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RESEARCH ARTICLE

Chronologies of active growth of ice wedges and Middle Holocene palaeoclimate at Lorino site, Chukchi Peninsula, easternmost Siberia

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Abstract
AMS radiocarbon ages of organic matter from ice wedges and enclosing peat were determined for the polygonal peatland at the Lorino site on the eastern coast of the Chukchi Peninsula. The study's goal was to fill a knowledge gap about the dynamics of polygonal peatlands with ice wedges and winter climate conditions during the Holocene in this easternmost region of the Russian Arctic. It has been found that peatland accumulated during the Younger Dryas and early Holocene, mostly between 14 and 9.9 cal ka BP, while ice wedges were dated from 7.7 to 6.6 cal ka BP. Since ice wedges have features of syngenetic growth, the discrepancy in the age of ice wedges and enclosing peatland may result from the significant presence of early and pre-Holocene peat. It is assumed that the older polygonal peatland deeply thawed during the Holocene optimum, and subsequently, when the permafrost aggraded, a new generation of ice wedges was formed. The AMS ^{14}C age (18.1 cal ka BP) of the ice wedge exposed below the peat indicates the presence of a Late Pleistocene generation of ice wedges at the study site. Paleotemperature reconstructions based on the stable isotope composition of ice wedges show that the mean January air temperature during the Northgrippian stage of the Holocene varied from –27 to –23°C, and at the end of the Late Pleistocene, from –32 to –26°C.

Introduction

Climate dynamics in the Arctic during the Holocene varies significantly for different regions, especially in the inland and coastal regions. The chronology of Holocene climate events and information on winter and January air temperatures in the Holocene are still insufficient for the easternmost region of the Russian Arctic, the Chukchi Peninsula, as this region is remote and only a few exposures with ice wedges have been studied so far. At present, the age of Holocene ice wedges based on the radiocarbon dating of enclosing sediments is established only for some locations of the Chukchi Peninsula (Anadyr, Lavrentia, and Uelen settlements on the coast and Lake Elgygytgyn in the continental part), as well as on the nearby Ayon and Wrangel Islands (Schwamborn et al. 2006; Vasil'chuk et al. 2018). The direct age (based on the AMS dating of microorganic inclusions from ice) has been determined only for a few Holocene ice wedges near the Anadyr site (Budantseva and Vasil'chuk 2019*)*.

The present study focuses on syngenetic ice wedges exposed in the peatland near the Lorino site on the eastern coast of the Chukchi Peninsula, which have been studied in detail by the authors over the past 10 years. The study's goal was to find out when peatlands formed and ice wedges grew. We accomplished this by applying radiocarbon dating to peat and organic micro-inclusions extracted directly from ice wedges, analyzing oxygen isotope ratios in ice wedge samples to determine their age, and estimating the mean January air temperature at that time.

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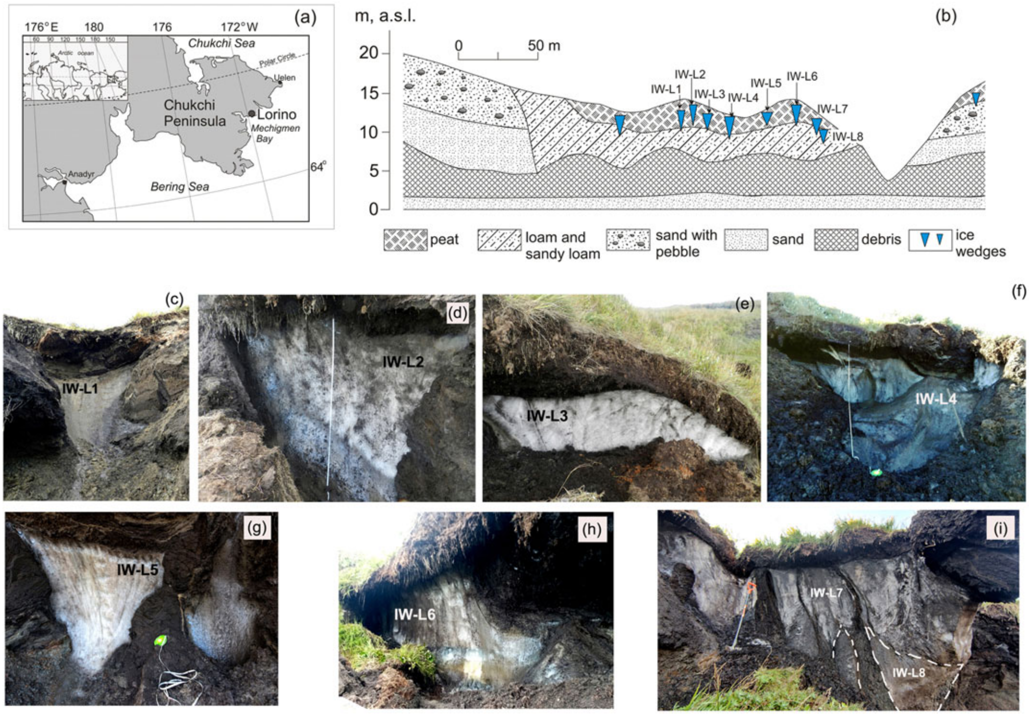

Figure 1. *Location of the Lorino site, eastern coast of Chukchi Peninsula (a), exposure of the third marine terrace at the study site (b) and studied ice wedges: IW-L1 (c), IW-L2 (d), IW-L3 (e), IW-L4 (f), IW-L5 (g), IW-L6 (h), and IW-L7–IW-L8 (i).*

Materials and methods

Study area

The study area is located on the coast of the Mechigmen Bay of the Bering Sea (65°30′00″ N, 171° 43′00″ W), 2 km from the Lorino settlement (Figure 1a). The peatland on the surface of the third marine terrace revealed a series of exposed ice wedges. The eastern coastal areas of the Chukchi Peninsula have a subarctic maritime climate. According to the nearest weather station in Uelen, the average annual air temperature varies from −6 to −4°C (data for the period 1929–2022). The coldest month of the year is January, with a mean January air temperature (T_{mJ}) of about −19.3°C, though recorded variations in T_{mJ} are more than 20ºC, from –29.2 to –6.5ºC (World Data Center 2024). The study area is characterized by continuous permafrost with a thickness of about 500−700 m in the uplands and about 200–300 m in the inland valleys. The mean annual ground temperature varies from −10 to −4°C (Gasanov 1969; Kolesnikov and Plakht 1989; World Data Center 2024).

Polygonal networks and ice wedges are common in river valleys and coastal areas. Recent ice veinlets entering the older Holocene ice wedges from the top indicate modern ice wedge growth.

Field studies and sampling

We conducted field studies in 2015–2017 and 2021–2022. Thermal erosion exposed a new outcrop with ice wedges during each field season. We studied eight ice wedges (IW-L1–IW-L8) in detail. We sampled the ice along both vertical and horizontal profiles using an axe. Before sampling, we cleaned the ice wedge wall of mineral and organic impurities as much as possible to avoid contamination by modern material from above. We packed the ice samples in a double polyethylene bag, melted them at

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room temperature, and then poured them into 30 mL plastic bottles sealed with Parafilm to prevent evaporation. Five ice wedge samples were AMS ^{14}C dated. Peat enclosing the ice wedges was also sampled for radiocarbon dating; in total, 11 samples of peat were conventional ^{14}C dated.

Radiocarbon dating

The Laboratory of Radiocarbon Dating and Electron Microscopy of the Geography Institute of the Russian Academy of Sciences (lab code $IGAN_{AMS}$-) and the Center for Applied Isotope Studies, University of Georgia (USA), conducted radiocarbon dating of microinclusions of organic material directly extracted from ice wedges. Radiocarbon dating of enclosing peat was carried out using a conventional method in the Institute for the History of Material Culture (lab. code Le-) and in the radiocarbon dating laboratory of the Geography Institute, Russian Academy of Sciences (lab code IGAN-). We calibrated all obtained radiocarbon dates using Oxal 4.4, based on the IntCal20 data set, and presented them as years cal BP (Bronk Ramsey 2021; Reimer et al. 2020).

Stable oxygen isotope analyses

The oxygen isotope composition ($\delta^{18}O$) of ice wedges sampled in 2015–2017 and 2021 was analyzed in the stable isotope laboratory of the Geography Faculty at Lomonosov Moscow State University (Prof. Yu. Vasil'chuk and Dr. N. Budantseva). International water standards (SMOW, GISP, GRESP, and SLAP) were used for calibration. Analytical precision was ±0.4‰. Oxygen isotope compositions of ice wedges sampled in 2022 were carried out at the Resource Center X-ray Diffraction Research Methods of the Science Park of St. Petersburg State University (Dr. I. Tokarev). International reference materials (V-SMOW-2, GISP, SLAP, USGS-45, and USGS-46) were used for the calibration. Analytical precision was ±0.02‰.

January paleotemperature reconstructions

The calculation of the mean January Holocene air paleotemperature was carried out by comparing the isotope composition of modern ice veinlets ($\delta^{18}O_{iv}$) and the mean January air temperature for the period of ice veinlet growth, i.e., for the last 60–100 years (Vasil'chuk 1992). As a result, the equation was obtained:

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

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 often 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. The slope of the δ^2H–$\delta^{18}O$ ratio line for the global meteoric water line (GMWL) is equal to 8. d_{exc} is calculated as $d_{exc} = \delta^2H - 8\delta^{18}O$ according to Dansgaard (1964). For the wedge ice, the slope of the δ^2H–$\delta^{18}O$ ratio line, as well as d_{exc} values are indicators of the meteoric nature of water (usually snowmelt) forming ice wedges and the impact of kinetic fractionation on the isotope composition of snow and snowmelt before filling frost cracks.

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Results and discussion

Cryostratigraphy

Ice wedges are located in the peatland, covering the remnants of the third marine terrace with a height of 22–25 m (Figure 1b). Fine to coarse sands with lenses, layers of gray loam, and sandy loam with pebble inclusions underlie the 2 to 5 m-thick peat. The peat also showed traces of gray loam lenses. Ice wedges are located at depths ranging from 0.4 m (directly under the active layer) to 0.7–0.8 m. The width of the ice wedges varied from 1 to 1.5 m, sometimes up to 3.5 m (in cases of non-frontal exposure, for example, IW-L7, see Figure 1i); the exposed height of the ice wedges varied from 1.5 to 3 m.

Soil inclusions occasionally trace the vertically foliated wedge ice. We noted the upward bending of the enclosing sediments in the frontal exposures of the ice wedges, indicating the syngenetic growth of the wedge. The tiered structure of the ice wedge adjacent to IW-L5 (see Figure 1g) is a sign of syngenetic growth. Modern ice veinlets up to 10 cm in width and up to 50 cm in height were found above the Holocene ice wedges. Fragments of the pre-Holocene generation of ice wedges were uncovered under the peat.

AMS radiocarbon age of ice wedges and enclosing sediments

We analyzed the radiocarbon ages of ice wedges IW-L6, IW-L7, and IW-L8 using direct AMS ^{14}C dating of organic microinclusions extracted from ice (Table 1, Figure 2). Ice wedge IW-L6 was dated to 7.64 cal ka BP at a depth of 0.6 m, 7.24 cal ka BP at a depth of 0.9 m, and 7.66 cal ka BP at a depth of 1.1 m. Ice wedge IW-L7 was dated to 6.56 cal ka BP at a depth of 0.3 m. Ice wedge IW-L8 exposed under the peatland was dated to 18.1 cal ka BP at a depth of 2.5 m.

Radiocarbon dates of the peat were obtained from five exposures at depths ranging from 0.4 to 2.5 m (see Figure 2). All dates for the peat fall in the range of 14.2 to 9.9 cal ka BP (see Table 1).

^{14}C age of peatlands of the eastern coast of Chukchi Peninsula

The dates obtained for the Lorino peatland indicate the beginning of peat accumulation at the study site at the end of the Younger Dryas (Allerød); the oldest ^{14}C dates are more than 13 cal ka BP. The reworking of ancient organic material due to sediment erosion on the third marine terrace may explain the inversions of the dates. Early Holocene accumulation of peatlands was also established for the other peatlands of the eastern coastal areas of Chukchi Peninsula: at the Uelen site, the ^{14}C dates around 13–12 cal ka BP were obtained (Budantseva et al. 2020), and near Anadyr town, the ^{14}C dates around 11 cal ka BP were obtained (Budantseva and Vasil'chuk 2019).

In regions with a marine climate, the sharp summer warming of the Bølling–Allerød period may have initiated peatland accumulation earlier than 12–11 ka BP, whereas the cooling of Younger Dryas (established approximately 13–12.6 cal ka BP) primarily occurred during winter seasons. During this period, wetlands expanded and peat accumulated in the coastal areas and on the islands of the Far East, and pollen data revealed the appearance of tree species (Lozhkin et al. 2011; Makeev et al. 1989; Mikishin et al. 2010). According to Mann and Gaglioti (2024), the climate along the Northwest Coast of North America and in the subarctic Pacific Ocean during Marine Isotope Stage 2 was largely determined by the sea surface temperature. During the Younger Dryas, ca. 12.8–11.7 ka BP, mean annual sea surface temperatures were 4–6ºC cooler than today in the Gulf of Alaska, and sea ice again expanded across the subarctic Pacific in winter. Extreme seasonal conditions are characterized by cold, dry winters and warm, steadily ameliorating summers caused by the southward diversion of the Aleutian Low (Mann and Gaglioti 2024).

For the peatland near Lorino, we also found that the ice wedges are noticeably younger than the enclosing peat: 7.7 to 6.6 cal ka BP for the ice wedges vs. 14.2 to 9.9 cal ka BP for the peat. Since ice

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Table 1. AMS radiocarbon ages of ice wedges and conventional ^{14}C ages of the enclosing peat, Lorino site, Eastern Chukchi Peninsula.

Ice wedge	Depth, m	Lab. ID	Uncal. ^{14}C age [BP]	Cal. age [cal BP][a] Age interval (2σ), probability 95.4%	Median age (1σ)
AMS radiocarbon ages of ice wedges					
IW-L6	0.6	$IGAN_{AMS}$-10433	6810±25	7683-7590	7640±24
	0.9	$IGAN_{AMS}$-10680	6320±40	7322-7162	7240±53
	1.1	$IGAN_{AMS}$-10431	6830±25	7708-7591	7660±28
IW-L7	0.3	$IGAN_{AMS}$-10683	5760±30	6656-6458	6560±48
IW-L8	2.5	$IGAN_{AMS}$-10678	14725±45	18207-17888	18100±86
Conventional radiocarbon ages of peat enclosing studied IWs					
IW-L1	1.2	Le-11262	11230±100	13316-12911	13140±101
IW-L2	0.9	Le-11260	9550±170	11265-10308	10880±237
	1.5	Le-11259	8800±80	10155-9556	9850±162
IW-L4	1.3	Le-11730	9860±140	10791-11820	11340±244
IW-L5	1.6	Le-11722	12180±180	14949-13614	14190±340
	2.5	Le-11723	11530±200	13985-13072	13410±198
IW-L7	0.4	IGAN-9662	11410±100	13468-13116	13290±93
	1.0	IGAN-9661	9870±100	11743-11102	11330±168
	1.5	IGAN-9660	10320±100	12600-11757	12150±216
	2.1	IGAN-9659	11450±100	13501-13124	13330±96
	2.5	IGAN-9663	11250±100	13329-12923	13160±97

[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).

wedges have features of syngenetic growth (large vertical dimension, upward bending of the enclosing sediments in the frontal exposures of the ice wedges, tiered structure of some exposed ice wedges), the obtained discrepancy in the age of ice wedges and enclosing peatland may result from the significant presence of early and pre-Holocene peat. It is assumed that the older polygonal peatland deeply thawed during the Holocene optimum, and subsequently, when the permafrost aggraded, a new generation of ice wedges was formed. However, the previously formed ice wedges under the peat thawed only partially. The 18.1 cal ka BP date for IW-L8 under the peatland indicates that it is a fragment of a buried and well-preserved Late Pleistocene ice wedge. Flooding and erosion during peatland thawing may explain age inversions. Significant age-unconformity between ice wedges and underlying sediments (more than 24 ka) found in the Barrow Permafrost Tunnel (Iwahana et al. 2024) was interpreted as the result of potential erosional events that removed surface materials before the overlaying sediment layer with ice bodies developed.

Oxygen isotope composition of ice wedges and paleotemperature reconstructions

For ice wedge IW-L1 $\delta^{18}O$ values ranging from –18 to –15.9‰, the mean value is –16.7‰ (Table 2). For the IW-L2, $\delta^{18}O$ values vary from –16.6 to –14‰, the mean value is –15.5‰. $\delta^{18}O$ values from –17 to –16.2‰, with a mean value of –16.4‰ were obtained for the IW-L3. The IW-L4 $\delta^{18}O$ values ranged from –18 to –14.2‰; the average value is –16.7‰, while higher $\delta^{18}O$ values were obtained from a narrower ice vein (possibly of Late Holocene generation) penetrating from above into a wider ice wedge, possibly of Late Holocene age. The IW-L5 $\delta^{18}O$ values ranged from –18.4 to –16.2‰, the mean value is –17.2‰.

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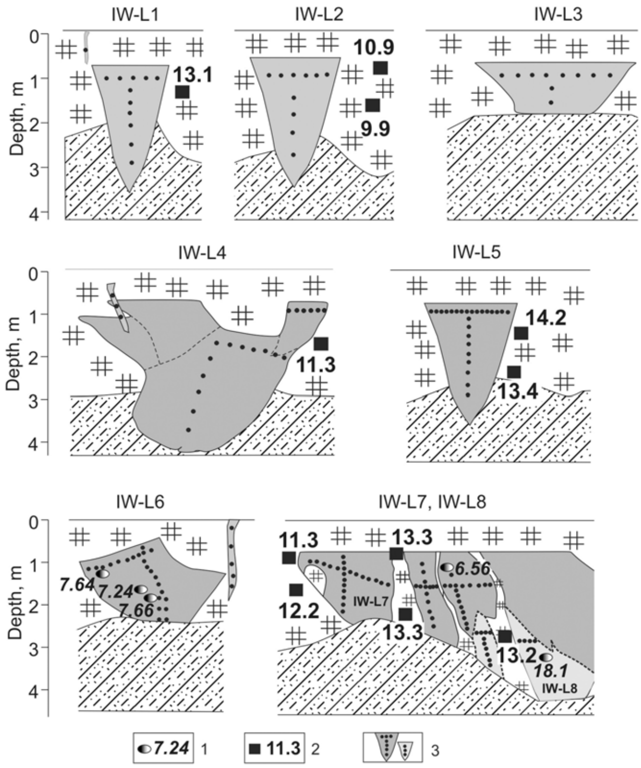

Figure 2. *Radiocarbon ages (cal years BP) of ice wedges (1) and enclosing peat (2), and sampling of ice for stable isotope analysis (3).*

The IW-L6 $\delta^{18}O$ values ranged from –18 to –15.8‰, the mean value is –16.8‰. The largest set of isotope data was obtained for the IW-L7 (62 samples); $\delta^{18}O$ values ranged from –17.9 to –15.1, the mean value is –16.8‰. The lowest $\delta^{18}O$ values were obtained for the IW-L8 from –21 to –18.1‰; the mean value is –19.5‰, which may also indicate its Late Pleistocene age. Earlier, close $\delta^{18}O$ values from –22.8 to –18.6‰ were obtained for the Late Pleistocene ice wedge on the eastern coast near the Anadyr site (Vasil'chuk 1992). Thus, in more than 80% of ice wedge samples, $\delta^{18}O$ values vary from –18 to –15‰, except for younger ice veins (with higher values) and pre-Holocene ice wedges (with lower values up to –21‰). In modern ice veinlets, $\delta^{18}O$ values are generally higher and range from –16.8 to –12.9‰ (see Table 2).

Previously, for some ice wedges (IW-L4, IW-L5 and IW-L7) we obtained coupled $\delta^{18}O$ and δ^2H values (Budantseva et al. 2023). For ice wedges IW-L4 and IW-L7 the slopes of δ^2H-$\delta^{18}O$ ratio lines were 8 and 7.3, respectively, which is close to the slope of GMWL and may indicate an insignificant influence of isotope fractionation on the original isotope signature of winter precipitation (thawed snow) during the growth of the ice wedges. For ice wedge IW-L5 the slope of δ^2H-$\delta^{18}O$ ratio line was 6.1, which may be explained by either an admixture of surface water or sublimation of snow before melting (Budantseva et al. 2023). Taking into account these data, we suppose that the obtained $\delta^{18}O$ values can be applied to an approximate paleotemperature assessment.

For the study region ratio (1) is correct as it was proved by comparison of $\delta^{18}O$ values in modern ice veinlets (from –16.8 to –12.9‰) and T_{mJ} recorded at the weather station in Uelen (mean value of T_{mJ} is –19.3°C, with variations from to –29.2 to –6.5°C).

The calculation according to equation (1) gives T_{mJ} values from –25.2 to –19.4°C, which is close to the real recorded values and also indicates that frost cracking and ice wedge growth occur mainly during the colder winters. Considering that the majority of obtained $\delta^{18}O$ values for the studied Holocene ice

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Table 2. *$\delta^{18}O$ values (minimum, mean, and maximum) in Holocene and modern ice wedges at the Lorino site, Eastern Chukchi Peninsula*

		$\delta^{18}O$, ‰		
Ice wedge ID	Amount of samples	Min	Mean	Max
IW-L1	10	–18.0	–16.7	–15.9
IW-L2	10	–16.6	–15.5	–14.0
IW-L3	10	–17.0	–16.4	–16.2
IW-L4	17	–18	–16.7	–14.2
IW-L5	25	–18.4	–17.2	–16.2
IW-L6	19	–18	–16.8	–15.8
IW-L7	62	–17.9	–16.8	–15.1
IW-L8	17	–21	–19.5	–18.1
Modern ice veinlets (located above the studied Holocene ice wedges)				
IW-L1	1	–	–16.8	–
IW-L4	3	–13.2	–13.1	–12.9
IW-L6	5	–15.6	–14.9	–14.4

wedges are in the range of –18 to –15‰, the calculation according to equation (1) showed that 7.7–6.6 cal ka BP (Northgrippian stage of the Holocene) T_{mJ} at Lorino site varied from –27 to –23°C. The older pre-Holocene ice wedges were formed in more severe winter climate conditions, when T_{mJ} varied from –31.5 to –25.5°C.

More severe winter climatic conditions on the eastern coast of the Chukchi Peninsula in the middle of the Holocene and at the end of the Late Pleistocene may have been determined by greater distance from the ocean (due to sea regression and shelf drainage). This may also be indicated by higher d_{exc} values in the Holocene and Late Pleistocene ice wedges (mean d_{exc} values from 8.7 to 11.1 ‰), compared with modern ice veinlets (mean d_{exc} values 4–6 ‰) and snow (mean d_{exc} values 5.2–6.3 ‰) (Budantseva et al. 2023). For comparison, modern ice veinlets and late Holocene ice wedges studied near the El'gygytgyn Impact Crater (located at least 150 km inland from the coast) are characterized by higher mean d_{exc} values, ranging from 8.2 to 9.1 ‰ (Schwamborn et al. 2006).

Conclusions

At the Lorino site on the eastern coast of the Chukchi Peninsula, pre-Holocene (more than 12 cal ka BP) and early Holocene onsets of peatland accumulation were recorded. All obtained ^{14}C dates for the peat fall in the range of 14.2 to 9.9 cal ka BP. Ice wedge formation in the peatland occurred during the Northgrippian period of the Holocene, about 7.7 to 6.6 cal ka BP. Early Holocene deep thawing and mixing of the previously existing polygonal peatland may explain the older age of the enclosing peat (compared with the ice wedges) and age inversions. After ~8 cal ka BP, permafrost aggraded, and a new generation of ice wedges was formed.

Most of the obtained $\delta^{18}O$ values for the studied Holocene ice wedges are in the range of –18 to –15‰, in modern ice veinlets, $\delta^{18}O$ values are generally higher and range from –16.8 to –12.9‰. The lowest $\delta^{18}O$ values from –21 to –18.1‰ were obtained for the fragment of Late Pleistocene ice wedge under the peatland.

The correlation of the isotope-oxygen composition of modern ice veinlets with the mean January air temperature has been confirmed. The assessment of the paleotemperature signal based on the $\delta^{18}O$ values in ice wedges studied at the Lorino site suggests that the approximate mean January air temperature during the Northgrippian stage of the Holocene varied from –27 to –23°C, and at the end of the Late Pleistocene it varied from –32 to –26°C.

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Competing of interests. The authors state that they have no conflicts of interest.

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