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GEOGRAPHY

A ^{14}C-Dating and Oxygen-Isotope Diagram of a Holocene-Reformed Ice Wedge on the Chara River (Transbaikal Region)

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The purpose of our work is to refine the age of the Holocene polygonal ice wedge complex in Terrace 1 of the Chara River, plot an isotope diagram, which allows one to reconstruct winter temperatures of the period of ice-wedge formation, and prove the possibility of active formation of ice wedges in the Holocene Optimum in even the southern regions of Siberia.

The climate of the Chara Depression (absolute height 708–740 m) is characterized by predominate continental air masses during the whole year, prevalence of western (zonal) air transfer, and a very nonuniform distribution of meteorological elements within the depression due to an echelon disposition of NE-oriented mountain ranges around the depression.

Climatic conditions in the settlement of Chara in the mid-1960s were as follows: annual mean air temperature (t_a) –7.8°C [1] (this is a long-term value, but the annual mean temperature in 1939–1965 differed by more than 3°C (from –5.8 to –9.1°C [2]); average January temperature (t_{jan}) –33.7°C; average winter temperature (t_w) –21.2°C; sum of winter temperatures (Σt_w) –4387 deg · day; absolute minimal temperature on the ground surface –57°C; average minimum –50°C; sum of summer temperatures (Σt_s) 1594 deg · day; and average July temperature (t_{jul}) 16.4°C.

Snow cover is retained in the depression for an average of 176 days per year. The average thickness of the snow cover varies from 15 to 20 cm. According to data from the Chara Meteorological Station, the maximal and minimal thicknesses of snow cover are 57 and 6 cm, respectively. Insignificant snow drift during storms enhances an even cooling of different landforms [2]. The defrosting effect of snow is very significant (temperature gradients in a snow mass exceeded 1.5 deg/cm [3]). Therefore, cooling in low-snow winters and a consequent cracking are rather intense. Due to friability and high heat-insulating capacity of snow, the greatest cold wave reaches the ground in February, i.e., 1.5 months after the maximal frost onset. The most intense frost cracking seems to occur in this winter period. The summer in the Chara Depression starts in the first ten days of June and ends in late August. The absolute minimal air temperature registered in the Chara settlement in July is –2°C [4].

Winter cooling of the Earth's surface and a sink of cold air to the depression, especially during anticyclones, provoke deep and prolonged subaerial temperature inversions. They are characterized by temperature increase with higher altitudes and very low temperatures near the surface (below –56°C) and on the ground surface, which facilitate intense frost cracking. Winter inversions usually start in November, and the total recurrence of days with inversions are 85–96%. The temperature difference between the subaerial layer and the upper boundary of the inversion layer is 20°C or more [4].

A seasonal thawing on terraces and the floodplain starts at the beginning of May and ends in October. The thickness of the seasonal thawing layer varies from 0.5–1 to 3.5 m [5]. The minimal thawing depth (up to 1 m) was registered on bare swamped sectors or areas with a thin larch forest. Hence, these areas are most favorable for the development and conservation of reformed ice wedges (RIW).

The annual mean ground temperature here in 1964 was rather high and varied from –2°C under the thin larch forest canopy to 1–2°C on dry sands and an open dry field [6]. A geocryological contrast is quite perceptible even within one landform, and annual mean ground temperatures can vary in the range of 2°C or more. The contrast is even greater, for example, near the thermal Verkhnii Chara sodium chloride–sulfate spring (near Lake Arbakalir in the northern Chara

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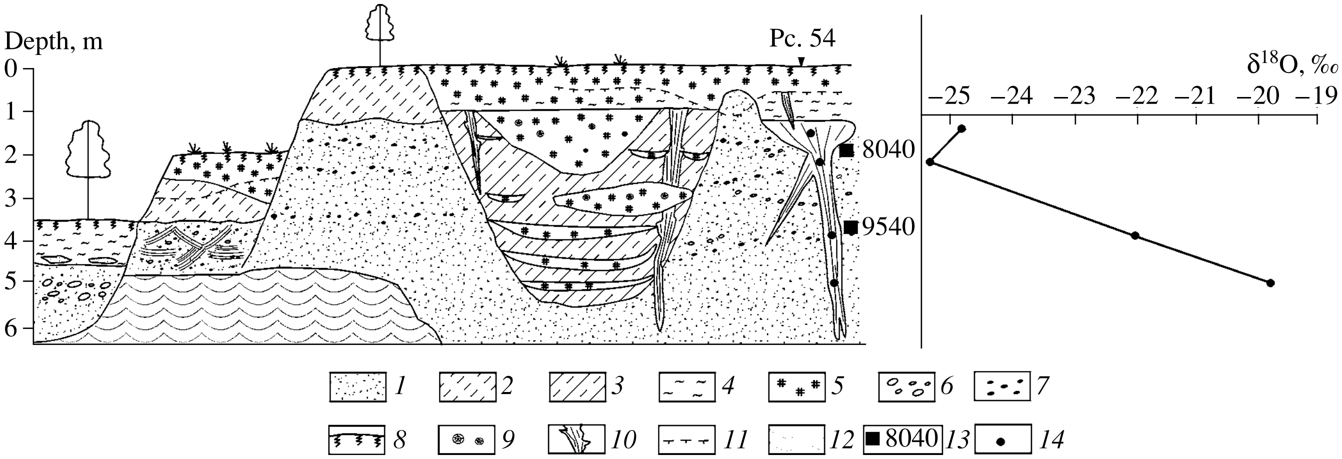

Fig. 1. Holocene syngenetic reformed ice wedge (RIW) in the exposure of the first (Belyi Klyuch) terrace on the Chara River and the isotopic diagram of the long and narrow ice wedge. (*1*) Sand; (*2*) sandy loam; (*3*) alternating peat, sandy loam, and loam; (*4*) silt; (*5*) peat; (*6*) pebbles; (*7*) gravel; (*8*) plant roots and moss; (*9*) shells; (*10*) RIW; (*11*) lower boundary of seasonally thawed layer; (*12*) direction of bedding; (13) ^{14}C dates; (14) sites of wedge ice sampling for oxygen isotope analysis.

Depression) with the temperature ranging from 41°C in April to 50.5°C in May [7]. The effect of hot thermal water of the main gryphon is very local and does not exceed a few hundred meters.

The Chara Depression incorporates diverse polygonal landforms [8, 9]. The reformed ice wedges described in [10–13] are widespread in the depression, and their ages are interpreted differently. Therefore, most researchers assumed that the RIWs of this depression are relict (Late Pleistocene) formations. As large wedges in most of the described fragments of exposures are hosted in sands (often, medium- and coarse-grained) with pebble interlayers, the researchers believed that geocryological conditions must certainly have been more rigorous than in the Recent and Holocene.

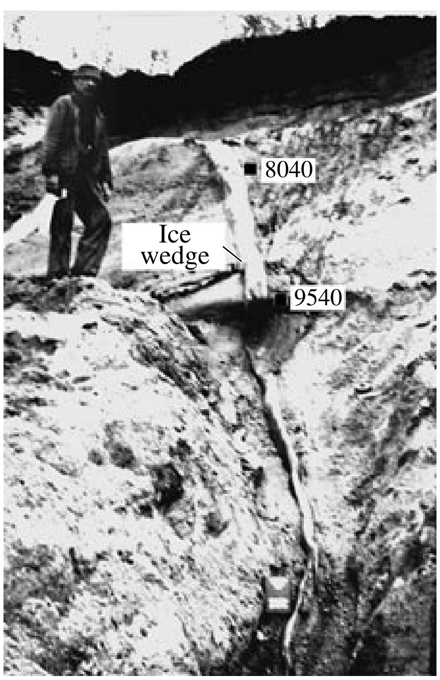

Fig. 2. Holocene syngenetic narrow-long RIW in gravelly sands in the Belyi Klyuch exposure of the Chara River Terrace 1 and ^{14}C dates of wedge-hosting sediments.

We studied the Belyi Klyuch (White Spring) section within the first (8-m-high) RIW-hosting terrace on the right bank of the Chara upstream from the settlement of Novaya Chara and the mouth of the Verkhnii Sakukan River (Figs. 1, 2).

The detailed sampling of different fragments of polygonal ice wedge systems for radiocarbon dating and refinement of paleotemperatures during the ice wedge formation allowed us to refine their timing and formation conditions. We determined winter paleotemperatures based on the oxygen isotope analysis and summer paleotemperatures based on the reinterpretation of palynological data in [11].

For an objective definition of the age of the 8-m-high terrace, organic remains were taken in its different parts and analyzed by the radiocarbon method (Table 1).

All 19 dates obtained were of the time interval from 10 to 7.5 ka. This period coincides with the first half of the Holocene Optimum for these regions of Siberia [13–15]. The lack of lacunas in wood dates shows that wood species were present throughout the whole period of the formation of sediments on the 8-m-high terrace.

Despite the presence of intermontane depression, where redeposition of organic matter is quite possible, radiocarbon dates demonstrate the lack of redeposition within the sequence of the 8-m-high terrace. This fact is supported by a direct relationship between the organic matter age and the sampling depth (Fig. 3).

It is also noteworthy that the ages obtained for wood and enclosing peat are similar (Table 1), peat ages being

Table 1. Radiocarbon analysis of the plant organic matter from ice wedge-hosting sediments in the first alluvial terrace

Field no.	Depth, m	Dated material	Lab. no.	^{14}C age, yr
353-YuV/1	1.5	Wood	GIN-5706	7840 ± 60
353-YuV/2	1.5	Peat	GIN-5709	7570 ± 250
353-YuV	4.7	The same	GIN-5707	9150 ± 80
353-YuV	4.7	Wood	GIN-5708	9740 ± 60
Z-PK-36	4.65–5.0	Plant detritus	Tln-1284	9450 ± 70
Z-PK-5	2.2	The same	Tln-1283	8875 ± 65
Z-PK-5	3.2	"	Tln-1290	8980 ± 80
Z-PK-33	4.5	Wood	Tln-1295	9610 ± 80
Z-PK-32	1.2–1.3	The same	Tln-1274	8350 ± 65
Z-PK-32	3.2	"	Tln-1273	9230 ± 40
Z-PK-32	3.4	"	Tln-1275	9180 ± 40
Z-PK-28-5	2.15	"	Tln-1294	8350 ± 60
Z-PK-28-5	2.15	Peat	Tln-1309	8035 ± 55
Z-PK-28-5	2.6	Wood	Tln-1291	8500 ± 80
Z-PK-28-5	3.5	The same	Tln-1296	9260 ± 55
Z-PK-28-5	3.5	Peat	Tln-1312	9320 ± 75
Z-PK-54	2.0	Wood	Tln-1301	8040 ± 100
Z-PK-54	3.7	The same	Tln-1297	9540 ± 190
Z-2025	1.65	"	Tln-1292	10230 ± 95

slightly younger than wood dates. This means that both peat and wood are synchronous. In this case, redeposition is unlikely. Hence, all the fragments of the section have been dated with adequate accuracy.

The structure of the alluvial terrace sequence varies in different exposed fragments of the section: in some fragments, rather pure and coarse sands occur almost on the surface; in other fragments, they are overlain by peat or more fine-grained sediments. Lithological distinctions in the structure of different fragments of the section indicate different facies conditions of the timing of the 8-m-high terrace. They are also in compliance with variations in the RIW structure in different sediments. It is most important that there is an indispensable presence of ice wedges, both in fine-grained sediments and coarse sand layers with pebble and gravel.

One of the fragments shows that sandy sediments include a lens with narrow superimposed ice wedges of the following composition (from top to bottom): (0–1.8 m) flat and wavy-bedded, sandy loam and loam with a low ice content and without visible organic inclusions; (1.8–3.3 m) horizontal alternation of peat, fine-grained sand, sandy loam, and loam (in places, the interlayers consist completely of plant detritus); (3.3–5.0 m) laminated, dark-gray to black, foliated sandy loam with horizontal interlayers of organic remains and ice schlieren (1 to 3–5 mm in the upper part and 1–2 mm to 2 cm in the lower part) and the content of organic matter increasing downsection; (5.0–6.7 m) gray, well-washed, medium-grained to coarse-grained sand with fine gravel and isolated quartz inclusions up to 1–2 cm in size. Diagonal bedding is observed in places.

Alternating fine- and medium-grained sands with gravel and pebble horizons up to 0.5 m high were revealed in another fragment of this exposure. Large RIWs as thick as 7 m were found there. Their heads occur at different depths, often below gravel–pebble layers (Fig. 4).

We took samples of ice wedge and streaky ice from enclosing sediments in two different years. The content of stable oxygen isotopes in the samples was determined in an isotope laboratory in Tallinn (Table 2).

$\delta^{18}O$ values of one of the largest ice wedges vary from –24.7 to –20.9‰. The values in other ice wedges show a similar variation. In ice wedge 3, $\delta^{18}O$ varies from –25.3 to –19.8‰ (wood fragments in the enclosing sediments are estimated at 8.0 and 9.5 ka at a depth of 2 and 3.7 m, respectively). In ice wedge 4, $\delta^{18}O$ varies from –25.7 to –24.6‰ (plant remains in enclosing sediments are dated at 8.8 and 8.9 ka at a depth of 2.2 and 3.2 m, respectively).

The isotopic composition of ice of small schlieren from sand with gravel is heavier ($\delta^{18}O$ values vary from –18.5 to –14.4‰). The $\delta^{18}O$ value is –16.1‰ in streaky ice from the overlying sandy loam and –14.3‰ above the peat base in large schlieren. At the same time, isotopes in ice from sandy loam underlying an oxbow peatbog are lighter ($\delta^{18}O$ = –19.5‰).

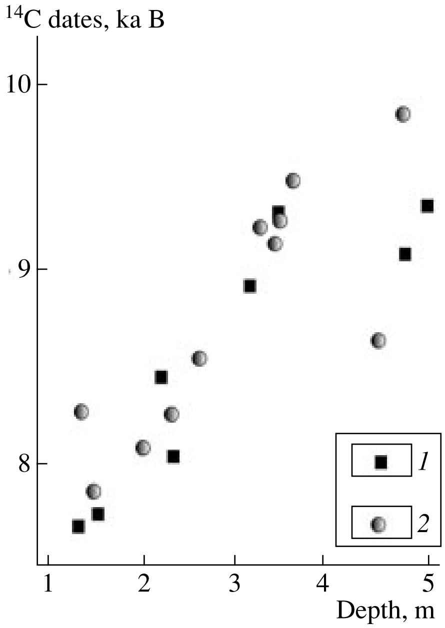

Fig. 3. Relation between the age and depth of organic matter sampling from RIW-hosting sediments of the Belyi Klyuch section on the 8-m-high terrace of the Chara River: (*1*) wood samples; (*2*) peat samples.

The data obtained suggest the presence of Holocene-age ice wedges in the sand–gravel sequence in the Chara Depression. The wedges formed, as a rule, from melted snow, but sometimes (especially, in the case of buried small wedges) with the participation of river water that was responsible for a heavier isotopic composition.

In general, severe winters and an extreme continental climate prevailed in the Transbaikalian depressions during the Holocene Optimum.

Judging from isotope data, the average winter temperature in the Chara Depression within the period from 7.5 to 10 ka varied from –26 to –21°C (–26, –23°C during the most part of the period); i.e., the winter temperature was considerably lower (by 3°C and more) than the current temperature. The average January temperature could reach –37,or even –39°C in the most severe winters; i.e., the January temperature was 3–5°C lower than today. The sum of winter temperatures (from –4500 to –5400 deg · day) was sometimes similar to the present-day sum, but more often was considerably more negative than at present.

The palynological analysis of Holocene sediments in the Chara Depression, which comprise ice wedges,

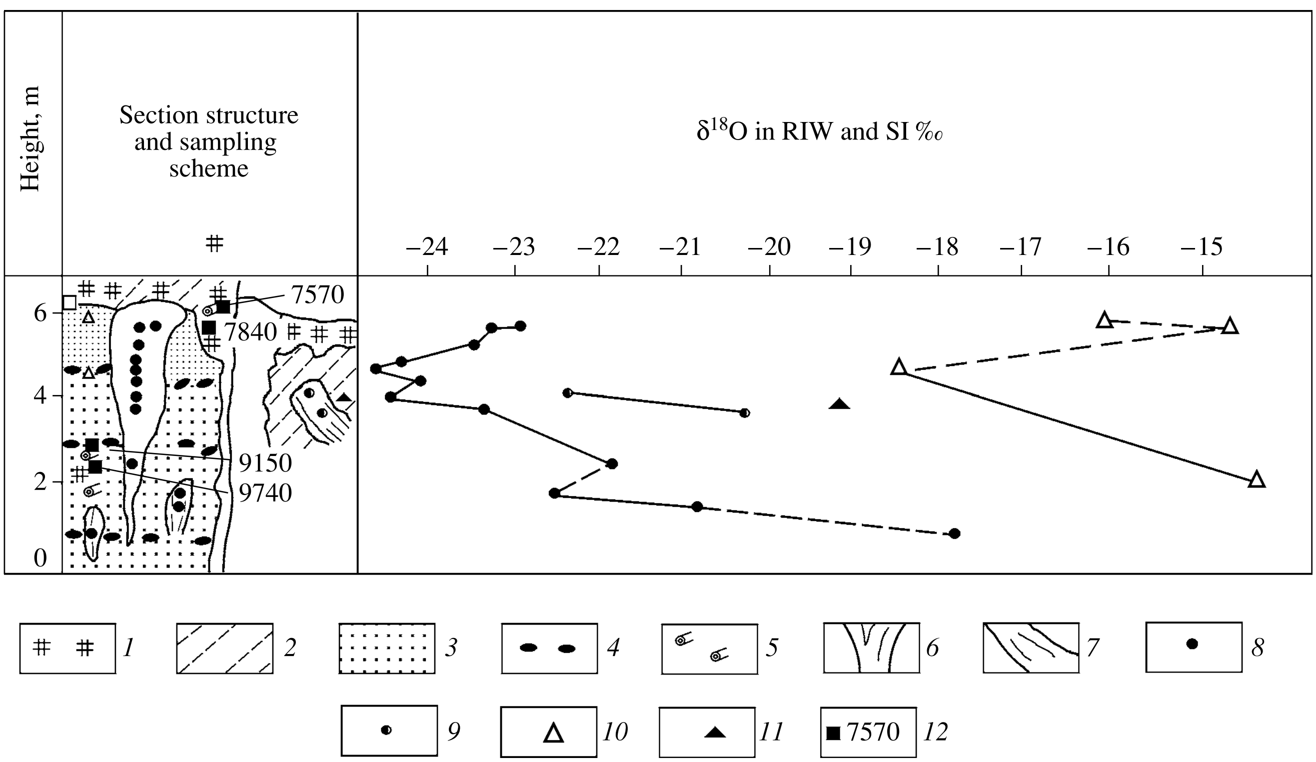

Fig. 4. The structure of the reference (Belyi Klyuch) cryolithological section in the Holocene 8-m-high terrace of the Chara River (Transbaikal region) and oxygen isotope diagrams of the RIW in sands and SI in host sediments (after [15]): (*1*) peat; (*2*) sandy loam; (*3*) sand; (*4*) gravel; (*5*) wood; (*6*) gray ice wedge in sands; (*7*) milky white ice wedge in oxbow sediments of adjacent floodplain; (*8–11*) sampling sites for oxygen isotope analysis: (*8*) from a large ice wedge and small buried wedges in sands, (*9*) from an ice wedge in oxbow sediments of the floodplain, (*10*) from streaky ice in terrace sediments, (*11*) from streaky ice in oxbow sandy loam; (*12*) ^{14}C dates, yr BP

Table 2. Content of oxygen stable isotopes ($\delta^{18}O$) in reformed ice wedge (RIW) and streaky ice (SI) in the first terrace of the Chara River, in the Rzhavyi Creek, rain, snow, and Chara River water

Field no.	Depth, m	Ice type	$\delta^{18}O$, ‰	Field no.	Depth, m	Ice type	$\delta^{18}O$, ‰
Wedge 1							
353-YuV/4	1.2	RIW	–23.3	353-YuV/12	4.3	RIW	–21.9
353-YuV/5	1.5	"	–23.5	353-YuV/13	5.0	"	–23.5
353-YuV/6	1.1	"	–23.0	353-YuV/16	5.2	"	–20.9
353-YuV/7	2.0	"	–24.7	353-YuV/17	5.4	"	–17.8
353-YuV/9	2.4	"	–24.1	353-YuV/23	0.7	"	–24.5
353-YuV/10	2.7	"	–24.5	353-YuV/24	2.5	"	–22.2
353-YuV/11	3.0	"	–23.9	353-YuV/25	1.2	"	–23.8
Germ of recent Wedge 2							
353-YuV/19	1.2	RIW germ	–22.4	353-YuV/20	1.6	RIW germ	–20.7
Streaky ice from sediments enclosing Wedge 1							
353-YuV/19	1.2	SI from sandy loam	–16.1	353-YuV/18	1.5	SI from peat	–14.3
353-YuV/15	4.7	SI from sand	–14.4	353-YuV/26	1.8	SI from oxbow sandy loam	–19.5
Wedge 3 from a fragment of exposure Z-PK-54							
Z-PK-54/1	1.3–1.4	RIW	–24.9	Z-PK-54/3	3.8–4.0	RIW	–22.0
Z-PK-54/2	2.1–2.2	"	–25.3	Z-PK-54/4	5.0–5.4	"	–19.8
Wedge 4 from a fragment of exposure Z-PK-5-15							
Z-PK-5-15/1	1.5	RIW	–24.6	Z-PK-5-15/3	3.4–3.5	RIW	–25.7
Z-PK-5-15/2	2.4–2.5	"	–25.0				
Wedge 4 from a fragment of exposure Z-PK-36							
Z-PK-36/1	1.4–1.6	RIW	–21.2				
Wedge 5 in the upper course of the Rzhavyi Creek, a tributary of the Nerungnakan River							
2094/1	2.7–2.8	RIW	–23.9	2094/3*	2.4–2.6	RIW	–30.0
2094/2	2.7–2.8	RIW	–25.2				
Meteoric and hydrospheric water							
353-YuV/21	0	Rain, Aug. 19, 1988	–15.8	353-YuV/22	0	Chara River water, Aug. 11, 1988	–19.5
Z-Y/1	0	Snow, Udokan Settlement	–39.9	Z-PK-33/1	0	The same, July 1987	–18.1

* The sample is likely to have been taken from a relict, older wedge.

was carried out by L.M. Vasil'eva [11]. These data suggest the following variations in summer temperatures during accumulation of sediments on the 8-m-high terrace.

The lower sandy sequence is composed of palynospectra, which are characterized by a slightly higher content of the pollen of conifers and lycopods. The maximal content of larch pollen is found at the base of the terrace down to a depth of 4.6 m. This is successively replaced by the maximal content of Scotch pine pollen and the maximum of birch pollen, with predomination of the pollen of wood species (64–70%) and participation of the pollen of Siberian stone pine and alder [11].

The ratio of main components is different in clay and sandy loam from the middle part of the section, which is dominated by spores of green mosses and ferns. The maximum content pollen from the Caryophyllaceae family was registered at a depth of 4.3 m, indicating the development of polygonal structures and the onset of deterioration of vegetation conditions. The content of the tree pollen decreases to 7–38%, while the content of spores increases to 58–90% at a depth of 4.3–3.4 m, owing to the participation of green mosses and Polypodiaceae ferns. In palynospectra of this interval, the pollen content of dwarf birches, thicket, and arborescent species of willow increases. Of grass pollen, the pollen of wormwood and other species of the Compositae family predominates. Pollen of the Chenopodiaceae family and French willow are also encountered. Local components of palynospectra are lacking. Hence, sediments accumulated in the course of a substantial deterioration of vegetation and an abrupt change in facies conditions of sedimentation.

In the upper part of the section (0.1–2.8 m), the content of tree pollen increases and the pollen of Scotch pine predominates. At a depth of 1.5 m, the content of the dwarf birch pollen is maximal. This is replaced by the maximum pollen content of birch and alders. The Ericales pollen, including Chenopodiaceae and wormwood pollen, predominates among the herbage. The *Ephedra* and *Chamaenerion* pollen are also found. Sphagnum spores predominate amidst spores [11]. This indicates the completion of bog formation and replacement of groundwater recharge by atmospheric alimentation.

Judging from ^{14}C ages, sediment accumulated rather rapidly within the interval of 10–7 ka BP, i.e., just in 3 ka. Conditions of the vegetation period during accumulation of the lower sequence were most favorable and characterized by rather high temperatures and humidity. Larch forests were most likely replaced by pine and birch forests with spruce and larch, as well as dwarf birch. The sum of positive temperatures was 1500–1700 deg · day, i.e., the temperature was slightly higher than the current one in some periods. The overlying 2-m-thick sandy loam and clay sequence comprises palynospectra, which characterizes landscapes with maximal development of lowland bogs and thin birch and pine forests. We suppose that the sum of positive temperatures decreased below the present-day values, to 1100–1200 deg · day. An increase in the content of the arborescent pollen indicates the improvement of vegetation conditions and development of forest phytocoenosis (birch and pine forests with larch and spruce). This is confirmed by the appearance of Ericales and Lycopodinae pollen in the spectra. The sum of positive temperatures is similar to the current one, making up 1500–1600 deg · day. The palynospectrum composition suggests the development of polygonal landscapes and a possible growth of ice wedges (mainly in width) at depths of 4.3, 2.7, and 1.5 m. The development of polygonal tundra is confirmed by an appreciable content of dwarf birch, Caryophyllaceae, and wormwood pollen against a background of dominating green moss and sphagnum spores.

Thus, palynological data indicate only a short-term decrease in summer temperatures relative to current values (under conditions of a slightly more positive summer temperature relative to the current one) in the Chara Depression within the period of 10–75 ka BP, whereas the oxygen isotope data on the RIW suggest that winter temperatures were constantly lower than the present-day temperatures.

The materials presented allowed us to prove the possibility of an intense growth of syngenetic RIWs in the sandy–gravel sequence in the Holocene Optimum in even the southern regions of the Siberian cryolithozone.

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