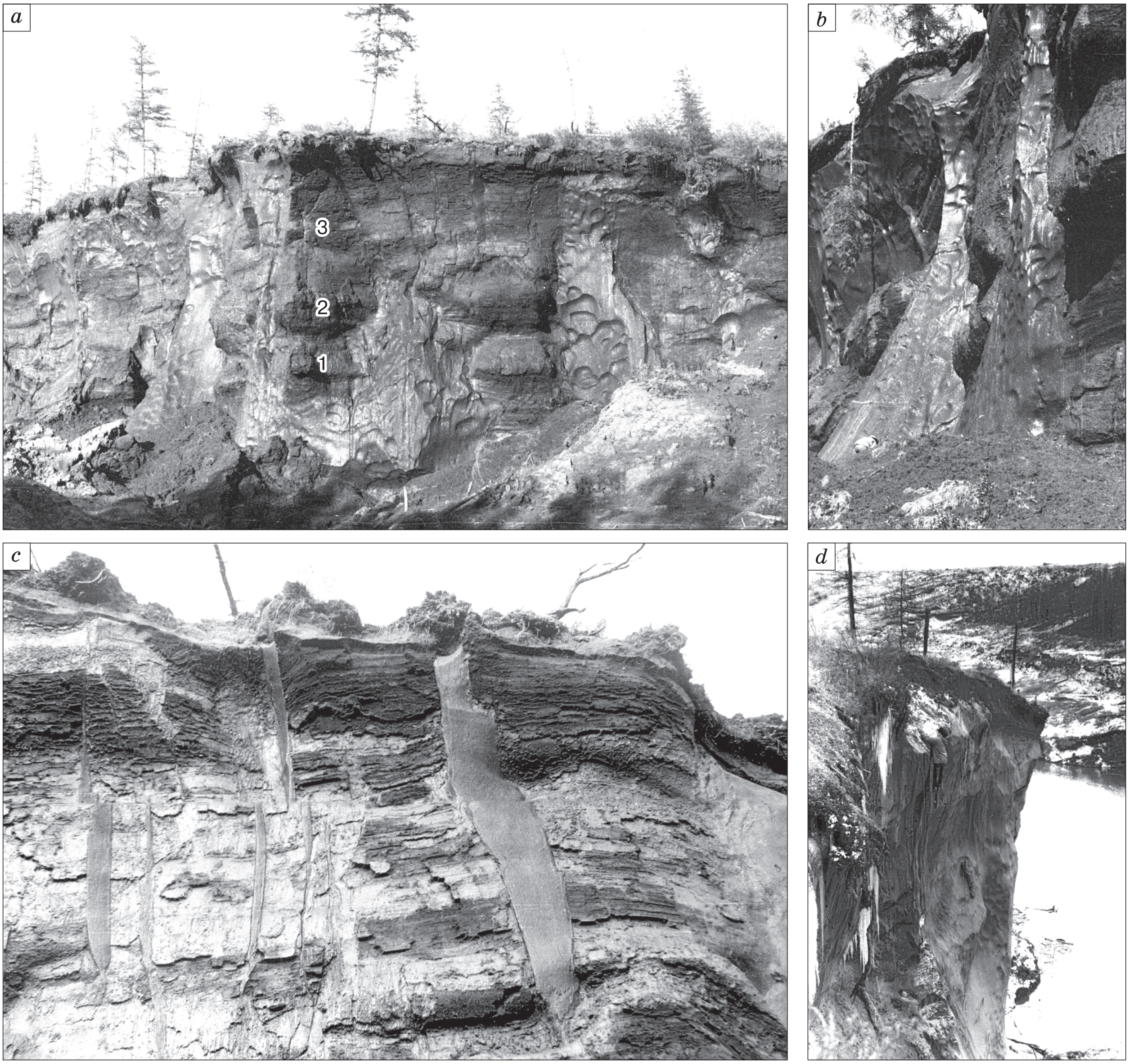

Fig. 2. Syngenetic Late Pleistocene ice wedges of Zelyony Mys on the right bank in the lower reaches of the Kolyma River.

a – general view, *b–d* – fragments. 1–3 – organic layers. Photo by Yu.K. Vasil'chuk.

Such a cryogenic structure is associated with the process of accumulation of the strata in the subaquatic environment and its freezing during the draining stage, i.e., during the formation of the peat horizon [*Vasil'chuk, 1999*].

Ice wedges dissect the entire yedoma deposits. In the lower part, the width of the ice wedges reaches 2.0–2.5 m in the frontal section, while in the upper part they are much narrower. Their width in the frontal section does not exceed 0.5–1.0 m, the distance between them is 2–5 m (Fig. 2). At the level of peat horizons "transit" ice wedges have pronounced shoulders.

The ice of wedges is gray, vertically banded; the banding is caused by elongated inclusions of sandy loam.

METHODS OF FIELD AND LABORATORY STUDIES

Organic matter for radiocarbon dating was sampled from the frozen wall of the outcrop. The roots for the dating were sampled immediately after the sampling of the frozen soil monolith. The water obtained during the melting of ice wedges was used for washing them. Samples of ice wedges were taken from the axial part of ice wedges with a volume of 0.5–1.0 dm^3, according to the method developed by Yu.K. Vasil-chuk [*Vasil'chuk, 1991, 1992*].

Radiocarbon age of ice wedges and host sediments. Radiocarbon dating of organic macrofossils (mainly grass roots and shrub twigs) out of the yedoma deposits has been carried out at the Geological Institute of the Russian Academy of Sciences, with the participation of L.D. Sulerzhitsky, the sample preparation has been performed by the authors within a month after the sampling.

The AMS dating of microinclusions of the organic matter directly extracted out of ice has been carried out at the accelerator mass spectrometer at laboratory of the Seoul National University with the assistance of professor J.-Ch. Kim. The samples for dating were stored in a laboratory refrigerator at a temperature of −10 °C. To calibrate ^{14}C dating, we used the OxCal calibration program [*Ramsey, 2009*], version 4.3, based on the IntCal13 calibration data set [*Reimer et al., 2013*].

Hydrogeochemistry of ice wedges and host sediments. Determination of the content of water-soluble salts in ice wedges has been performed by titration in the laboratory of PNIIIS within a month after sampling.

Isotopic analysis of ice wedges has been performed in the laboratory of the Water Problems Institute of the Russian Academy of Sciences (senior researcher A.D. Esikov) on a Varian Mat 250 mass spectrometer, sample preparation was carried out by the authors within a month after sampling.

RESULTS OF LABORATORY STUDIES

Radiocarbon dating of host sediments and directly of ice wedges. Four dates, which were the ba-

Table 1. **Radiocarbon dating of organic material of Late Pleistocene yedoma sediments in Zelyony Mys section, right bank in the lower reaches of the Kolyma River**

Sample ID / source	Depth, m	^{14}C age, BP	Lab. ID	Material	Calibrated ^{14}C ages, 99.7 % (cal BP)	Median calendar age (cal BP)
[*Gubin, Lupachev 2008*]	3.2	13 140 ± 140	EP-941615	Soil	16 350–15 145	15 761
308-YuV/46	12.0	28 600 ± 1500	GIN-3574	Roots	40 105–28 927	32 936
315-YuV/5	12.0	33 800 ± 900	GIN-3850	Roots	41 558–35 410	38 177
[*Zanina, 2005*]	12.0	30 500 ± 1400	IEMAE-1179	Ground squirrel burrow, seeds, P-917	41 070–31 105	34 833
[*Zanina, 2005*]	12.0	32 800 ± 1400	IEMAE-1178	Ground squirrel burrow, seeds, P-923	42 616–33 675	37 278
315-YuV/4b	12.0	43 700 ± 800	GIN-3849	Mammoth tibia	49 905–45 100**	47 043
315-YuV/4d	12.0	>50 000	GIN-3848	Mammoth jaw	–	–
308-YuV/27	16.4	27 900 ± 1200	GIN-3575	Roots	37 024–28 776	32 220
308-YuV/27	16.4	>39 000	GIN-3575	Roots	–	–
308-YuV/28	23.7	37 600 ± 800	GIN-3576	Roots	44 202–39 986	41 977
308-YuV/28	23.7	>40 000	GIN-3576	Roots	–	–
352-YuV/1	20.0	42 800 ± 700	GIN-5710	Bison horn	48 824–44 381	44 381
[*Gubin, Zanina, 2013*]	The lower part of the yedoma	43 600 ± 1000*	GIN-8014	Large branches	49 857–44 998**	46 943
[*Gubin, Zanina, 2013*]	The lower part of the yedoma	43 400 ± 1000*	GIN-8013	Large branches	49 752–44 796**	46 743
[*Gubin, Zanina, 2013*]	The lower part of the yedoma	> 48 000*	GIN-8011	Large branches	–	–
[*Gubin, Zanina, 2013*]	The lower part of the yedoma	> 48 000*	GIN-8012	Large branches	–	–
[*Lozhkin, 1977*]	The lower part of the yedoma (8 m above river level)	35 200 ± 800	MAG-295	Roots	42 250–37 103	39 829
		28 240 ± 330	MAG-294	Roots	33 529–31 187	32 162
		27 200 ± 200	MAG-298	Roots	31 574–30 763	31 155
[*Veksler, Prede, 1985*]	The lower part of the yedoma	33 900 ± 500	RI-111	Poorly decomposed peat	40 153–36 366	38 312
[*Veksler, Prede, 1985*]	The lower part of the yedoma	38 700 ± 700	RI-115	Poorly decomposed peat	44 741–41 383	42 736

Note: ^{14}C dates were calibrated using OxCal 4.3 [*Ramsey, 2009*] based on the Intcal13 calibration data [*Reimer et al., 2013*].

* The sampling has been carried out in the lower part of the ravine at residual yedoma outcrop. Upper part has been demolished by slope processes [*Gubin, Zanina, 2013*].

** Based on the results of calibration in the OxCal 4.3, the dating may be beyond the limit of ^{14}C method.

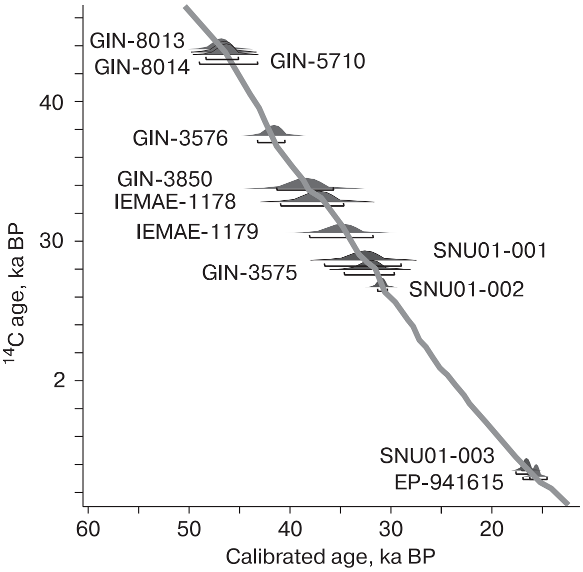

Fig. 3. Calibrated radiocarbon ages of Zelyony Mys yedoma sediments and ice wedges.

sis for the initial referencing of the wedges in time, have been obtained based on the roots, i.e. on organic residues occurring *in situ*. In the upper peaty layer, those dates are 32.2 and 32.9 cal ka BP, in the middle layer it is 38.1 cal ka BP, and in the lower one the date is 41.9 cal ka BP (Table 1, Fig. 3).

Due to the low content of organic matter in the upper part of the yedoma, the time of the end of its accumulation was first determined to be approximately 13 ka BP [*Vasil'chuk, 1992, p. 384*]. Thus, the time interval for the formation of wedges was approximately estimated from 45 to 13 ka BP, which corresponds to the time interval from 48 to 15 cal ka BP. Later the upper time limit of the yedoma formation has been confirmed by the ^{14}C dating of a buried soil horizon near the day surface (which was 15.7 cal ka BP). Later on, ground squirrel burrows (34.8 and 37.2 cal ka BP, Table 1) [*Zanina, 2005*] and large branches from the base of the yedoma (46.9 and 46.7 cal ka BP) [*Gubin, Zanina, 2013*] were dated in the same interval of the middle layer. Those dates (from 48 to 15 cal ka BP) have fully confirmed the reliability of the Zelyony Mys yedoma chronology proposed in [*Vasil'chuk et al., 1985*].

The uppermost date obtained by the authors out of a sample taken directly from the ice, has confirmed the time of the end of the wedge formation – 15.7 cal ka BP (Fig. 3, Table 2).

Out of the axial part of the ice wedge, the dates of 16.4, 30.8 and 32.7 cal ka BP have been obtained at the depths of 3, 6.5 and 8 m correspondingly (Table 2). On the whole, those dates fit well into the gene-

Table 2. **The AMS radiocarbon dating of organic microinclusions in syngenetic Late Pleistocene ice wedges in Zelyony Mys section, right bank in the lower reaches of the Kolyma River**

Sample ID	Depth, m	^{14}C age, BP	Lab. ID	δ^{13}C of organics, ‰	Calibrated ^{14}C ages, 99.7 % (cal BP)	Median calendar age (cal BP)
315-YuV/16	3.0	13 600 ± 200	SNU01-003	–32.5	17 386–15 591	16 422
315-YuV/11	6.5	26 700 ± 300	SNU01-002	–25.4	31 457–29 868	30 879
315-YuV/8	8.0	28 700 ± 500	SNU01-001	–30.2	34 261–31 208	32 728

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

Sample ID	Depth, m	Solids content, mg/L	Major ions, mg/L						pH
			HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	$Na^+ + K^+$	
308-YuV/52	3.0	78.0	72.0	5.7	7.4	16.0	6.1	4.4	7.15
315-YuV/11	6.5	94.0	68.3	8.5	13.2	16.8	6.8	5.3	7.00
315-YuV/9	7.5	84.0	68.3	6.4	9.9	16.0	6.3	4.4	7.07
308-YuV/55	8.0	74.0	56.1	5.7	10.7	11.6	6.1	5.1	7.13
308-YuV/56	8.5	60.0	41.5	5.7	8.2	8.0	4.4	5.8	6.97
315-YuV/6	9.0	86.0	74.4	6.4	9.1	16.8	7.5	3.0	7.13
308-YuV/40	9.5	120.0	85.4	6.0	**21.4**	12.2	7.8	18.4	7.30
308-YuV/43	11.6	104.0	85.4	5.3	18.1	13.4	**8.1**	13.6	7.65
315-YuV/21	13.1	**134.0**	**102.5**	6.3	4.1	**25.3**	7.8	1.2	6.83
315-YuV/22f	13.1	82.0	58.6	**9.8**	11.5	9.2	2.7	18.4	7.05
315-YuV/23f	13.1	88.0	79.3	7.7	6.6	12.8	5.1	13.8	7.10
308-YuV/48	15.5	100.0	70.8	6.0	**21.4**	10.0	7.0	9.9	**7.70**
308-YuV/5	15.6	100.0	73.2	7.8	18.1	7.6	5.2	**22.8**	7.50
308-YuV/8	17.0	104.0	75.6	6.0	19.7	15.4	2.8	18.9	**7.70**

Note: the maximum values are shown in bold.

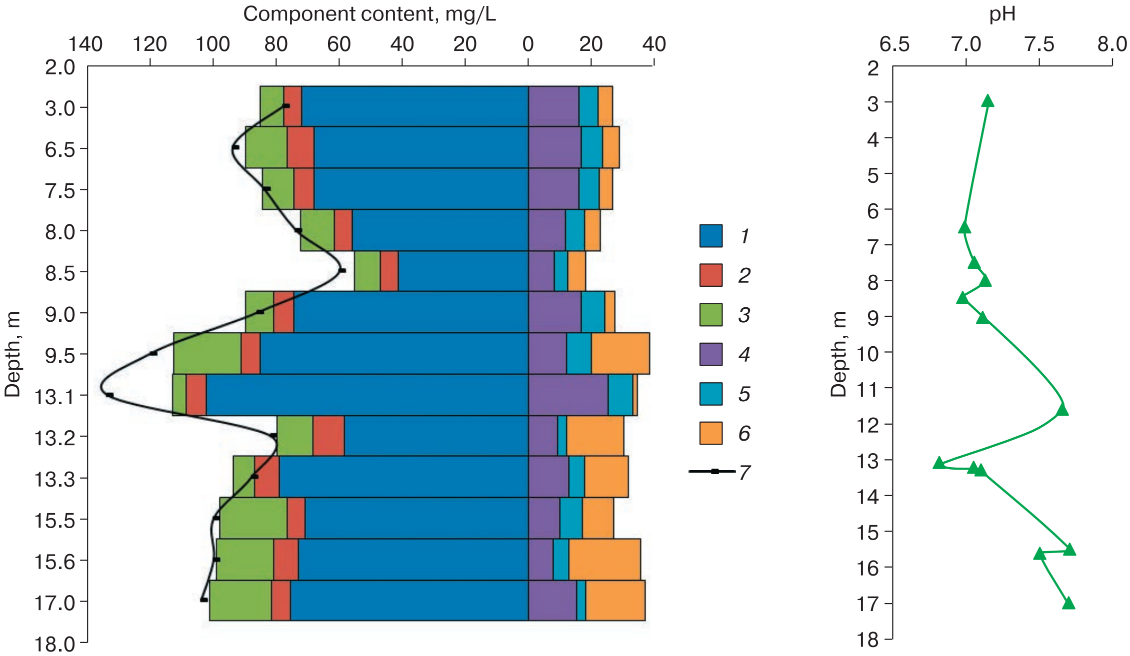

Fig. 4. Composition of water-soluble salts in syngenetic ice wedges in the Zelyony Mys yedoma:
1 – HCO_3^-; *2* – Cl^-; *3* – SO_4^{2-}; *4* – Mg^{2+}; *5* – Ca^{2+}; *6* – $Na^+ + K^+$; *7* – solids content.

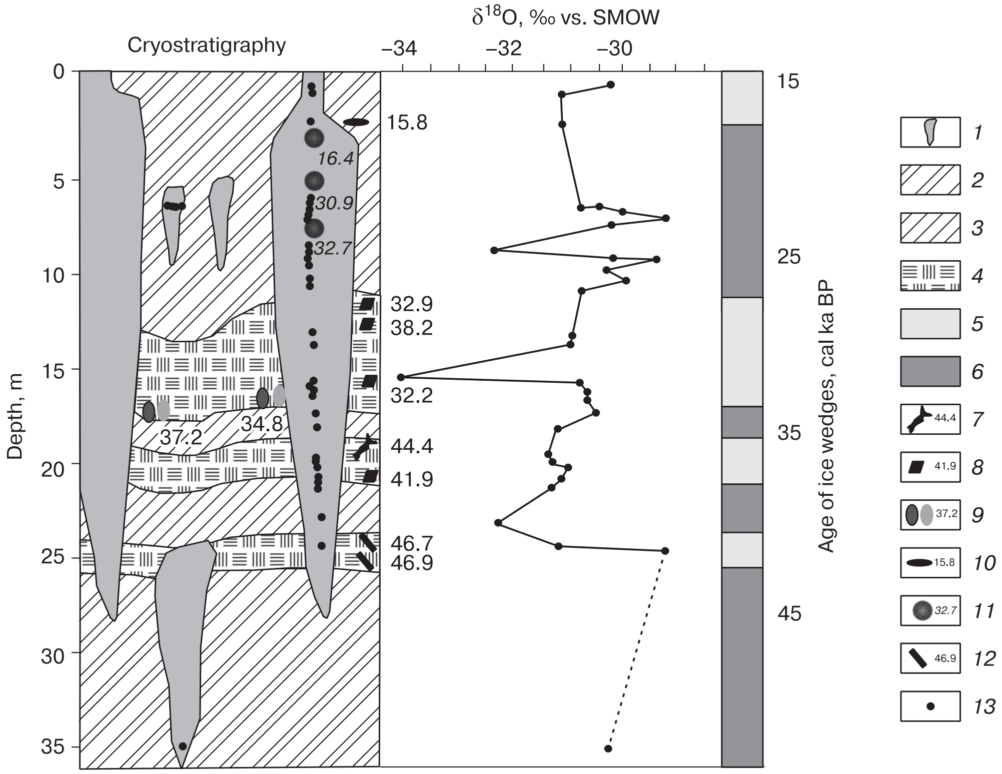

Fig. 5. δ^{18}O values in ice wedges of Zelyony Mys yedoma.

1 – ice-wedge ice; *2* – frozen gray sandy loam with layered and reticulate cryostructure (thin to medium layers); *3* – frozen brownish-gray sandy loam with layered cryostructure thin to medium layers); *4* – frozen peat of cross-layered, reticulate cryostructure; *5* – sediments of the subaerial stage of yedoma accumulation; *6* – sediments of the subaqueous stage of yedoma accumulation; calibrated ^{14}C age of: *7* – bones, *8* – peat, *9* – seeds from burrows, *10* – soils, *11* – ice wedge, *12* – branches; *13* – sampling sites of ice wedges for isotope analysis. (Sampling sites for ^{14}C dates on seeds from buried burrows, soils and large branches are shown conditionally, since the sampling was carried out in different seasons or not from the main wall of the outcrop.)

ral time range of the formation of the upper part of that ice-wedge complex. Based on direct dating, it can be assumed that the rate of accumulation of ice wedges varied from 0.2 to 1 m per thousand years.

Older dates obtained from a mammoth's bones indicate redeposition of the latter. There is reason to believe that the 47 cal ka BP date of the mammoth bone refers to the initial stage of yedoma accumulation, especially since the horn of a bison dated of about 46 cal ka BP (42 800 ± 700 – GIN-5710) found at the footslope showed similar date. Since those bones lie apart from the skeleton, they are certainly redeposited.

Hydrochemical features of wedge ice. The mineralization of ice wedges is not high (60–134 mg/L); bicarbonates (up to 102 mg/L) dominate in the composition of the salts. The mesocyclicity is clearly visible – in the lower parts of the cycles the ice is more mineralized (100 mg/L and more), further upward mineralization decreases (to 60–80 mg/L), then it increases again (to 94 mg/L), and above it decreases to 78 mg/L (Table 3, Fig. 4).

The authors believe that most important is that the low mineralization of ice is quite consistent with the predominant formation of ice wedges out of melted snow. The maximum mineralization at a depth of 13.1 m is due to the maximum content of carbonate ion (102.5 mg/L) and calcium ion (25.3 mg/L). In the lower part of the wedges, the maximum content of $Na^+ + K^+$ cations is noted (22.8 mg/L). We also note three rhythms that stand out in the distribution of sulfate ion, potassium and sodium ions content. The relatively high content of sulfate ion comparing to chloride ion indicates a high degree of the climate continentality during the period of ice wedges formation.

Oxygen isotope composition of ice wedges. On the oxygen isotope diagrams for thick wedges (Fig. 5) the range of the $\delta^{18}O$ values (from –34.1 to –29.4 ‰) is comparatively large. The data on the buried wedges located at a depth of 7 m lie within the range of –30.5 to –29.1 ‰ (Table 4, point 341-YuV).

In isotopic terms, ground ice in the host sediments is slightly heavier than wedge ice; the $\delta^{18}O$ values in it vary from –30.6 to –27.0 ‰ [*Vasil'chuk, 1992*]. That ratio of isotopic characteristics does not contradict the hypothesis of the lacustrine origin of yedoma on the slope of the Kolyma River valley.

In veinlets at the Kolyma River floodplain near Zelyony Mys the $\delta^{18}O$ values vary from –26.1 to –23.0 ‰, while in segregated and pore ice of the floodplain alluvium the $\delta^{18}O$ values range from –23.0 to –19.1 ‰; i.e., the Pleistocene wedges are almost by 8 ‰ lighter than modern ones, and the segregated and pore ice, as a rule, is by 4–5 ‰ lighter them.

Table 4. **$\delta^{18}O$ values in the Late Pleistocene ice wedges (IW), segregated and pore ice (I) in the Zelyony Mys section, right bank in the lower reaches of the Kolyma River and in veinlets (V) on the floodplain**

Sample ID	Depth, m	$\delta^{18}O$, ‰	Ice type	Sample ID	Depth, m	$\delta^{18}O$, ‰	Ice type
Syngenetic Late Pleistocene ice wedges in Zelyony Mys yedoma							
308-YuV/49	0.5	–30.3	IW	308-YuV/48	15.5	–34.1	IW
308-YuV/50	1.0	–31.3	IW	308-YuV/5	15.6	–30.9	IW
308-YuV/51	2.0	–31.3	IW	308-YuV/6	15.7	–30.7	IW
308-YuV/54	7.0	–30.9	IW	308-YuV/7	16.3	–30.7	IW
341-YuV/51	7.0	–30.5	IW	308-YuV/8	17.0	–30.6	IW
341-YuV/52	7.0	–30.0	IW	308-YuV/9	17.6	–31.2	IW
341-YuV/53	7.0	–29.1	IW	308-YuV/10	18.3	–31.5	IW
341-YuV/54	7.0	–30.2	IW	308-YuV/37	18.7	–31.4	IW
308-YuV/55	8.0	–32.8	IW	308-YuV/12	19.7	–31.1	IW
308-YuV/56	8.5	–30.3	IW	308-YuV/13	20.6	–31.4	IW
308-YuV/40	9.5	–29.4	IW	308-YuV/14	21.5	–31.6	IW
308-YuV/41	9.8	–30.4	IW	308-YuV/16	23.5	–32.4	IW
308-YuV/42	10.2	–29.9	IW	308-YuV/17	24.3	–31.3	IW
308-YuV/43	11.6	–30.7	IW	308-YuV/18	24.9	–29.2	IW
308-YuV/44	13.4	–31.0	IW	341-YuV/40	35.0	–30.2	IW
308-YuV/45	14.0	–31.1	IW				
Syngenetic segregated and pore ice in Zelyony Mys yedoma							
341-YuV/8	10.0	–30.6	I	341-YuV/1	10.9	–27.0	I
341-YuV/4	10.7	–27.6	I	341-YuV/36	33.2	–29.6	I
Veinlet penetrating into Holocene ice wedges at Kolyma floodplain near Zelyony Mys							
15-TYa/2	0.7	–25.6	V	15-TYa/3	0.8	–25.4	V
Veinlets penetrating into Holocene ice wedges at the floodplain on Ambolikha channel near Chersky							
9-TYa/1	0.4	–23.0	V	7-TYa/1a	0.5	–24.0	V
7-TYa/1	0.5	–24.1	V	8-TYa/1	0.5	–26.1	V

DISCUSSION

Radiocarbon age of the yedoma sediments and ice wedges. Based on a set of ^{14}C dates, the period of the Zelyony Mys yedoma formation lasted about 33 ka, i.e., between 48 and 15 cal ka BP. The lower limit of the yedoma strata formation has been recorded by three dates of large branches and vertebrate bones (mammoth, bison; Table 1); and the upper limit has been determined by the ^{14}C dating out of the buried soil sampled by A. Pfeffer close to the permafrost top – 15.7 cal ka BP (Table 1), and by the AMS dating of material obtained directly out of ice wedge – 16.4 cal ka BP (Table 2).

The dates of 35.2, 28.2, and 27.2 ka BP (39.8, 32.1, and 31.1 cal ka BP), – obtained for peaty layers of the yedoma exposed 8 m above the water level on the right bank of the Kolyma River, in Chersky area [*Lozhkin, 1977*], – are in good agreement with the chronology proposed by the authors.

For correct dating, the data on seed in buried burrows of ground squirrels are also important, since these dates have been obtained from obviously synchronous organic material. Such findings testify the cyclic variable subaqual-subaerial genesis of the syngenetic ice-wedge complexes. The dates from the Zelyony Mys yedoma burrows (37.2 and 38.4 cal ka BP [*Zanina, 2005*]) indicate the subaerial phase of the terrain development when the ice wedges were actively growing in width.

Based on the model of the cyclical process of the syngenetic formation of thick ice wedges [*Vasil'chuk, 1999*], it is possible to estimate the ratio of the time duration of the subaqueous and subaerial conditions, i.e., the periods when the layers of almost organic-free sandy loam were accumulated and the periods of peat accumulation or the formation of soil horizons (Fig. 5). At the same time, under subaerial conditions, the wedges increased in width, and at the stage of subaqueous sedimentation, the growth of the wedges slowed down or stopped, as evidenced by small buried veins. Heads of veins lie at the level of the lower peat layer at 25 m depth and similar small wedges are found on the level of the soil horizon with heads at a depth of 3 m. Evaluating the series of the ^{14}C dates, we note that at the yedoma section base, the branches of large shrubs, dated 49–45 cal ka BP are often found, as well as plant remains and bones with dates beyond the limit of radiocarbon method. The overlying peat layer fix the time of subaerial phase and is dated to 44.4–41.9 cal ka BP.

It is obvious that a layer of gray-brown sandy loam has been accumulated rather quickly, which is typical of the subaquatic phase. The next subaerial phase can be distinguished not only by the dates of the roots washed up from a layer with a high concentration of organic matter (38.2 cal ka BP), but also by the dates of seeds from ground squirrel burrows (34.8 and 37.3 cal ka BP). The third pronounced organic layer (fixing the next subaerial phase) is dated by the roots 32.2 and 32.9 cal ka BP. Those data are in good agreement with dating of Stanchikovskiy Yar yedoma [*Gubin, Zanina, 2013*], which is also located on the right bank of the Kolyma River near the Zelyony Mys section. There are three layers with a high content of plant residues. The lowest layer and the middle one are dated from 49.9 to 41.8 and from 41.7 to 38.3 cal ka BP, respectively. The upper layer with a high organic content is dated at 32.2–31.5 cal ka BP.

During the period yedoma accumulation at Zelyony Mys and Stanchikovsky Yar there were at least three subaerial phases lasted 2–3 ka. The sediments of subaquatic phases clearly predominate, but that is not due to the duration of sedimentation, but owing to its greater intensity. During the subaqueous phase the same amount of sediment accumulates 2–3 times faster than in the subaerial phase.

Variations of $\delta^{18}O$ values in ice wedges for the period of yedoma formation. A characteristic feature of the isotope diagram of ice wedges of Zelyony Mys is extremely low $\delta^{18}O$ values, especially in the lower parts of ice wedges (Fig. 5). This probably indicate extremely severe (even for cold winters of the Late Pleistocene) winter conditions in that region.

The isotopic composition of ice wedges at the level of the lower peat layer is characterized by the $\delta^{18}O$ values of –31.3 to –29.2 ‰. The $\delta^{18}O$ values in ice wedges at a depth of 16–17 m at the level of the middle layer vary slightly from –31.2 to –30.7 ‰. The minimum $\delta^{18}O$ values for the section (–34.1 ‰) have been obtained at a depth of 15.5 m. A local minimum of the $\delta^{18}O$ values (–32.8 ‰) has also been obtained at a depth of 8 m. Thus, three cycles can be distinguished in the isotopic composition of ice wedges. After an increase of $\delta^{18}O$ values (up to –29 and –30 ‰), a sharp drop is noted (up to –32 or even up to –34 ‰), indicating a significant winter cooling 46–41 cal ka BP and 38–32 cal ka BP. The time of the third cycle can be determined only indirectly, approximately as 24–22 cal ka BP.

In 2005 D.V. Mikhalev et al. [*2012*] had sampled the remaining unexposed upper eight-meter part of Zelyony Mys yedoma and had obtained the $\delta^{18}O$ values of –32.5 to –31.2 ‰ (close to those obtained by us in the upper part), and the δ^2H values of – 248.5 to –240.2 ‰.

At Chersky settlement on the right bank in the lower reaches of the Kolyma River (68.7592° N, 161.3325° E) Yu.K. Vasilchuk and N.A. Budantseva [*2018*] have investigated residual yedoma outcrop preserved within the settlement 300 m downstream the pier. Here the yedoma inset into pre-Pleistocene rocks. The deposits are dark-gray sandy loam with a low organic content. The outcrop is 20–25 m high. Ice wedges are exposed at the depth of 1.0–1.5 m. The age of the ice wedge can be approximately estimated

Table 5. **Mean January air temperature (t_J) in the northwest of Yakutia for the period between 47 and 12 cal ka BP reconstructed based on oxygen isotope composition of ice wedges ($\delta^{18}O_{IW}$)**

The name of reference section	Coordinates	$\delta^{18}O_{IW}$, ‰		t_J, °C		Source
		Paleo	Current	Paleo	Current	
1	2	3	4	5	6	7
47–42 cal ka BP						
Zelyony Mys	68.7875° N, 161.3806° E	–30.2	–25.5	–45	–36	This article
Duvanny Yar	68.6000° N, 159.1000° E	–31.9	–25.1	**–48**	–35	[*Vasil'chuk et al., 2001*]
Kotelny Island	74.2778° N, 147.6059° E	–29.5	–18.0	–44	–29	[*Vasil'chuk et al., 2019*]
Oyogos Yar	72.6775° N, 143.5550° E	–29.5	–24.4	–44	–30.4	[*Opel et al., 2017*]
Bolshoy Lyakhovsky Island	73.3333° N, 141.6667° E	–30.0	–20.4	–45	–31	[*Meyer et al., 2002*]
Mamontova Khayata	71.7695° N, 129.4547° E	–30.2	–23.0	–45	–31	[*Meyer et al., 2002; Wetterich et al., 2011*]
Kurungnakh Island	72.3282° N, 126.2843° E	–31.8	–24.6	**–48**	–34.3	[*Schirrmeister et al., 2003*]
Kular	70.6333° N, 131.8833° E	–31.0	–25.0	–46	–37	[*Vasil'chuk, Vasil'chuk, 2020*]
37–32 cal ka BP						
Zelyony Mys	68.7875° N, 161.3806° E	–33.0	–25.5	**–49**	–36	This article
Duvanny Yar	68.6000° N, 159.1000° E	–32.0	–25.1	–48	–35	[*Vasil'chuk et al., 2001*]
Bison	68.6250° N, 159.2894° E	–32.0	–26.0	–48	–35	[*Vasil'chuk et al., 2003*]
Kotelny Island	74.2778° N, 147.6059° E	–29.0	–18.0	–43	–29	[*Vasil'chuk et al., 2019*]
Mamontova Khayata	71.7695° N, 129.4547° E	–31.0	–23.0	–46	–33	[*Meyer et al., 2002*]
30–25 cal ka BP						
Zelyony Mys	68.7875° N, 161.3806° E	–30.2	–25.5	–45	–36	This article
Duvanny Yar	68.6000° N, 159.1000° E	–31.9	–25.1	–48	–35	[*Vasil'chuk et al., 2001*]
Bison	68.6250° N, 159.2894° E	–33.0	–26.0	–49	–35	[*Vasil'chuk et al., 2003*]
Plakhinskii Yar	68.6788° N, 160.2852° E	–34.8	–25.8	**–51**	–35	[*Vasil'chuk, Vasil'chuk, 2018*]
Kotelny Island	74.2778° N, 147.6059° E	–29.0	–18.0	–43	–29	[*Vasil'chuk et al., 2019*]
Mamontov Klyk	73.6072° N, 117.1250° E	–30.0	–21.3	–45	–33	[*Schirrmeister et al., 2008*]
Mamontova Khayata	71.7695° N, 129.4547° E	–31.0	–23.0	–46	–33	[*Meyer et al., 2002*]
Buor-Khaya	72.3333° N, 126.2833° E	–31.0	–23.0	–45	–34	[*Schirrmeister et al., 2003*]
Kular	70.6333° N, 131.8833° E	–32.0	–26.0	–47	–37	[*Vasil'chuk, Vasil'chuk, 2020*]
24–22 cal ka BP						
Zelyony Mys	68.7875° N, 161.3806° E	–30.4	–25.5	–45	–36	This article
Duvanny Yar	68.6000° N, 159.1000° E	–32.2	–25.1	**–48**	–35	[*Vasil'chuk et al., 2001*]

Table 5, continued

1	2	3	4	5	6	7
Plakhinskii Yar	68.6788° N, 160.2852° E	−31.6	−25.8	−47	−35	[*Vasil'chuk, Vasil'chuk, 2018*]
Kotelny Island	74.2778° N, 147.6059° E	−25.0	−18.0	−37	−29	[*Vasil'chuk et al., 2019*]
Mamontova Khayata	71.7695° N, 129.4547° E	−29.5	−23.0	−44	−33	[*Meyer et al., 2002*]
20–18 cal ka BP						
Zelyony Mys	68.7875° N, 161.3806° E	−31.6	−25.5	−47	−36	This article
Duvanny Yar	68.6000° N, 159.1000° E	−30.5	−25.1	−46	−35	[*Vasil'chuk et al., 2001*]
Plakhinskii Yar	68.6788° N, 160.2852° E	−32.0	−25.8	**−48**	−35	[*Vasil'chuk, Vasil'chuk, 2018*]
Kotelny Island	74.2778° N, 147.6059° E	−25.0	−18.0	−37	−29	[*Vasil'chuk et al., 2019*]
16–12 cal ka BP						
Zelyony Mys	68.7875° N, 161.3806° E	−30.7	−25.5	−45	−36	This article
Duvanny Yar	68.6000° N, 159.1000° E	−31.0	−25.1	**−46**	−35	[*Vasil'chuk et al., 2001*]
Plakhinskii Yar	68.6788° N, 160.2852° E	−31.0	−25.8	**−46**	−35	[*Vasil'chuk, Vasil'chuk, 2018*]

N o t e: extremely low values for each period are shown in bold.

based on radiocarbon dates obtained by B.G. Miller (as he describes 'out of a 10–15 m terrace on the right bank of the Kolyma River'). Two dates have been obtained here: 33 900 ± 500 years (RI-111) for poorly decomposed peat with herbaceous inclusions and, down the section, 38 700 ± 700 years (RI-115) for poorly decomposed peat [*Veksler, Prede, 1985*]. Ice wedges are relatively narrow, not more than 1 m wide. For the best-exposed ice wedge at a depth of 1.5 to 4 m, the $\delta^{18}O$ values variations have been analyzed. The calculation using the formula of Yu.K. Vasil'chuk, allows us to say that at Chersky area at the end of the Pleistocene the mean air temperature of the coldest winter month (January or February) varied from −47 to −49 °C (Table 5).

Mean January air temperature during yedoma formation. The authors have reconstructed the mean January air temperature (t°_{J}) by the sections of the lower reaches of the Kolyma River. The reconstruction was based on a comparison of the isotopic composition of veinlets ($\delta^{18}O_{IV}$) and the modern mean January air temperature for the period of ice wedge formation, i.e., the for the last 60–100 years [*Vasil'chuk, 1991, 1992*]. As a result, the equation has been obtained:

$$t^{\circ}_{J} = 1.5 \cdot \delta^{18}O_{IV}\ (\pm 3\ °C).$$

A range of ±3 °C indicates the average range of variations in the reconstructed temperature within the analyzed time interval.

According to the above-given equation, the mean January air temperature of the Late Pleistocene (48–15 cal ka BP) has been calculated for certain periods for key sections in the lower reaches of the Kolyma River (Table 5).

For the period of 47–42 cal ka BP, the lowest air January temperature is noted for the region of Duvanny Yar (−48 °C). Equally low temperatures were at the Kurungnah Island during that period. At Zelyony Mys section of the Kolyma valley the mean January air temperature was lower than −45 °C (Table 5). Later, 37–32 cal ka BP, the mean January air temperature dropped to −49 °C in the Zelyony Mys area. Further to the north, for example, on the Kotelny Island, the mean January air temperature during that period did not exceed −43 °C. Between 30 and 25 cal ka BP the mean January air temperature in Zelyony Mys area was −45 °C, and in Plakhinskii Yar area decreased to −51 °C. In the period of 24–22 cal ka BP, the mean January air temperature in the Kolyma valley did not change compared to the previous interval: in the Zelyony Mys region it was −45 °C, and in the Duvanny Yar region it was −48 °C (Table 5). For the period between 20 and 18 cal ka BP the lowest mean January air temperatures in the Kolyma River valley have been recorded for Plakhinskii Yar, Duvanny Yar, and Zelyony Mys areas: −48 °C, slightly above −46 and −47 °C, correspondingly. I.e., these temperatures are not the coldest. For Kotelny Island, the reconstructed mean January air temperature is noticeably higher than –37 °C. In the period of 16–12 cal ka BP the mean January air temperature in the Kolyma River valley remained low in the areas of Zelyony Mys (–45 °C), Duvanny Yar and Plakhinskii Yar (–46 °C).

Isotope data demonstrate that mean January air temperatures in the coldest epochs were by 12–15 °C lower than current ones and ranged from –48 to –51 °C, and in periods with less severe conditions varied from –40 to –45 °C.

CONCLUSIONS

The cyclical structure of the Zelyony Mys yedoma and the cyclic change in the conditions of ice wedges formation have been confirmed; subaquatic and subaerial stages of accumulation of yedoma sediments and ice wedges have been identified.

Zelyony Mys outcrop in the lower reaches of the Kolyma River represents three or two levels of wide Late Pleistocene ice wedges and buried narrow ice veins fixing the stages of yedoma formation.

The age of Zelyony Mys yedoma has been established: the beginning and completion of the yedoma accumulation date back correspondingly to 48 and 15 cal ka BP.

In Zelyony Mys section, three cycles of the change in the isotopic composition of ice wedges have been identified: 46–41 cal ka BP, 37–32 cal ka BP, and approximately 24–22 cal ka BP.

Comparison with isotopic composition of ice wedges in the yedoma reference sections of Plakhinskii Yar, Duvanny Yar, Stanchikovsky Yar, Chersky and others allow us to conclude that the winters in the lower reaches of the Kolyma River at the end of the Late Pleistocene cryochron, were significantly more severe than modern ones.

The lowest mean January air temperature (by 15 °C lower than modern ones) in the lower reaches of the Kolyma River has been obtained by the authors for the period of 37 to 25 cal ka BP, which corresponds to a decrease in temperature on a global scale.

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