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EARLY HOLOCENE OXYGEN ISOTOPE CHRONOLOGIES (11,267–6420 CAL BP) FROM ICE WEDGE AT CHARA, TRANSBAIKALIA

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ABSTRACT. Accelerator mass spectrometry radiocarbon (AMS ^{14}C) dating was used for determining the age of wedge ice. It has been found that between 11,270 and 6420 cal BP, or the Greenlandian and Northgrippian stages of the Holocene, ice wedges grew syngenetically in sandy deposits with gravel in the Chara River valley. The variations of $\delta^{18}O$ values in the ice wedges are about 8‰, from –25.5‰ to –18.8‰. Based on the stable isotope composition of ice wedges, paleotemperature reconstructions revealed that the mean January temperature was as low as –38°C during the coldest periods of the early half of the Holocene and as high as –28°C during the warmer periods.

KEYWORDS: AMS, Chara, Holocene, ice wedge, oxygen isotopes, peat, radiocarbon, Transbaikalia, veinlets.

INTRODUCTION

The syngenetic ice wedges exposed in the gravel sands of Northern Transbaikalia's Chara River basin are the subject of the study (Figure 1). This outcrop was studied previously (Klimovsky and Naprasnikov 1967; Romanovsky et al. 1988), previous studies of the authors of the present study obtained ^{14}C data of peat and wood from first terrace spanning from 11,950 cal BP to 8400 cal BP (Vasil'chuk et al. 2018). However, due to the lack of direct dating of ice wedge and scarce isotope data, additional chronological and isotopically studies are required for the paleotemperature reconstructions. The study's objectives are to estimate the approximate mean January air temperature, compile all available oxygen isotope data of the Holocene ice wedges in the Chara River valley, and determine the radiocarbon age of organic microinclusions that have been directly collected from the ice wedges.

MATERIALS AND METHODS

Field Studies and Sampling

Field studies of wedge ice were carried out by the authors three times between 1985 and 2023. The study area is located in the Kalarsky region of Transbaikalia. The key site is located in the valley of the Chara River, in its middle course, 8 km southwest of Novaya Chara settlement, at the confluence of the Belenky Creek and Chara River (56°45'38.72"N, 118°11'30.12"E). The first alluvial terrace is composed of Holocene channel and floodplain sands, often with gravel. In the upper part of the section, oxbow, marsh, sandy loam, and peat are revealed. Plant cover is dominated by light forests of Cajander larch (*Larix cajanderi*) with an undergrowth of splayed birch (*Betula divaricata*) and dwarf pine (*Pinus pumila*). Soil cover is characterized by Gley Soils, which are divided into cryogenic-ferruginous cryoturbated permafrost and cryogenic-ferruginous post-pyrogenic permafrost. The climate in the study region is sharply continental; according to the data from the weather station "Chara," the mean annual air temperature increased from –8.1 to –6°C between 1959 and 2019 (Sergeev 2020).

The mean January air temperature increased from –34°C (1930-1966) to –33°C (1967–2000) and to –32°C in 2001–2017 (Vasil'chuk and Surkova 2021). In recent 6 years (2018–2023), the mean January air temperature was about –31.5°C (www.pogodaiklimat.ru). For the Chara basin, both

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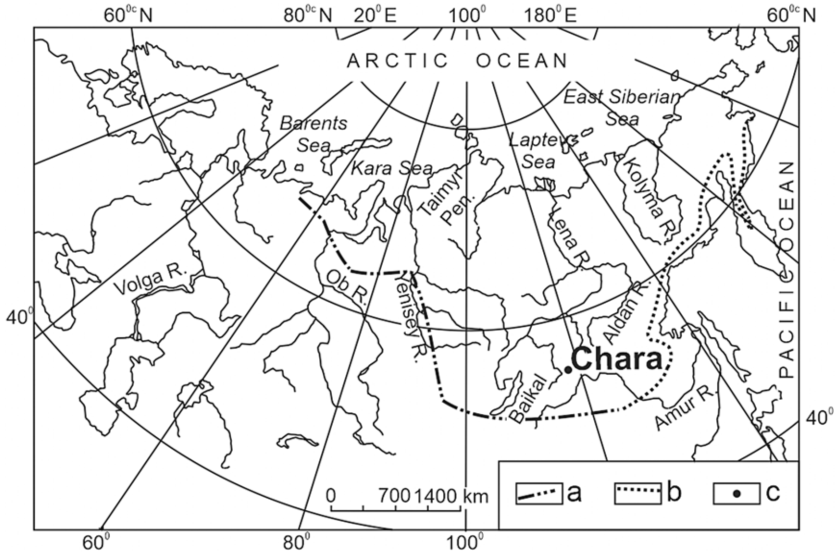

Figure 1 Southern boundary of known (a) and estimated (b) ice wedge distribution in Eurasia (from Vasil'chuk 2013), and Chara ice wedge site (c).

areas without permafrost and permafrost with a thickness of about 450 m are described. Within watershed areas of mountain ranges, permafrost thickness reaches 900 m. Ground temperature in the study area varies in different landscapes from –7 to +2°C (Sergeev 2020).

Using a Bosch GSR 36 VE-2-LI drill with a steel crown 51 mm in diameter, samples of ice were taken from the ice wedges (IW) along vertical and horizontal profiles at a step of 10 cm. After being placed in double polyethene bags, the ice samples were allowed to melt at room temperature before being transferred into 30 ml HDPE vials and covered with parafilm to prevent evaporation.

Radiocarbon Dating

Radiocarbon dating of microinclusions of organic material extracted directly from ice wedges carried out at the "Laboratory of Radiocarbon Dating and Electron Microscopy" of the Geography Institute of the Russian Academy of Sciences and the Center for Applied Isotope Studies, University of Georgia (USA) were carried out on the 500 kV NEC 1.5SDH-1 pelletron (CAMS). Organic microinclusions for ^{14}C AMS analysis were extracted from 5 samples. ^{14}C ages of enclosed sediments were previously obtained at the Institute of Geology RAS (lab code GIN) and Institute of Geology of the Estonian Academy of Sciences (lab code Tln). All obtained radiocarbon dates were calibrated using OxCal 4.4 based on the IntCal20 data set and given as yrs cal BP (Bronk Ramsey 2021; Reimer et al. 2020).

Stable Water Isotope Analyses

Measurements of the stable oxygen and hydrogen isotope composition in ice were carried out using a Picarro L 2130-i laser infrared spectrometer at the Resource Center "X-ray Diffraction Research Methods" of the Science Park of St. Petersburg State University. International reference materials V-SMOW-2, GISP, SLAP, USGS-45, and USGS-46 were used for the

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calibration. The values are presented in δ-notation in per mille (‰) relative to the Vienna Standard Mean Ocean Water (VSMOW). The analytical precision was ±0.02‰ for $\delta^{18}O$. In total, 84 samples of wedge ice were analyzed for their stable isotope composition.

January Paleotemperature Reconstructions

Particularly in high-latitude areas, stable isotope ratios ($\delta^{18}O$ and δ^2H) in precipitation provide as accurate indicators of air temperature (Vasil'chuk 1991; Brezgunov et al. 1998; Opel et al. 2018; Vasil'chuk and Surkova 2020). Since ice wedges are primarily composed of snow meltwater, they may provide a winter paleoclimate record since they retain the stable isotope signature of winter precipitation for millennia. It has been determined that the main factor influencing $\delta^{18}O$\ fluctuations in precipitation in the Siberian Arctic throughout the winter is air temperature. There is a slight impact from additional mechanisms and processes, such as changes in moisture sources, air transport, and snow evaporation in the winter (Meyer et al. 2015; Opel et al. 2018).

Since Prof. Vasil'chuk first proposed a regression equation (Vasil'chuk 1991) to calibrate the stable isotope composition of ice wedges to winter air temperatures in most regions of the Russian permafrost zone, including the continental areas of Central Yakutia and Transbaikalia, stable oxygen isotope values of ice wedges have been used as a basis for winter paleotemperature reconstructions. The following formula is used to get the mean paleotemperature for January:

$$T_{mJ} = 1.5\delta^{18}O_{iw}(\pm\ 3°C)$$

where T_{mJ} and $\delta^{18}O_{iw}$ are mean January air temperature and $\delta^{18}O$ values in modern ice veinlets, respectively. Prof. Vasil'chuk deduced with this type of equation (which has an acceptable error of ±3°C but no free term) after analyzing mean January air temperatures for over 250 weather stations in Russian permafrost regions and stable oxygen isotope values for modern ice veinlets (not older than 60–100 years). It should be emphasized that this kind of equation includes the natural variability of the mean January air temperature and provides approximate paleotemperature values with an acceptable error of ±3°C.

The validity of $\delta^{18}O$ data for paleotemperature reconstructions is verified using the δ^2H–$\delta^{18}O$ ratio and deuterium excess (d_{exc}) values if coupled isotope data ($\delta^{18}O$ and δ^2H) are available. $d_{exc} = \delta^2H - 8\delta^{18}O$ is the formula for deuterium excess (Dansgaard 1964). Indicating the meteoric nature of water (usually snowmelt) forming ice wedges and the negligible impact of kinetic fractionation on the isotope composition of snow and snowmelt before filling frost cracks. The slope of the δ^2H–$\delta^{18}O$ ratio line in the study area is close to 8 (i.e., close to that of the global meteoric water line, GMWL) or, in some cases, close to the slope of the local meteoric water line (LMWL).

RESULTS AND DISCUSSION

Cryogenic Structure, ^{14}C Age and $\delta^{18}O$ Values of the Studied Ice Wedges

IW-1. It is exposed in the outcrop of the left bank of the Belenky creek, about 300 m from the place where the creek flows into the Chara River (56°45'32.28"N, 118°11'12.07"E). The ice wedge was exposed at the depth of 1.8 m from the surface (Figure 2A). The visible portion of the ice wedge measured roughly 1.0 m in height and ranged in breadth between 10 and 15 cm. The oxygen isotope data was obtained for 12 ice samples, $\delta^{18}O$ values vary from −24.05 to −16.33‰ (Table 1).

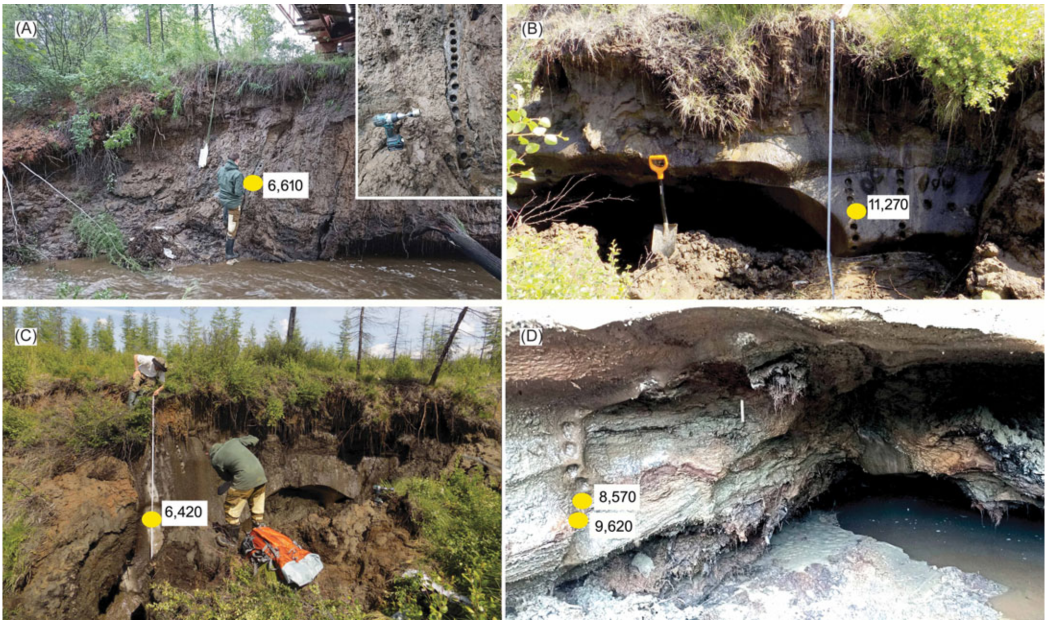

Figure 2 Ice-wedge sampling in the Chara River valley: (A) IW-1; (B) IW-2; (C) IW-3; (D) IW-4. AMS ^{14}C dates (cal years BP) are also shown in the white boxes.

Table 1 $\delta^{18}O$ values in ice wedges in the Chara River valley.

Number of samples	$\delta^{18}O$ (‰) Min.	Mean	Max.	Number of samples	$\delta^{18}O$ (‰) Min.	Mean	Max.
IW-1					IW-3		
12	−24.05	−22.73	−16.33	22	−25.94	−25.24	−24.05
IW-2					IW-4		
20	−25.47	−24.27	−21.75	11	−21.60	−19.72	−17.61

The highest value, −16.33‰, was obtained only for one sample (that probably resulted from the admixture of isotopically enriched segregated ice); all other samples are characterized by $\delta^{18}O$ values less than −22.5‰ (Figure 3A). *IW-2.* It was exposed on the right side of a shallow, wide thermo-erosion gully, perpendicular to the Chara River channel (56°45'38.86"N, 118° 11'19.95"E). The ice wedge was exposed at a depth of 1.2 m from the surface (Figure 2B). The length of the visible part is about 0.7 m. $\delta^{18}O$ values range from –25.41 to –21.75‰, most values are less than –23‰ (Figure 3B).

IW-3. It was exposed near the IW-2 (56°45'38.84"N, 118°11'29.26"E). The ice wedge was exposed at a depth of 1.0 m from the surface (Figure 2C). The length of the visible part is about 5 m. The width of the almost frontally exposed right part is about 2 m. $\delta^{18}O$ values for the ice vary in a narrow range from −25.94 to −24.05‰ and were the lowest for the four studied ice wedges (Figure 3C).

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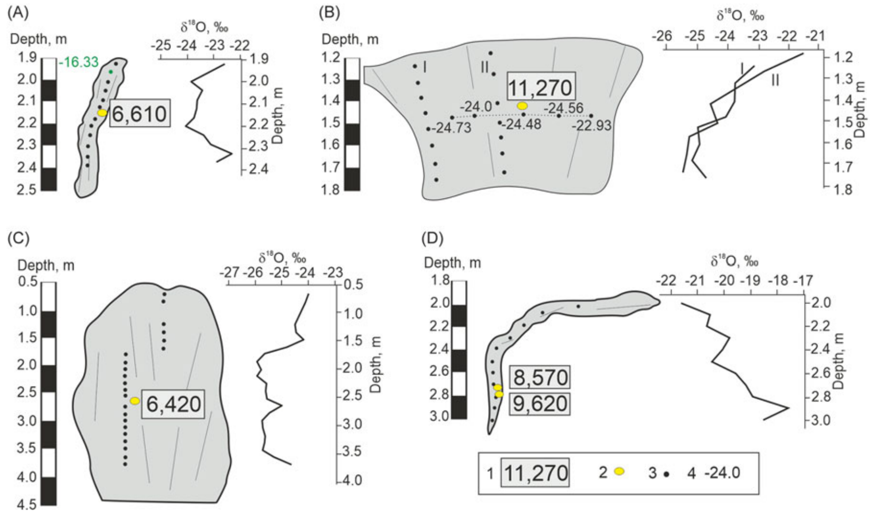

Figure 3 δ18O plots and AMS 14C dates for the ice wedge in the Chara River valley: (A) IW-1; (B) IW-2; (C) IW-3; (D) IW-4. 1—AMS 14C dates (cal years BP) of organic matter microinclusions from the ice wedges; 2—points of ice sampled for AMS 14C dating; 3—points of ice sampled for stable isotope analysis; 4—δ18O values in IW-2 sampled from along the horizontal profile.

IW-4. It is exposed on the steep left bank of the Belenky Creek, about 250 m from its mouth (56°45'32.87"N, 118°11'11.83"E). The ice wedge was exposed at a depth of 2.0 m from the surface (Figure 2D). The length of the visible part of the ice wedge was about 2 m, and the width 0.15–0.3 m. The δ18O values vary in a wide range from −21.6 to −17.61‰; high isotope values were obtained in the tail part and are probably explained by the admixture of segregated ice from the enclosing sediments sampled together with the ice wedge (Figure 3D).

AMS Radiocarbon Age of Ice Wedge

The radiocarbon age of the ice wedge was determined with a high degree of accuracy due to direct AMS 14C dating of organic microinclusions in the ice wedges (Table 2).

According to the obtained dates, IW-2 is the oldest of the studied ice wedges; it was dated to 11,270 ± 42 cal BP at a depth of 1.48–1.6 m; IW-1 and IW-3 are the youngest; the dates 6610 ± 40 cal BP and 6420 ± 37 cal BP were obtained at a depth of 2.12–2.16 m in IW-1 and at a depth of 2.52–2.78 m in IW-3. The age of IW-4 was obtained from two subsequent 14C dates: 8570 ± 32 cal BP at a depth of 2.7 m and 9620 ± 53 cal BP at a depth of 2.8 m.

The oldest ice wedge is dated to the early Greenlandian stage of the Holocene (Walker et al. 2019; Budantseva 2022) with 11,270 ± 42 cal BP, and the youngest one is dated to the middle of the Northgrippian stage with 6420 ± 37 cal BP.

Radiocarbon Dating of the Enclosing Sediments

To estimate the age of alluvial terrace sediments enclosing studied ice wedges, organic remains were sampled during the 1985 and 1988 field seasons, with the following radiocarbon dating (Table 3).

Table 2 Radiocarbon ages of ice wedges in the Chara River valley.

Sample ID	Depth (m)	Lab ID	Uncal. ^{14}C age (yr BP)	Cal age [cal BP][a] Age interval (2σ), probability 95.4%	Median age (1σ)	$\delta^{18}O$ (‰)
Ch-1-22-1/4, IW-1	2.12–2.16	10438	5805 ± 20	6670–6500	6610 ± 40	–23.61
Ch-1-22-2/4, IW-2	1.48–1.6	10439	9880 ± 30	11,390–11,220	11,270 ± 42	–24.05
Ch-1-22-3/15, IW-3	2.52–2.78	10440	5640 ± 20	6490–6320	6420 ± 37	–25.48
Ch-1-22-4/6, IW-4	2.7	10441	7795 ± 25	8640–8480	8570 ± 32	–19.17
Ch-1-22-4/7, IW-4	2.8	10442	8690 ± 30	9720–9540	9620 ± 53	–18.93

[a]The resulting ^{14}C ages were calibrated using the IntCal20 calibration curve (Reimer et al. 2020) and the Oxcal version 4.4.4 program (Bronk Ramsey 2021).

All 19 dates obtained for the host sediments fall into the range of 11.9 to 8.4 cal ka BP. This period corresponds to the first half of the Holocene optimum for the continental Siberia regions (Vasilchuk and Vasil'chuk 1995) and to the Greenlandian–early Northgrippian stages of the Holocene as well. The lack of gaps in the dating of the wood remains indicates that woody vegetation was present during the entire period of the terrace formation. It was marked by a direct dependence of the ^{14}C age of the organic matter vs. the sampling depth; the deeper the peat and wood remain, the older they are (Vasil'chuk et al. 2018).

Isotope Composition of Previously Studied Ice Wedges and Palaeotemperature Reconstructions

A series of ice wedges were previously studied by the authors (1985, 1988, 2006, 2007) and sampled for stable oxygen isotope analysis (IW-1_{prev} to IW-6_{prev}., Table 4). The sampling of the ice wedge was carried out according to a unified methodology. All earlier obtained $\delta^{18}O$ values are very close to the newly obtained, and for the majority of ice wedges, $\delta^{18}O$ values vary in a range between –19.34 and –25.7‰, while mean $\delta^{18}O$ values range from –21.4 to –25.1‰ (see Table 4).

The obtained results allow us to consider active and widespread syngenetic permafrost aggradation in the Northern Transbaikalia in the Holocene, including the optimum period, which is supported by data obtained for both neighboring and distant regions. For example, ice wedges in the Holocene deposits were studied by Popp et al. (2006) in the coastal outcrop of the upper Tumara River, central Yakutia and by Vasil'chuk et al. (2023) in northwestern Siberia.

In the Tumara River valley, the ice wedge dissected a thick layer of peat and penetrated the underlying alluvial sand and gravel deposits. Organic remains from the underlying sandy deposits at a depth of about 2.5 m were dated to 8539 ± 44 BP (KIA–19144) (9560–9460 cal BP, median age 9520 ± 30 cal BP), which indicates that the studied ice wedge was formed in the first half of the Holocene optimum, synchronously with the ice wedges in the Chara River valley. Stable isotope data for the ice wedge in the Tumara River valley (mean $\delta^{18}O$ value is –25.94‰) is close to the mean $\delta^{18}O$ values obtained for the ice wedges in the Chara River valley and therefore points to similar winter temperature conditions. These data also indicate that both in Central Yakutia and Northern Transbaikalia, ice wedges actively grew during the Holocene optimum, even in sandy gravel deposits, due to rather severe winters. A ^{14}C age of 7.46 cal ka BP was identified in the peat above the ice wedge near Seyakha village on the eastern coast of

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Table 3 Radiocarbon ages from the organic plant material in the terrace sediments enclosing the ice wedges (Vasil'chuk et al. 2018).

Depth (m)	Dated material	Lab ID	Uncal. ^{14}C age (yr BP)	Cal. age (cal BP)[a]	
				Age interval 95.4% (2σ)	Median age (1σ)
Sampled in 1985					
1.5	Wood	GIN-5706	7840 ± 60	8980–8450	8630 ± 120
1.5	Peat	GIN-5709	7570 ± 250	9020–7870	8400 ± 290
4.7	Peat	GIN-5707	9150 ± 80	10,560–10,180	10,340 ± 90
4.7	Wood	GIN-5708	9740 ± 60	11,270–10,800	11,170 ± 110
Sampled in 1988					
4.65–5.0	Plant fragments	Tln-1284	9450 ± 70	11,080–10,500	10,700 ± 150
2.2	Plant fragments	Tln-1283	8875 ± 65	10,190–9710	9990 ± 130
3.2	Plant fragments	Tln-1290	8980 ± 80	10,280–9770	10,090 ± 130
4.5	Wood	Tln-1295	9610 ± 80	11,200–10,710	10,950 ± 140
1.2–1.3	Wood	Tln-1274	8350 ± 65	9520–9130	9360 ± 90
3.2	Wood	Tln-1273	9230 ± 40	10,510–10,250	10,390 ± 70
3.4	Wood	Tln-1275	9180 ± 40	10,500–10,240	10,340 ± 70
2.15	Wood	Tln-1294	8350 ± 60	9520–9130	9360 ± 90
2.15	Peat	Tln-1309	8035±55	9090–8640	8890 ± 100
2.6	Wood	Tln-1291	8500 ± 80	9670–9290	9490 ± 80
3.5	Wood	Tln-1296	9260 ± 55	10,580–10,250	10,430 ± 90
3.5	Peat	Tln-1312	9320 ± 75	10,710–10,260	10,520 ± 120
2.0	Wood	Tln-1301	8040 ± 100	9260–8600	8900 ± 160
3.7	Wood	Tln-1297	9540 ± 190	11,280–10,250	10,860 ± 260
1.65	Wood	Tln-1292	10,230 ± 95	12,480–11,400	11,950 ± 240

[a]The resulting ^{14}C ages were calibrated using the IntCal20 calibration curve (Reimer et al. 2020) and the Oxcal version 4.4.4 program (Bronk Ramsey 2021).

Table 4 The $\delta^{18}O$ values in previously studied ice wedges ($_{prev}$) near the Chara settlement (from Vasil'chuk et al. 2018)

$\delta^{18}O$ (‰)			$\delta^{18}O$ (‰)		
Min.	Mean	Max.	Min.	Mean	Max.
IW-1_{prev}				IW-4_{prev}	
−24.07	−23.5	−21.9	−23.53	−21.4	−19.34
IW-2_{prev}				IW-5_{prev}	
−25.3	−23.0	−19.8	–23.71	−23.38	–23.06
IW-3_{prev}				IW-6_{prev}	
−25.7	−25.1	−24.6	−23.9	−22.7	−21.7

the Yamal Peninsula, and a 10.49 cal ka BP age has been identified near the ice wedge's "tail". Here, ice wedges were formed following the late Greenlandian to early Northgrippian stages of the Holocene (Vasil'chuk et al. 2023).

Equation (1) was used to determine the mean air temperature in January during the growth of IWs based on the $\delta^{18}O$ values. In the sampled IWs, the mean d_{exc} values range from 4.3 to 6.6, while the slope of the δ^2H-$\delta^{18}O$ ratio line varies from 6 to 8.5. These results suggest that fractionation occurring prior to melting and filling frost cracks may modify the isotopic composition of snow to some extent. Higher d_{exc} values were found in the research region with new snow (Vasil'chuk et al. 2018). Modern ice veinlets sampled in the Chara River terrace exposure yielded $\delta^{18}O$ values ranging from –20.7‰ to –22.4‰. Equation (1) shows that these values are in good agreement with the region's current mean January air temperature (from –31.5 to –34°C) in the study area.

Therefore, the obtained new $\delta^{18}O$ data can be used for approximate paleotemperature reconstructions with a mandatory error of ±3°C.

The obtained isotope data indicates that during the Greenlandian-Northgrippian stages of the Holocene, from 11.27 to 6.42 cal ka BP, the mean January air temperature in the Chara region ranged from –28 to –30°C during the warmer periods, but it was mostly close to –33, –35°C, which is about 1°C lower than the modern one. In the coldest periods, the mean January air temperature dropped to –38°C (i.e., it was 4–6°C lower than the modern one recorded since the 1930s).

If consider the dynamics of the temperature regime on the example of the largest IW-4_{prev}, then we can conclude that frost cracking and the growth of IW-4_{prev} started at the water level. The formation of ice in the "tail" of IW-4_{prev} occurred in more severe climatic conditions (based on the $\delta^{18}O$ values of –22.2 and –23.5‰) at the mean January air temperature about –35°C. Than the ice wedge slowly grew syngenetically, in milder climatic conditions ($\delta^{18}O$ = –20 . . . –20.7‰) at the mean January air temperature of about –31°C. It can be concluded that winter temperature conditions during IW-4_{prev} growth were close to the modern one, but in some periods mean January air temperatures were lower by 1–2°C.

CONCLUSIONS

The syngenetic ice wedge geochronology in the Transbaikalia valley of the Chara River can be estimated due to the newly obtained radiocarbon data. With the application of direct AMS ^{14}C dating of organic microinclusions from the ice wedges, it is possible to estimate the January air

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paleotemperature for the selected time intervals with an accuracy of ±3°C. Previous ^{14}C dates on the enclosing sediments only roughly allowed to propose the syngenetic growth of ice wedges.

1. Between 11.27 and 6.42 cal ka BP, or during the Greenlandian and Northgrippian stages of the Holocene, ice wedges in the Chara River valley formed syngenetically.
2. The mean $\delta^{18}O$ values in ice wedges vary by more than 8‰, ranging from –25.5‰ to –18.8‰; nevertheless, they generally vary between –25 and –22‰.
3. The mean $\delta^{18}O$ value for the ice dated to the early Greenlandian stage, 11.3 cal ka BP, is −24.0‰, which allows us to reconstruct the average air temperature during this period in January at −36°C.
4. The mean $\delta^{18}O$ values for the ice, which is dated to the early Northgrippian stage (9.6 to 8.6 cal ka BP), are −19.1‰ and −18.9‰. This suggests that the average air temperature in January was −28.5°C and −28°C.
5. The wedge ice that dates to the termination of the Northgrippian stage (6.6−6.4 cal ka BP) displays mean $\delta^{18}O$ values of −25.5‰ and −23.6‰, indicating a mean air temperature in January during this time between −38°C and −35°C.
6. It was previously implied that winter temperatures at the Holocene thermal maximum were severe than they are currently. According to new results, the early Holocene can be divided into three periods when severe climate conditions (in terms of mean January air temperature) were alternated by milder ones.

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DATA AVAILABILITY STATEMENT

Original data are available at: Vasil'chuk YK., Vasil'chuk AC, Stanilovskaya JV. (2020): Early Holocene climate signals from stable isotope composition of ice wedges in the Chara Basin, northern Transbaikalia, Russia. PANGAEA, https://doi.org/10.1594/PANGAEA.915943

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

DECLARATION OF COMPETING INTERESTS

The authors state that they have no competing interest.

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