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FIRST DIRECT RADIOCARBON DATING (22–27 CAL KA BP) OF MASSIVE ICE AT THE MECHIGMEN AND LAVRENTIYA BAYS COAST, EASTERN CHUKOTKA

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ABSTRACT. The Eastern Chukotka is considered a unique permafrost region where massive ice bodies are widespread. However, the origin and age of these ice formations are often discussed. The age of the massive ice of Chukotka was established for the first time using AMS ^{14}C dating. It was revealed that three massive ice bodies on the coast of Mechigmen Bay were formed at the end of the Late Pleistocene: a) near the Akkani site, 21,612 to 22,147 cal BP; b) near the Lavrentiya settlement, 27,553 cal BP; and c) near the Lavrentiya settlement, 22,193 cal BP. Stable isotope values in the studied massive ice vary in a rather wide range by about 10‰ for $\delta^{18}O$ values (from –14.8‰ to –24.5‰) and about 75‰ for the δ^2H values (from –116‰ to –191‰). The studied massive ice bodies are of intrasedimental genesis and formed epigenetically during the final stage of MIS2 (22–27 cal ka BP).

KEYWORDS: AMS, deuterium, Late Pleistocene, massive ice, oxygen isotopes, radiocarbon.

INTRODUCTION

The objects of study are three massive ice bodies exposed on the coast of Mechigmen and Lavrentiya Bays, Eastern Chukotka (Figure 1). Chukotka Peninsula, as well as Yamal and Gydan Peninsulas and Anzhu Islands, is a unique area in the Russian Arctic where massive ice bodies are widespread (Vasil'chuk and Murton 2016).

In North America, massive ice bodies were described in the Mackenzie Delta (Mackay and Dallimore 1992; Murton et al. 2004, 2005), on Herschel Island, and on Richards Island (Pollard 1990; Murton 2009; Fritz et al. 2011; Wetterich et al. 2023). Massive ice bodies of various morphology, layered and non-layered with inclusions of fine sediments and coarse particles and relatively pure, thick (up to 10–15 m) and thin (no more than 1 m or less), are found in the inner regions of Chukotka, in the Tanyurer River valley (Kotov 1998), in the Amguema River valley (Korolev 1993; Kotov 1997), and in coastal areas, on the east coast along the shores of the Krest Bay (Gasanov 1964, 1969), on the Rogozhny Cape along the Onemen Bay (Kotov 2001), along the Mechigmen Bay and Lavrentiya Bay (St. Lawrence Bay) coast, and in the basin of Koolen' Lake (Vasil'chuk 2012; Vasil'chuk et al. 2021). The earliest descriptions of the massive ice on Chukotka were made by Shvetsov (1938, 1947) and Soloviev (1947). A detailed study was later carried out by Gasanov (1964, 1969), who proposed the generally intrasedimental origin of massive ice and the segregation and re-injection mechanisms of its formation. Numerous massive ice bodies in Chukotka were studied by Kotov (1997, 1998, 1999, 2001), and most of them are considered to be of intrasedimental origin. However, massive ice in the Tanyurer River valley (central Chukotka) and Ekityki River (northern Chukotka) was attributed to relict glaciers (Kotov 1998, 1999). In the Amguema River valley, massive ice uncovered by a series of pits and boreholes was classified both as relict glacial ice (Korolev 1993) and as intrasedimental massive ice (Kotov 1997). The age of massive ice bodies in Chukotka was proposed to be Late Pleistocene based on the fact that they occurred within Late Quaternary terraces.

In this regard, the aim of this study is to analyze the age of organic micro-inclusions in massive ice using the AMS ^{14}C dating approach, to obtain the first direct ^{14}C dates for the massive ice

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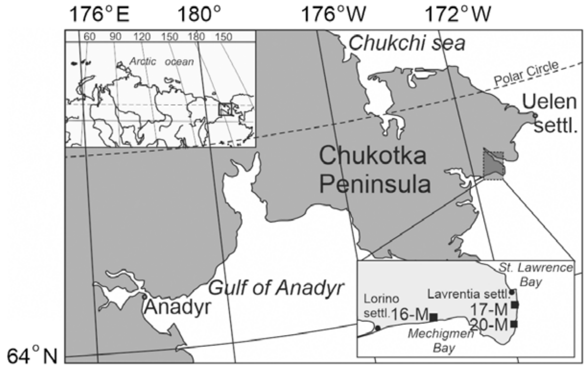

Figure 1 Map of the study area and location of sites with massive ice bodies (black box) sampled for ^{14}C dating.

on Chukotka, as well as to clarify the origin of the studied massive ice (epigenetic intrasedimental or syngenetic buried) based on stable isotope ($\delta^{18}O$ and $\delta^{2}H$) values of ice.

MATERIALS AND METHODS

Study Area

The three key sites of the studied massive ice bodies are located on the coast of Mechigmen and Lavrentiya Bays: a) 2 km southeast from the Chulkheveem (Akkani) River (site 16-M), b) 2 km south of the Lavrentiya settlement (site 17-M), and c) 7 km south of the Lavrentiya settlement (site 20-M).

The climate of Eastern Chukotka is sharply continental; the average annual air temperature varies from –4 to –6°C. The coast of Mechigmen and Lavrentiya Bays is an area of continuous permafrost with a thickness of 100 to 300 m and a mean ground temperature in the range of –3 to –5°C. The depth of the active layer varies within 0.47–0.56 m (Maslakov 2017).

Field Studies and Sampling

Field studies of the Eastern Chukotka's massive ice were carried out in 2016, 2017, and 2020. Ice was sampled mainly vertically and, if possible, horizontally with a step of 10 cm using a Bosch drill with steel crowns 51 mm in diameter. Ice samples were packed in a double polyethylene bag, melted at room temperature, and then poured into 30 mL plastic bottles sealed with Parafilm to avoid evaporation.

Laboratory Treatment and Radiocarbon Dating

Radiocarbon dating of micro-inclusions of organic material extracted directly from massive ice samples was 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) on the 500 kV NEC 1.5SDH-1 Pelletron (CAMS). Stable oxygen and hydrogen compositions in ice were analyzed in the stable isotope laboratory of the Faculty of Geography at Lomonosov Moscow State University using a Finnigan Delta-V Plus mass spectrometer applying equilibration techniques. The values are presented in δ-notation in per mille (‰) relative to the Vienna Standard Mean Ocean Water (VSMOW).

International reference materials (V-SMOW-2, GISP, and SLAP) were used for the calibration. The analytical precision is ±0.1‰ for $\delta^{18}O$ and ±0.8‰ for δ^2H. Deuterium excess (d_{exc}) was calculated as $d_{exc} = \delta^2H - 8\delta^{18}O$ (Dansgaard 1964). Totally, 84 samples of massive ice were analyzed for stable isotope composition, and organic micro-inclusions for ^{14}C AMS analysis were extracted from 5 samples. ^{14}C ages are reported in ^{14}C years before present (BP) following international conventions (Stuiver and Polach 1977; Millard 2014). Calibrated ages in calendar years were obtained using OxCal v 4.4.4 (Bronk Ramsey 2021) and the IntCal20 calibration curve (Reimer et al. 2020).

RESULTS AND DISCUSSION

Cryostratigraphy

Massive ice at site 16-M. Heterogenic massive ice body (Figure 2a) was located 2 km southeast from Chulkheveem (Akkani) River mouth and 1 km west from Akkani sea hunters base on the Mechigmen Bay coast (65°30'28.4"N, 171°11'50.2"W). A thick and relatively extended layer of ice, 45 m wide and up to 2.7 m thick, was exposed in a thermocircus 25 m from the shoreline. The thermocircus base is located at an altitude of 3 m a.s.l. and is 50 m wide with walls up to 4.5 m in height. The exposed ice was clean, with a great amount of air bubbles and a slightly dispersed layered structure. Ice layers 10–15 cm thick alternated with 0.1–3.0 cm layers of gray loam. The boundary between the ice and the overlying sediments is smooth, clear, and discordant. The overlying sediments, 1.7–3.0 m thick, are represented by dark yellow and bluish-grey loam with boulders.

Massive ice at site 17-M. Homogeneous massive ice (Figure 2b) is located on the coast of Lavrentiya Bay (St. Lawrence Bay), about 3 km south of the Lavrentiya settlement (65° 32'51"N; 170°58'24"W). The massive ice body is exposed in a thermocircus on the seashore, at an altitude of 5 m a.s.l. The width of the body is 18.6 m, and the visible thickness is 3.1 m. It is covered with a 1.5-3-m layer of unsorted dark yellow loam with gravel and boulders. The upper boundary of the ice was smooth and fuzzy. The ice is represented by a sequence of clear and bubbly ice layers and dark gray ice-rich loam with inclusions of debris (Figure 2b).

Massive ice at site 20-M. The homogeneous massive ice body (Figure 2c) is located on the coast of Lavrentiya Bay (St. Lawrence Bay), about 5 km south of the Lavrentiya settlement (65° 31'44.16"N; 170°58'55.40"W). The vertical thickness of the massive ice is approximately 2.5 meters; the upper boundary is smooth, clear, and discordant. It is overlaid by 0.7–2.0-m-thick dark gray loam with gravel inclusions and rounded nests of black peat. The massive ice is composed of pure, dislocated, layered ice. Layers with a thickness ranging from 0.2–0.3 cm to 20 cm have a mainly horizontal direction. The layering of ice is emphasized by interlayers of gray loam, including rock particles of 2 × 3 mm in size. In some locations, layering is disturbed by the inclusion of slightly rolled boulders 30 cm in diameter. The boundary between ice and overlying sediments is clear and discordant.

AMS Radiocarbon Age of Massive Ice

In this study, the first direct age measurements of the massive ice in Chukotka are discussed; in earlier studies, the age of the massive ice in Chukotka was estimated only on the basis of the ^{14}C age of the enclosing sediments.

The radiocarbon age of three massive ice bodies was determined with a high degree of accuracy due to direct AMS ^{14}C dating of organic micro-inclusions extracted from ice (Table 1).

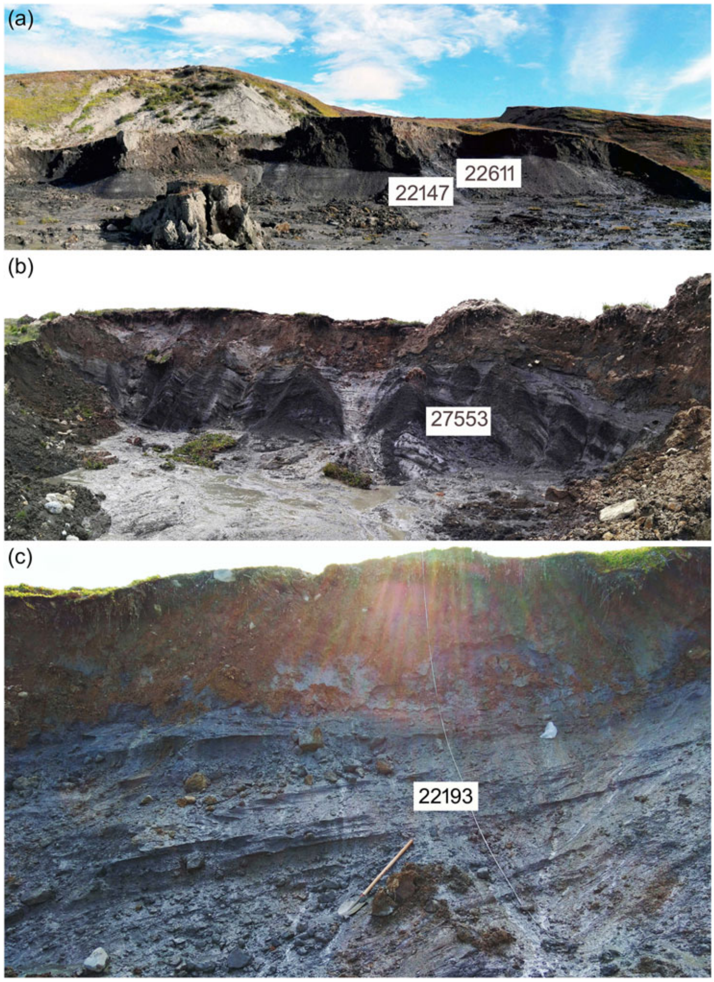

Figure 2 Radiocarbon AMS dates of massive ice samples (in white boxes) on the coast of Mechigmen and Lavrentiya Bays: (a) massive ice at site 16-M (Akkani); (b) massive ice at site 17-M (Lavrentiya); (c) massive ice at site 20-M (Lavrentiya).

For the massive ice at site 16-M (Akkani), the dates 22,147 cal BP at a depth of 34.7 m and 21,611 cal BP at a depth of 41.4 m were obtained (Figure 2a). For the massive ice at site 17-M (Lavrentiya), the oldest date of 27,553 cal BP at a depth of 1.0–1.3 m was obtained (Figure 2b). For the massive ice at site 20-M (Lavrentiya), the date 22,193 cal BP at a depth of 0.7–1.4 m was obtained (Figure 2c).

$\delta^{18}O$ and $\delta^{2}H$ Values of the Studied Massive Ice

Massive ice at site 16-M. Variations of $\delta^{18}O$ and $\delta^{2}H$ values in ice samples were insignificant: $\delta^{18}O$ varied from –16.3‰ to –17.9‰; $\delta^{2}H$ varied from –121.6‰ to –135.8‰ (Table 2, Figure 3).

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Table 1 AMS radiocarbon ages of three massive ice bodies on the coast of Mechigmen and Lavrentiya Bays, Eastern Chukotka, and stable isotope ($\delta^{18}O$, $\delta^{2}H$) composition of dated ice.

Sample ID	Depth (m)	Lab ID	Uncal. ^{14}C age (yr BP)	Cal. age (cal yr BP): Age interval (2σ), probability 95.4%	Cal. age (cal yr BP): Median age (1σ)	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)
a) Akkani River mouth, site 16-M							
16-M-83	34.7	$IGAN_{AMS}$-10436	18,185 ± 85	22,342–21,956	22,147 ± 97	–17.15	–126.1
16-M-85	41.4	$IGAN_{AMS}$-7333	17,790 ± 60	21,859–21,385	21,611 ± 131	–16.99	–127.3
b) Near Lavrentiya settl., site 17-M							
17-M-20-24	1.0–1.3	$IGAN_{AMS}$-10434	23,335 ± 60	27,731–27,359	27,553 ± 103	–17.33	–136.2
c) Near Lavrentiya settl., site 20-M							
20-M-04-06	0.7–1.4	$IGAN_{AMS}$-10437	18,240 ± 115	22,414–21,959	22,193 ± 117	–20.2	–158.9

Table 2 Stable isotope ($\delta^{18}O$, δ^2H and d_{exc}) minimum, mean, and maximum values for massive ice in Eastern Chukotka.

	$\delta^{18}O$ (‰)			δ^2H (‰)			d_{exc} (‰)		
N	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.
a) Akkani River mouth, site 16-M									
33	–17.88	–17.13	–16.27	–135.8	–128.1	–121.6	4.2	9.0	15.8
b) Near Lavrentiya settl., site 17-M									
26	–18.96	–16.97	–14.84	–148.4	–131.4	–116.3	–2.48	4.52	11.02
c) Near Lavrentiya settl., site 20-M									
11	–21.3	–18.7	–16.6	–163.9	–145.8	–123.9	–6.5	4.1	14.2

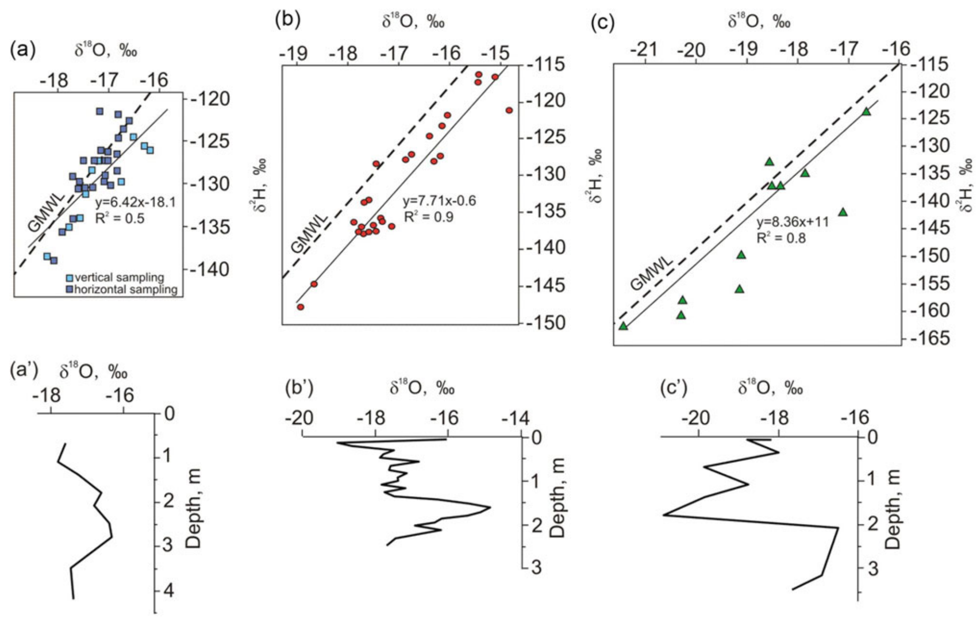

Figure 3 Co-isotope δ^2H-$\delta^{18}O$ lines for the massive ice bodies on the northeast of Chukotka and distribution of $\delta^{18}O$ values in the massive ice vs depth: a (a') – 16-M (for ice sampled along vertical profile); b (b') – 17-M; c (c') – 20-M. GMWL (Global Meteoric Water Line) is given for comparison.

Massive ice at site 17-M. The values of $\delta^{18}O$ in massive ice range from –14.8‰ to –19‰, and δ^2H values vary from –116.3‰ to –148.4‰. Vertical isotope profiles show a rather contrasting distribution of values, with a positive peak at the depth of 1.6 m, a negative peak at the depth of 0.15 m, and minor isotope variations at the depth of 0.5–1.4 m.

Massive ice at site 20-M. This massive ice is characterized by lower isotope values: $\delta^{18}O$ ranges from –16.6‰ to –21.3‰; δ^2H – from –123.9‰ to –163.9‰ (see Table 2). Vertical isotope profiles show a sharp negative shift at depths of 1.8-2 m and a positive trend from this depth to the subsurface horizon.

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Co-Isotope δ^2H-$\delta^{18}O$ Ratio of the Studied Massive Ice

Slopes of the δ^2H-$\delta^{18}O$ lines lower than 8 commonly indicate the evaporation of initial water or isotope fractionation during freezing. On the co-isotope diagram (Figure 3), the slope of the δ^2H-$\delta^{18}O$ ratio line for massive ice from Akkani (site 16-M) is 6.4, and isotope variations along horizontal and vertical profiles do not exceed 1.7‰ for $\delta^{18}O$ values. This may indicate that this ice was formed in open system conditions from water influenced by evaporation before freezing. For massive ice bodies from Lavrentiya (17-M and 20-M), the slopes of the δ^2H-$\delta^{18}O$ ratio lines are close to the global meteoric water line (GMWL) and are equal to 7.71 and 8.36, respectively (Figure 3).

But observed at some fragments, downward depletion of the isotope composition of ice may be a sign of closed-system freezing at equilibrium following Rayleigh-type isotope fractionation (Souchez et al. 2000) at some stages of intrasedimental massive ice formation. A similar isotope trend was traced in the ice core of pingo studied in Mongolia (Ishikawa and Yamkhin 2016), where the ice is undoubtedly of intrasedimental origin.

Radiocarbon Dating of Previously Studied Massive Ice

According to Kato et al. (1988), the age of massive ice at Peninsula Point (northern Canada) ranges from 20,628 to 17,406 cal BP (Table 3), with a general trend of age increasing towards lower elevation. Later, similar dates (from 24,851 to 16,821 cal BP) for tabular massive ice at Peninsula Point were obtained by Moorman et al. (1998).

For the massive ice on Herschel Island, a radiocarbon date of 21,226 cal BP (see Table 3) on CO_2 derived from air inclusions was obtained (Moorman et al. 1996). As dissolved organic carbon (DOC) from massive ice is not necessarily composed of only "fresh" carbon but might include "older" carbon (Lachniet et al. 2012), Wetterich et al. (2023) regard DOC ages between about 33,039 and 26,096 cal BP as maximum ages and assume that the youngest measured age (25,830 cal BP) is closest to the age of the buried glacier ice. The $^{14}C_{DOC}$ ages of massive ice in marine-deltaic sediments in Eureka Sound Lowlands, Fosheim Peninsula, range from 30,461 to 9,953 cal BP and from 27,428 to 15,181 cal BP (Table 3). The $^{14}C_{DOC}$ ages generally show an upward trend. However, according to Roy et al. (2023), $^{14}C_{DOC}$ data reflect the age of the DOC in the water source but do not date the time of freezing and massive ice formation.

The AMS-dated tabular massive ground ice studied in the central part of the Yamal Peninsula was formed from 42,847 to 38,443 cal ka BP (Chizhova et al. 2022). Contrast stable isotope values in ice ($\delta^{18}O$ values range from –19.9 to –23.1‰, δ^2H values range from –151.8 to –164.7‰ and d_{exc} values range from 6.5 to 20.4‰) and the low slope of the co-isotope line allow us to propose that massive ice was formed from water saturated under lake talik sediments during rapid non-equilibrium freezing (Chizhova and Vasil'chuk 2022).

Isotope Composition of Previously Studied Massive Ice in Chukotka

The isotope composition of the most of Late Pleistocene massive ice studied in Chukotka is very close to the isotope values of modern winter precipitation and Holocene intrasedimental ice lenses. In the intrasedimental massive ice on the easternmost part of Chukotka, on the Daurkin Peninsula, the $\delta^{18}O$ values in the injection-segregation massive ice vary from –22.4 to –20.6‰ (Vasil'chuk et al. 2021). In the intrasedimental massive ice near Anadyr town variations of $\delta^{18}O$ values are negligible: from –19.7 to –19.6‰. In the massive ice in the

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Table 3 Results of ^{14}C AMS dating of massive ice in northern Canada and Yamal Peninsula.

Depth (m)	Lab ID	Uncal. ^{14}C age (yr BP)	Cal. age (cal BP) Age interval (2σ), probability 95.4%	Median age (1σ)
North Point (Moorman et al. 1996)				
	AA-13658	10,500 ± 120	12,724–11,996	12,411 ± 213
Herschel Island (Moorman et al. 1996)				
	AA-14234	17,570 ± 120	21,715–20,899	21,226 ± 202
Tabular massive ice at Peninsula Point (Moorman et al. 1998)				
1	AA-13013	13,860 ± 100	17,081–16,490	16,821 ± 156
3	AA-21173	20,530 ± 1,250	27,781–22,260	24,851 ± 1,422
7	AA-21174	>27,200		
11	AA-21175	20,475 ± 925	26,996–22,866	24,721 ± 1036
17	AA-21176	>32,150		
Massive ice at Peninsula Point (Kato et al. 1988)				
11.2*	NUTA-594	14,270 ± 250	18,160–16,737	17,406 ± 358
21.1*	NUTA-593	17,000 ± 250	21,200–19,889	20,544 ± 317
21.5*	NUTA-589	17,070 ± 180	21,028–20,166	20,628 ± 212
Herschel Island (Wetterich et al. 2023)				
7	7725.1.1	26,716 ± 1,755	36,176–27,770	31,438 ± 2,232
7	7726.1.1	27,873 ± 2,250	40,427–28,296	33,039 ± 3,290
7	7727.1.1	23,202 ± 1,400	31,076–25,001	27,711 ± 1,562
7	7728.1.1	21,668 ± 1,371	29,285–23,060	26,096 ± 1,568
Tabular massive ice at three sites in Eureka Sound Lowlands (Roy et al. 2023)				
0–0.71	UOC-18609	8,849 ± 45	10,161–9,726	9,953 ± 127
0.71–1.35	UOC-18610	19,495 ± 113	23,786–23,157	23,488 ± 177
	UOC-18612	26,152 ± 333	31,065–29,947	30,461 ± 312
0.12–0.98	UOC-18611	23,126 ± 214	27,769–27,125	27,428 ± 179
0.95–1.34	UOC-6091	12,729 ± 52	15,334–15,000	15,181 ± 83
Massive ice at Yamal Peninsula (Chizhova et al. 2022)				
1.4	$IGAN_{AMS}$-7699	33,515 ± 130	39,091–37,688	38,443 ± 399
3	$IGAN_{AMS}$-7700	39,520 ± 220	43,108–42,598	42,847 ± 131

*Below surface of massive ice

Amguema River valley, the range of $\delta^{18}O$ values is about 4‰ (from –29 to –25‰) both along vertical and horizontal profiles (Korolev 1993). In the intrasedimental massive ice on the Onemen Bay coast, $\delta^{18}O$ values range from –20.7 to –12.9‰, $\delta^{2}H$ values vary from –155.2 to –114 ‰. In the massive ice in the Tanyurer River valley, $\delta^{18}O$ values range from –23.6 to –21.7‰, $\delta^{2}H$ values vary from –181.3 to –165.2‰ (Kotov 1998).

In the north of Canada, isotope values of the Late Pleistocene massive ice are usually very low and are not comparable with those of modern precipitation and Holocene intrasedimental ice; they are rather close to the isotope composition of polar ice caps. In the large massive ice of Herschel Island, $\delta^{18}O$ values vary from –33.48 to –32.57‰, $\delta^{2}H$ values from –259.5 to –253.2‰ (Wetterich et al. 2023). At three sites in the Eureka Sound lowland, mean $\delta^{18}O$ values vary from −34.9‰ to −25.5‰ (Roy et al. 2023). The isotope composition of the massive ice in the north of Canada is assumed to have both buried and intrasedimental origins.

One of the key points in the distribution of ^{14}C dates in massive ice is the commonly observed trend of decreasing age from the bottom upward. This corresponds to the hypothesis of syngenetic ice growth from bottom to top. Syngenetic accumulation of permafrost deposits usually occurs within peatlands, on floodplains, and on slopes, where new layers of sediment gradually pass into the permafrost state. Perhaps massive ice may form in the same way: after the formation of the first ice layer in freezing sediments, every new portion of water freezes above the previously formed layer, so ice becomes younger from the bottom to the top. However, this assumption still requires new evidence.

The mean $\delta^{18}O$ values in the studied three massive ice bodies are in the range of –17 to –18‰, which are close to the $\delta^{18}O$ values of modern and Holocene winter precipitation in this region, which would probably indicate the Holocene age of massive ice. However, it is known that due to isotope fractionation during water freezing, ice is always isotopically enriched by 2–3‰ (for $\delta^{18}O$ values) relative initial water, even during a single stage of freezing. Therefore, initial water as a source of massive ice formation was characterized by $\delta^{18}O$ values from –20 to –21‰.

Moreover, if assumed evaporation of initial water before freezing (that is indicated by $\delta^{2}H$-$\delta^{18}O$ line slope 6.4 for massive ice body in Akkani) and isotope fractionation during freezing of water in closed system conditions (indicated by contrast isotope distribution in massive ice bodies near Lavrentiya settlement), it may be concluded that $\delta^{18}O$ values of initial water may be as low as –23 to –25‰. These isotope values are undoubtedly more realistic for the Late Pleistocene surface waters of the eastern Chukotka. The $\delta^{18}O$ values for modern and Holocene surface waters are usually higher by 6-10‰.

CONCLUSIONS

1. Micro-inclusions of organic material in three massive ice bodies in the northeast of Chukotka (the Mechigmen and Lavrentiya Bays coast) were dated for the first time using the AMS approach.
2. The studied massive ice bodies are of intrasedimental origin and formed at the end of the Late Pleistocene (22–27 cal ka BP).

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