Radiocarbon, Vol 64, Nr 6, 2022, p 1419–1429 DOI:10.1017/RDC.2022.15
Selected Papers from the 3rd Radiocarbon in the Environment Conference, Gliwice, Poland, 5–9 July 2021

AMS ^{14}C DATING OF SEYAKHA YEDOMA AND JANUARY AIR PALAEOTEMPERATURES FOR 25–21 CAL KA BP BASED ON THE STABLE ISOTOPE COMPOSITIONS OF SYNGENETIC ICE WEDGES

Yurij Vasil'chuk* • Alla Vasil'chuk • Nadine Budantseva

Department of Geography, Lomonosov Moscow State University, 119991, Moscow, Russia

ABSTRACT. Yedoma sediments with thick syngenetic ice wedges have been studied on the Yamal Peninsula, northwestern Siberia. The accumulation of yedoma strata occurred under alternating subaqueous-subaerial conditions, and three tiers of ice wedge were formed mainly on subaerial stages. The ice wedges and enclosing sediments were dated, revealing that the ice wedges were formed between 29 and 18 cal ka BP, while the enclosing sediments are generally older, possibly due to contamination with ancient material (especially in the central part of the yedoma). However, the termination of yedoma complex formation was dated not later than 13.5 cal ka BP. Stable oxygen-isotope data for the ice wedges indicate more severe winter climate conditions during 25–21 cal ka BP, when mean January air temperatures were at least 10°C lower that modern ones, favoring syngenetic ice wedge growth. Yedoma accumulation in the western part of northern Siberia does not support the existence here of an ice sheet during the LGM.

KEYWORDS: mean January palaeotemperature, northwestern Siberia, radiocarbon age, yedoma, ice wedges.

INTRODUCTION

Yedoma sediments are a particular kind of Quaternary deposit in permafrost terrain that are widespread in central and northeastern Siberia and the High Arctic, but only a few of them have been found and described in northwestern Siberia. Yedoma exposure in the Seyakha River mouth east of the Yamal Peninsula is the first to have been studied in detail. Yedoma is ice-saturated sediment (containing 50–90 vol. % of ice) which is, as a rule, rich in organic material (>1–2% of C_{org}); yedoma consists of clayey and silty loams, loamy sands, or fine sands dated to the Late Pleistocene. Yedoma sediments contain thick (1–3.5-m wide and 15–20-m thick or more) syngenetic ice wedges that are often multitiered (Vasil'chuk and Vasil'chuk 2020).

The discovery of Seyakha yedoma strata with syngenetic ice wedges and their dating (Vasil'chuk and Trofimov 1984) resulted in a significant refinement of the Eurasian ice sheet boundary on the Yamal Peninsula during the Late Glacial Maximum (LGM). According to earlier studies, the Barents-Kara Sea Ice Sheet covered a large part of northern Siberia, including the Yamal Peninsula (Forsstrom and Greve 2004). Later, in publications of Svendsen et al. (2004, 2014) and Hughes et al. (2016), it was proposed that the ice sheet did not reach the northern rim of the mainland of most part of Western Siberia and European sector of Northern Russia during the LGM (20–25 ka BP) and its boundary was located in the Kara Sea, to the west of the Yamal Peninsula. The position of the last Eurasian ice sheet was determined on the basis of a chronological series of more than 5000 age determination of Late Quaternary sediments in more than 2500 locations. These dates indicate the terrace formation, vegetation growth, and other events that could not occur in ice sheet conditions. Accumulation of yedoma strata in northwestern of Siberia is important evidence of non-glacial but severe geocryological conditions during the LGM.

*Corresponding author. Email: vasilch_geo@mail.ru

https://doi.org/10.1017/RDC.2022.15 Published online by Cambridge University Press

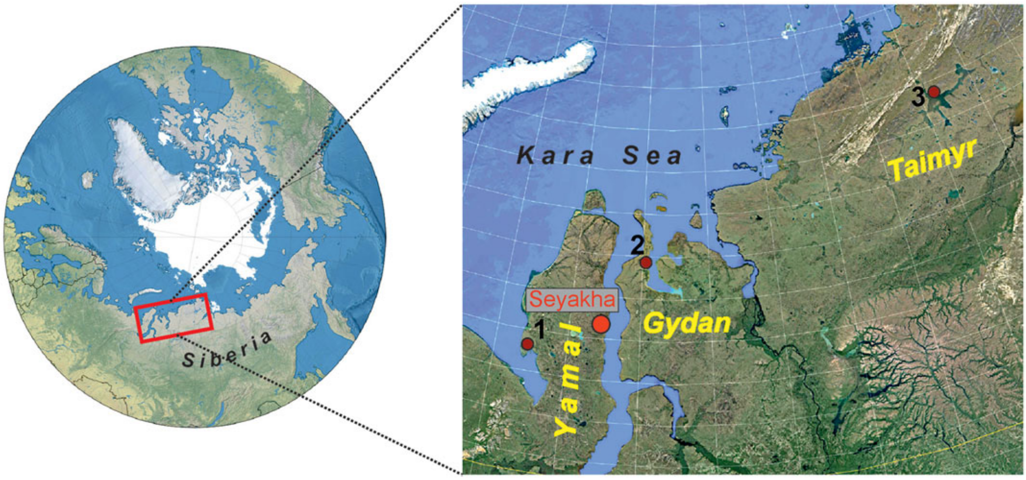

Figure 1 Location of Seyakha yedoma and nearest yedoma exposures at the western part of northern Siberia: Marresale (1), Ery-Maretayakha (2), and Sabler Cape (3).

Connecting the stable isotope records on ice wedges to a timescale based on ^{14}C dating of ice wedge was a basis for reconstruction of mean January air temperatures. Detailed isotope diagrams with a mean temporal resolution of less than 100 years were obtained for some ice wedges of Seyakha yedoma (Vasil'chuk et al. 2019) that allowed us to estimate winter climate conditions for the eastern Yamal Peninsula during the LGM.

MATERIAL AND METHODS

Study Area

Yedoma exposures in northwestern Siberia, on the eastern coast of the Yamal Peninsula at the Seyakha River mouth (70.157364°N, 72.569100°E, Figure 1) were studied in detail.

The cryostratigrapy of the central part (Figure 2A) of the exposure can be divided into three units. The lowest 11-m unit is characterized by 3-m-wide ice wedges consisting of pure ice. The enclosing sediments accumulated under alternating subaqueous-subaerial conditions, which is indicated by lamination of sediments and admixture of organic material such as rootlets, stems, and leaves (subaerial layers) or sandy loam (subaqueous layers). In the middle unit (8–9 m thick) narrower (up to 1–1.5 m wide) ice wedges with vertical layers of mineral inclusions are found. These wedges pierce the ice wedges of the lower stage. Surrounding sediments are clearly laminated but are almost lacking in organics. These sediments are capped by 2–3 m of laminated yellow sand (subaqueous conditions) from where a third generation of ice wedges pierces the underlying unit. It is assumed that this unit accumulated during a period of high Ob' Bay level, which is also proved by the presence of well-preserved *in situ* sub-saline foraminifera: *Elphidium subclavatum Gudina, Pninaella pulchela Parker, Protelphidium parvum Gudina,* etc. (Vasil'chuk et al. 1998).

The edge of the yedoma was studied in 2016 (see Figure 2B). In the upper 5-m part of the outcrop (from +11.5 to +16.5 m asl) grayish yellow fine sand with an admixture of organic material was

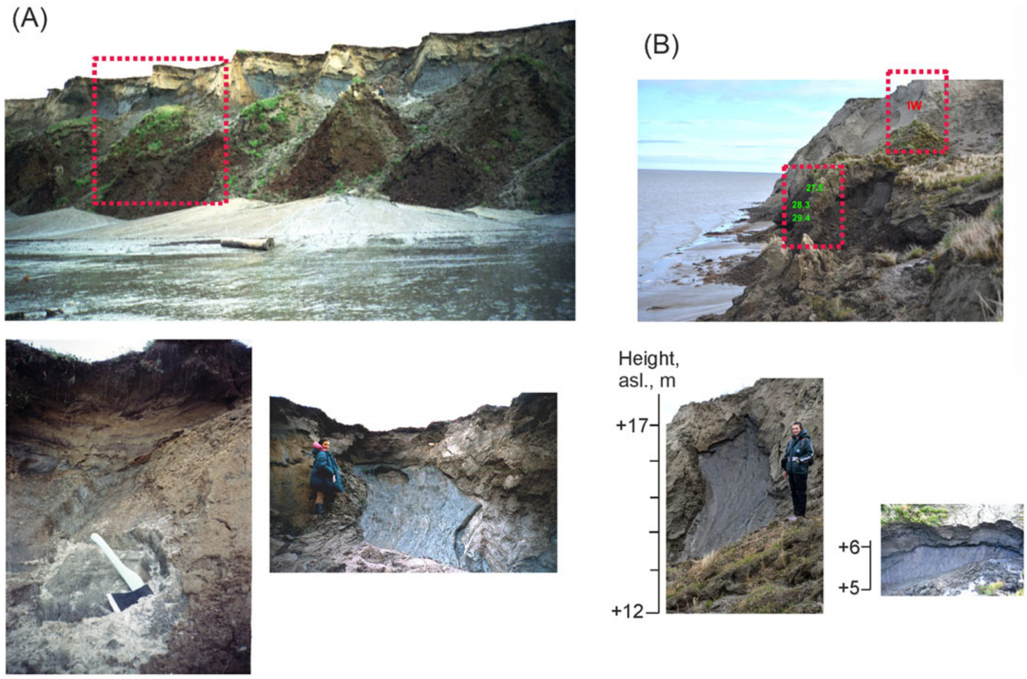

Figure 2 Seyakha yedoma exposure: central part (A) and edge part (B).

revealed. Ice wedges up to 1.0–1.5 m wide at the top were exposed. At a height of +5 to +6 m, the paragenesis of the ice wedge and a lens of segregated ice was found. In a *baidzherakh* (in permafrost areas, a remnant of frozen sediments surrounded by ground subsided along thawed ice wedges) located at heights of 0 to +7 m, stratified peat containing remains of plants, subshrubs, and hypnum mosses were identified.

Field Studies and Sampling

Field studies of Seyakha yedoma were carried out by the authors four times over the period 1978 to 2016. During the field studies of 1996 and 2016, four ice wedges were selected for sampling. Ice samples for ^{14}C dating and stable isotope analysis were cut from ice wedges using an ice axe. Since the samples were taken at temperatures above zero, a layer of ice at least 5 cm thick was removed before sampling to avoid the possible admixture of modern water. The surface of each ice sample was scraped off with clean blades to remove surface dirt and washed with meltwater from the same sample of ice. To separate the organic material, ice samples were thawed at a temperature of about 5°C and stood for at least 24 hr, and then sediment was collected in plastic vials. Samples for isotope analysis were taken from the same ice wedges both along the axial parts and horizontal profiles. Each sample of ice was packed in a double plastic zip-bag, where ice melted at a temperature slightly above 0°C. The water poured into plastic vials and sealed with parafilm to avoid evaporation. The enclosing sediments with organic material were also sampled for conventional radiocarbon (^{14}C) dating.

https://doi.org/10.1017/RDC.2022.15 Published online by Cambridge University Press

Laboratory Treatment and Radiocarbon Dating

Accelerator Mass Spectrometry (AMS) ^{14}C Dating of Ice Wedges

The first radiocarbon measurements (after field studies of 1996) were made in using a Tandetron AMS at the Center for Isotope Research at the University of Groningen (van der Plicht et al. 1995). Sediment with organic matter from ice wedges was chemically treated to extract the alkaline fraction (dissolved organic carbon—DOC) and fraction >400 µm (particulate organic carbon—POC) for each sample. These two fractions were then prepared separately for analysis: they were combusted in an automatic element analyzer Carlo Erba 1500, connected to a Micromass Optima IRMS and a gas chromatographic column to separate the isotopes close to ^{14}C, such as ^{13}C, and ^{15}N. AMS radiocarbon dating of organic matter from the ice wedge (total organic carbon—TOC) sampled in 2016 was carried out at the Laboratory of Radiocarbon Dating and Electron Microscopy of the Institute of Geography of the Russian Academy of Sciences (obtaining counting material) and the Center for Isotope Research of the University of Georgia in the USA (direct measurements on an accelerator mass spectrometer).

Conventional Dating of Sediments

Organic matter from the enclosing sediments was dated using a conventional method at the Institute for the History of Material Culture, St. Petersburg (lab code LE), Institute of Geology RAS (lab code GIN), and Helsinki University (lab code Hel); one sample of moss from a bulk sample was dated at Helsinki University and Uppsala University AMS (lab code Hela). All obtained radiocarbon dates were calibrated using OxCal 4.4 based on the IntCal20 data set and given as yrs cal BP (Bronk Ramsey 2009; Reimer et al. 2020).

Stable Isotope Analysis

Stable isotope (oxygen and hydrogen) analysis in ice-wedge ice was carried out in the Stable isotope laboratory of the Geography Faculty at Lomonosov Moscow State University using a Finnigan Delta-V Plus mass spectrometer. Analytical precision was ±0.4‰ for $\delta^{18}O$ and ±1‰ for $\delta^{2}H$. Oxygen isotope measurements of some ice wedges sampled before 2016 were carried out using a G-50 device at the isotope hydrology laboratory at the Institute of Water Problems of Russian Academy of Science (Dr. A. Esikov), at the isotope geology laboratory at the Institute of Geology, Tallinn, Estonia (Prof. R. Vaikmäe), at the Isotope Laboratory of Helsinki University (E. Sonninen and Prof. H. Jungner), and in the Hannover Isotope Laboratory (Prof. M. Geyh). All values are presented in δ-notation in per mille (‰) relative to the Vienna Standard Mean Ocean Water (VSMOW).

January Paleotemperature Reconstructions

Reconstructions of mean January temperatures ($T_{mean\ Jan.}$, °C) were carried out by comparing the isotope composition of modern ice veinlets ($\delta^{18}O_{iv}$) and mean January temperatures (t °J) for the period of ice veinlet growth, i.e., for the last 60–100 years (Vasil'chuk 1991). As a result of this comparison, the equation is obtained:

$$T_{mean\ Jan.} = 1.5\,\delta^{18}O_{iv}(\pm 3°C) \tag{1}$$

The range of ±3°C indicates the average range of variations of the reconstructed temperatures.

https://doi.org/10.1017/RDC.2022.15 Published online by Cambridge University Press

Table 1 ^{14}C dates of organic remains in ice wedges from middle and lower parts of Seyakha yedoma and enclosing sediments (edge part of yedoma exposure).

Lab ID	Height, m asl	^{14}C, yr BP (1σ)	Calibrated age, 95.4%, cal yr BP	Median age, cal yr BP	Dated material
AMS ^{14}C dates of ice wedges					
$IGAN_{AMS}$-7335	+15.2	17680 ± 50	21738–21126	21399	TOC
$IGAN_{AMS}$-7338	+12.1	21755 ± 55	26245–25859	25969	TOC
$IGAN_{AMS}$-6907	+6.0	24495 ± 80	29005–28758	28755	TOC
$IGAN_{AMS}$-6908	+6.0	25281 ± 80	29875–29241	29551	TOC
Conventional ^{14}C dates of enclosing sediments					
Le-11408	+2.0	25200 ± 420	30325–28645	29497	Peat
Le-11407	+3.0	24100 ± 300	28294–27736	28292	Peat
Le-11406	+5.0	23300 ± 640	29865–25902	27596	Peat
Le-11409	0 (Ob' Bay beach)	12950 ±100	15783–15200	15488	Peat

*Calibrated using OxCal 4.4 equipped with IntCal20 (Reimer et al. 2020).

RESULTS

Radiocarbon Dating

Four new AMS ^{14}C dates were obtained for ice wedges from the middle and lower parts of Seyakha yedoma (the edge part of the section). Ice wedges from the middle part were dated from 21 to 25 cal ka BP. Ice wedges from the lower fragment were dated from 28 to 29 cal ka BP. These are the oldest dates for ice wedges of Seyakha yedoma. Three new radiocarbon ages ranging from 27.5 to 29.4 cal ka BP were obtained for the enclosing sediments at absolute heights of +2 to +5 m (Table 1, Figure 3A). Previous ^{14}C AMS dates (Vasil'chuk et al. 1998, 2000a, 2000b) from 17.7 to 25.3 cal ka BP were obtained for three fragments of ice wedges (the central part of the section), and the enclosing sediments were dated from 13.5 cal ka BP at an absolute height of +21 m to 41 cal ka BP from sample at an absolute height of +1 m (Table 2, see Figure 3A).

Stable Isotope Composition of Ice Wedges

The new high-resolution oxygen isotope record (with a temporal resolution of 80-100 yrs) covers the entire period between 25 and 21 cal ka BP. The $\delta^{18}O$ values in the upper ice wedge vary from –25.75 to –23.15‰ (see Figure 3C). Two isotope trends were established: in the interval from +12 to +14.2 m, the $\delta^{18}O$ values vary in a range of about 1.5‰ (–24.18 to –25.75‰); in the interval from +14.2 to +15.8 m, a clear tendency toward the upward increase of $\delta^{18}O$ by 2.6‰ was noted (–25.75 to –23.15‰). For the lower section of ice wedge exposed at a height of +6 m $\delta^{18}O$ values vary from –23.41 to –26.63‰, that corresponds to the isotope range for the upper ice wedge (from –23.4 to –25.75‰). The previously-obtained oxygen isotope values for the ice wedges in the central part of the

https://doi.org/10.1017/RDC.2022.15 Published online by Cambridge University Press

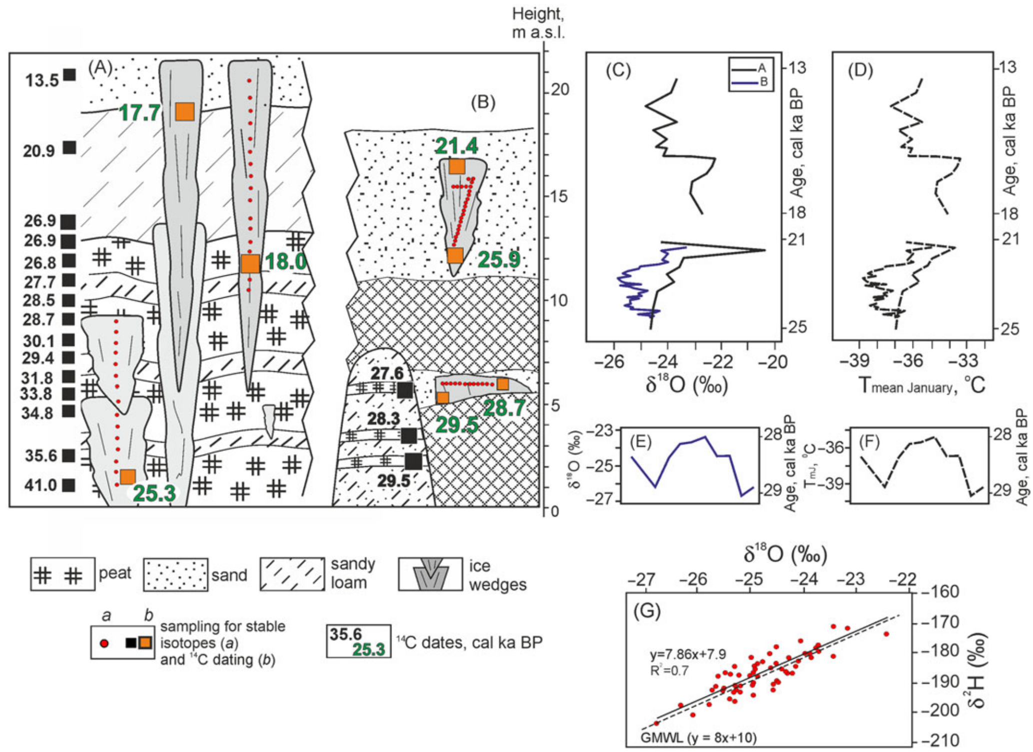

Figure 3 Cryostratigraphy and ^{14}C dates of ice wedges and enclosing sediments for the central (A) and edge (B) parts of Seyakha yedoma, $\delta^{18}O$ diagrams for dated ice wedges (C) and reconstructed mean January air temperatures (D) for the period of 29–13.5 cal ka BP. Co-isotope line for ice wedges is also shown (E).

Seyakha yedoma (Vasil'chuk 1992; Vasil'chuk et al. 2000b) vary between –20.4 to –25‰, which is rather close to the isotope data for ice wedges from the edge part of the yedoma (–23.4 to –25.75‰).

The slope of the $\delta^{18}O$-δ^2H ratio line for the ice wedge ice is 7.8, which is close to that of precipitation (global meteoric water line—GMWL). This indicates that the ice wedges were formed mainly through precipitation (melted winter snow) which was not subject to significant isotopic transformations. Thus, the $\delta^{18}O$ values are valid for paleotemperature calculations.

INTERPRETATION AND DISCUSSION

The Age of Ice Wedges of the Seyakha Yedoma

According to the obtained AMS ^{14}C dates, ice wedge growth occurred between 29 and 18 cal ka BP. The age of 17.7 cal ka BP from the upper ice wedge (see Figure 3A) seems too old as it is supposed that this ice wedges could have been contaminated with older organic dust, which blew into frost cracks from the neighboring exposures. The additional evidence for this was a high concentration of re-deposited pollen and spores of pre-Pleistocene age in the upper part

https://doi.org/10.1017/RDC.2022.15 Published online by Cambridge University Press

Table 2 ^{14}C dates of organic remains in ice wedges and enclosing sediments (central part of Seyakha yedoma exposure).

Lab ID	Height, m asl	^{14}C, BP (1σ)	Calibrated age, 95.4%, cal yr BP	Median age, cal yr BP	Dated material
AMS ^{14}C dates of ice wedges					
GrA-10538	+20.2	14550 ± 100	18127–17421	17768	POC>400μm
GrA-10539	+10.0	14720 ± 100	18254–17742	18032	POC>400μm
GrA-10536	+1.4	20960 ± 140	25678–24966	25296	POC>400μm
Conventional ^{14}C dates of enclosing sediments					
Hel-3942	+21.2	11620 ± 150	13790–13181	13486	Peat
Hel-4023	+18.8	17290 ± 250	21725–20317	20904	Peat
GIN-2473	+13.4	22700 ± 300	27621–26370	26979	Peat
GIN-2475	+12	22600 ± 600	28059–25771	26880	Peat
GIN-8931	+11	22510 ± 330	27353–26014	26790	Peat
GIN-2474	+10	23500 ± 400	28679–27133	27731	Peat
GIN-2476	+10	24300 ±300	29107–27842	28480	Peat
GIN-4043	+10	24460 ± 650	30071–27484	28725	Peat
MSU-1017	+9.5	24760 ± 2500	40136–24549	30092	Peat
MSU-1016	+9.0	25000 ± 1200	32160–27110	29396	Peat
Hel-3943	+6.8	27890 ± 90	32043–31557	31792	Peat
GIN-8936	+1.5	29500 ± 400	34772–33024	33999	Peat
GIN-2477	+1.1	30100 ± 1500	39112–31551	34785	Peat
Hela-201	+1.1	31200 ± 90	35947–35293	35561	Larix
Hel-3950	+1.1	36800 +3300 –2100	. . . < 26478	41022	Peat

*Calibrated using OxCal 4.4 equipped with IntCal 20 (Reimer et al. 2020).

https://doi.org/10.1017/RDC.2022.15 Published online by Cambridge University Press

of the section. The termination of yedoma accumulation and ice wedge growth may have been established by the ^{14}C date of 13.5 cal ka BP at a depth of 0.8 m.

Comparison of Dates for Ice Wedges and Enclosing Sediments

Radiocarbon dates for the ice wedges and enclosing sediments in the edge part of Seyakha yedoma show a non-inversion series from 29 to 21 cal ka BP. Dates from *baidzherakh* sediments—from 29.5 to 27.6 cal ka BP—are comparable with AMS ^{14}C dates of organic matter from ice wedges at the same depth. It should be noted that *baidzherakh* sediments occur in permafrost state and had not thawed and been reworked, but this block of frozen sediments has set down (by a maximum of 1.5 m) due to the thawing of ice wedges. Therefore, the dated organic horizons from this *baidzherakh* were initially located at heights of +3.5 to +6.5 m, i.e., at the same height as the lower ice wedge fragment. From this, it can be assumed that the lower ice wedge was formed synchronously with the enclosing sediments about 29-27 cal ka BP.

A comparison of the obtained dates for ice wedges (from 25.3 to 18 cal ka BP) and enclosing sediments at the same depth (from 41 to 26.8 cal ka BP) in the central part of the yedoma exposure demonstrates a discrepancy (see Figure 3A), indicating that the sediments must have been contaminated by older organic material.

It has been established that reworked organic matter noticeably complicates the dating of syngenetic permafrost sediments like yedoma strata (Vasil'chuk and Vasil'chuk 2017). All yedoma sediments in alluvial conditions were once at a beach level and most of the material for yedoma accumulation was re-worked from older sediments. The proportion of reworked material can be very high in accumulative coastal areas, even distant from abraded shores. Ancient organic detritus was washed out by thermal abrasion and deposited in the scalloped form of an almost pure organic matter. For example, peat from the beach under Seyakha yedoma exposure was dated to 15.5 cal ka BP (see Table 1), but visually it was similar to the *in situ* peat layers exposed in the outcrop. This peat could be identified as autochthonous although it is generally allochthonous. The admixture of such allochthonous material may cause an overestimation of the real age of the sediments by thousands and even dozens of thousands of years.

Paleotemperature Calculations and Chronological Scale for Isotope Data

A comparison of ^{14}C dated oxygen isotope curves (obtained for different parts of the yedoma section) show a good correlation for the period from 25 to 21 cal ka BP: the $\delta^{18}O$ values generally vary within the range from –23 to –25‰ (see Figure 3C).

Paleotemperature reconstructions based on Equation (1) show that from 25 to 21 cal ka BP $T_{mean\ January}$ varied from –36 to –39°C (see Figure 3D) that is, it was 10–14°C lower than modern mean January air temperature at the Seyakha site. In the ice wedge formed from 18 to 13.5 cal ka BP, there is a general trend of an upward decrease of $\delta^{18}O$ values from –22 to –24.5‰ (Vasil'chuk et al. 2000b). Accordingly, $T_{mean\ Jan.}$ during 18–13.5 cal ka BP varied from –33 to –37°C, decreasing during the terminal stage of ice wedge growth.

https://doi.org/10.1017/RDC.2022.15 Published online by Cambridge University Press

Synchronism of Yedoma Strata Formation and Mean January Air Temperature in the Western Sector of Siberian Arctic 30–19 cal ka BP

The ^{14}C dates and stable isotope compositions of ice wedges of the Seyakha yedoma were compared with yedoma exposures at three nearest sites in western part of Siberia: Marresale site (western coast of the Yamal Peninsula, 69.720ºN, 66.800ºE), Ery-Maretayakha (north of the Gydan Peninsula, 71.833ºN, 75.216ºE) (Forman et al. 2002; Oblogov et al. 2012; Streletskaya et al. 2013), and Sabler Cape on the Taimyr Peninsula (74.550ºN, 100.533ºE) (Derevyagin et al. 1999). Radiocarbon ages for these yedoma sections range from 36 to 10 cal ka BP. According to Forman et al. (1999, 2002), active ice wedge growth and eolian and fluvial deposition occurred during the Late Weichselian, ca. 40–11 ka BP on the western Yamal Peninsula. In the ice wedges formed between 19.7 and 14.2 cal ka BP the $\delta^{18}O$ values vary from −24.8 to −23.4‰ (Streletskaya et al. 2013). For the Ery-Maretayakha yedoma, the ice wedge which has been dated to about 26 cal ka BP is characterized by $\delta^{18}O$ values from −22.6 to −24.6‰ (Oblogov et al. 2012). The range of stable isotope data is close to that of the Seyakha ice wedges indicating similar winter climate conditions during yedoma strata formation between 26 and 14 cal ka BP.

Yedoma strata on Sabler Cape reveal a notable similarity in stratigraphy and synchronicity with the Seyakha yedoma. At this location, a series of ^{14}C dates of enclosing sediments, almost without inversions, was obtained by Sulerzhitsky (1982). One series of eight dates from 28.5 to 13.5–14 cal ka BP was obtained for the depth range 1–17 m; later, 13 dates from 35.1 to 11.8 cal ka BP were obtained for the depth range 3–25 m (Andreev et al. 2003). Thus, yedoma strata at Sabler Cape accumulated synchronously with Seyakha yedoma, from 35–29 to 13–12 cal ka BP.

Three tiers of ice wedges were described in the Sabler Cape yedoma exposure. The oxygen isotope composition ($\delta^{18}O$) of ice wedges dated between 34.5 and 30.9 cal ka BP vary from –31.5 to –28.3‰; in ice wedges dated between 22 and 14 cal ka BP, $\delta^{18}O$ values vary between –29.5 and –24.3‰. These values are lower than in the ice wedges of Seyakha yedoma, which is explained by the more severe winter climate conditions of the Taimyr Peninsula during the Late Pleistocene. However, the general trend of increasing of $\delta^{18}O$ values in ice wedges at the final stage of their growth was observed at both sites. The mean $\delta^{18}O$ values in the modern ice veinlets at the Sabler Cape site is –20.6‰ (Derevyagin et al. 1999), so the difference in the isotopic composition of Late Pleistocene and modern ice wedges is 6–9‰. The same difference in mean isotope values between Late Pleistocene and modern ice wedges was obtained for the Seyakha site.

Stratigraphic and geomorphic observations and associated chronologic controls do not support the existence of an ice sheet or even the proximity of a glacier margin in the western section of north Siberia between 30–29 and 20–19 cal ka BP. During this period winter climatic conditions were much more severe than modern ones: the mean January air temperature was on average 10°C lower than modern one and varied from −35 to −36°C on the Yamal and Gydan Peninsulas to −44 to −40°C on the Taimyr Peninsula, which favored the active growth of syngenetic ice wedges. These conclusions are in good agreement with the data for the Polar Ural region where due to cold and dry winter climate conditions prevailed during the MIS 2 even in the mountains only small local glaciers could exist (Svendsen et al. 2014).

https://doi.org/10.1017/RDC.2022.15 Published online by Cambridge University Press

CONCLUSIONS

Yedoma strata with thick ice wedges (over 20 m high) were formed in northwestern Siberia during the Late Pleistocene cryochron (dated to 50–11.7 cal ka BP). Direct dating of ice wedges of the Seyakha yedoma on the Yamal Peninsula allows us to conclude that ice wedges were formed between 29 and 18 cal ka BP, and the termination of yedoma strata accumulation had occurred by 13.5 cal ka BP. The $\delta^{18}O$ values in ice wedges formed 25–21 cal ka BP vary from –23 to –25‰ and the reconstructed mean January air temperatures during this period were on average –36°C, that is at least 10°C lower than modern ones. Active accumulation of yedoma sediments with ice wedges on the Yamal, Gydan, and Taimyr Peninsulas proves that vast areas of the western sector of the Siberian Arctic were not covered by the Eurasian ice sheet during the LGM (between 25 and 20 cal ka BP).

ACKNOWLEDGMENTS

We thank the Associate Editor, Dr. Ya. Kuzmin and two anonymous reviewers for their helpful and constructive comments and suggestions during reviewing process. The research was financially supported by the Russian Scientific Foundation (grant № 19-17-00126). The authors state that they have no conflicts of interest.

REFERENCES

Andreev AA, Tarasov PE, Siegert C, Ebel T, Klimanov VA, Melles M, Bobrov AA, Dereviagin AYu, Lubinski DJ, Hubberten HW. 2003. Late Pleistocene and Holocene vegetation and climate on the northern Taymyr Peninsula, Arctic Russia. Boreas 32:484–505.

Bronk Ramsey C. 2009. Bayesian analysis of radiocarbon dates. Radiocarbon 51(1):337–360.

Derevyagin AY, Chizhov AB, Brezgunov VS, Siegert C, Hubberten HW. 1999. Isotopic composition of ice wedges of Cape Sabler (Lake Taymyr). Kriosfera Zemli 3(3):41–49. In Russian with English abstract.

Forman SL, Ingólfsson Ó, Gataullin V, Manley W, Lokrantz H. 2002. Late Quaternary stratigraphy, glacial limits, and paleoenvironments of the Marresale Area, western Yamal Peninsula, Russia. Quaternary Research 57(3):355–370.

Forman SL, Ingólfsson Ó, Manley WF, Lokrantz H. 1999. Late Quaternary stratigraphy of Western Yamal Peninsula, Russia: New constraints on the configuration of the Eurasian ice-sheet. Geology 27(9):807–810. doi: 10.1130/0091-7613(1999)027<0807:LQSOWY>2.3.CO;2.

Forsstrom L, Greve R. 2004. Simulation of the Eurasian ice sheet dynamics during the last glaciation. Global and Planetary Change 42(1–4):59–81.

Hughes ALC, Gyllencreutz R, Lohne ØS, Mangerud J, Svendsen JI. 2016. The last Eurasian ice sheets—a chronological database and time-slice reconstruction, DATED-1. Boreas 45(1):1–45.

Oblogov GE, Streletskaya ID, Vasiliev AA, Gusev EA, Arslanov HA. 2012. Quaternary deposits and geocryological conditions of Gydan Bay Coast of the Kara Sea. In: Mel'nikov VP, Drozdov DD, Romanovsky V, editors. Proceedings of the 10th International Conference on Permafrost. Salekhard, June 25–29, 2012. Salekhard. Northern Publisher. p. 293–296.

Reimer PJ, Austin WEN, Bard E, Bayliss A, Blackwell PG, Bronk Ramsey C, Butzin M, et al. 2020. The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal ka BP). Radiocarbon 62(4):725–757.

Streletskaya ID, Vasiliev AA, Oblogov GE, Matyukhin AG. 2013. Isotope composition of ground ice of Western Yamal (Marre-Sale). Led i sneg 2(122):83–92. In Russian with English abstract.

Sulerzhitsky LD. 1982. The accuracy of radiocarbon ages and reliability of dates. In: Kind N, editor. The Antropogene of the Taimyr Peninsula. Moscow: Nauka. p. 10–17. In Russian.

Svendsen, JI, Alexanderson H, Astakhov VI, Demidov I, Dowdeswell JA, Funder S, Gataullin V, Henriksen M, Hjort C, Houmark-Nielsen M, Hubberten HW, Ingolfsson O, Jakobsson M, Kjaer KH, Larsen E, Lokrantz H, Lunkka JP, Lysa A, Mangerud J, Matiouchkov A, Murray A, Moller P, Niessen F, Nikolskaya O, Polyak L, Saarnisto M, Siegert C, Siegert MJ, Spielhagen RF, Stein R. 2004. Late Quaternary ice sheet history of northern Eurasia. Quaternary Science Reviews 23(11–13):1229–1271.

Svendsen JI, Krüger LC, Mangerud J, Astakhov VI, Paus A, Nazarov D, Murray A. 2014. Glacial and vegetation history of the Polar Ural Mountains in northern Russia during the Last Ice Age, Marine Isotope Stages 5–2. Quaternary Science Reviews 92:409–428.

van der Plicht J, Aerts A, Wijma S, Zonder A. 1995. First results from the Groningen AMS facility. In Proceedings of the 15th International ^{14}C Conference. Radiocarbon 37(2):657–661.

Vasil'chuk YK. 1991. Reconstruction of the paleoclimate of the Late Pleistocene and Holocene on the basis of isotope studies of subsurface ice and waters of the permafrost zone. Water Resources 17(6):640–647.

Vasil'chuk YK. 1992. Oxygen isotope composition of ground ice (application to paleogeocryological reconstructions). 2-vols. Theoretical Problems Department, Moscow, Russian Academy of Sciences and Lomonosov Moscow University Publ. In Russian with English contents section.

Vasil'chuk YK, Budantseva NA, Vasil'chuk AC. 2019. High-resolution oxygen isotope diagram of Late Pleistocene ice wedges of Seyaha yedoma, eastern Yamal Peninsula. Doklady Earth Sciences 487(1):823–826.

Vasil'chuk YK, Trofimov VT. 1984. Isotope-oxygen diagram of ice wedges of Western Siberia, its radiological age and paleogeocryological interpretation. Doklady of the Academy of Sciences of the USSR. 275(2): 425–428. In Russian.

Vasil'chuk YK, van der Plicht J, Jungner H, Sonninen E, Vasil'chuk AC. 2000a. First direct dating of Late Pleistocene ice-wedges by AMS. Earth and Planetary Science Letters 179(2):237–242.

Vasil'chuk YK, van der Plicht J, Jungner H, Vasil'chuk AC. 2000b. AMS-dating of Late Pleistocene and Holocene syngenetic ice-wedges. Nuclear Instruments and Methods in Physics Research B (172):637–641.

Vasil'chuk YK, Vasil'chuk AC. 2017. Validity of radiocarbon ages of Siberian yedoma. GeoResJ 13: 83–95.

Vasil'chuk YK, Vasil'chuk AC. 2020. Syngenetic ice wedges and age of slope yedoma deposits of the foothills of the Kular Ridge. Earth's Cryosphere XXIV(2):3–13.

Vasil'chuk YK, Vasil'chuk AC, Jungner H, Korneeva GA, Budantseva NA. 1998. Hydrobiochemical composition of syngenetic ices of Seyakha thickness as indicator of Ob Bay level in the Late Pleistocene. Kriosfera Zemli II (1):48–54. In Russian with English abstract.

https://doi.org/10.1017/RDC.2022.15 Published online by Cambridge University Press