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OXYGEN STABLE ISOTOPE VARIATION IN LATE HOLOCENE ICE WEDGES IN YAMAL PENINSULA AND SVALBARD

ABSTRACT. The stable oxygen isotope composition of Late Holocene syngenetic ice wedges from the Erkutayakha River valley in the Yamal Peninsula and from the Adventdalen valley in Svalbard was studied. It was demonstrated that the studied ice wedges located 2000 km apart were formed during the last 2–3.5 ka and continue to grow at present. Variations of $\delta^{18}O$ values of the ice of both ice wedges do not exceed 2–3.5‰. Based on the oxygen isotope variations is has been calculated that mean winter air temperatures did not change by more than 3°C during the Late Holocene.

KEY WORDS: permafrost, oxygen isotopes, ^{14}C-dating, ice wedge, winter palaeotemperatures.

INTRODUCTION

The last two-three thousand years are of special interest for the palaeoclimatic reconstructions. There are detailed palaeoclimatic curves based on studies of lacustrine clay on Baffin Island [Thomas, Briner, 2009], tree rings in the Alps [Buntgen et al., 2005], and multi-disciplinary research on palaeoclimatic changes of the last twenty centuries in different regions of the Earth [Goosse et al., 2006; Jones and Mann, 2004; Lilleøren et al., 2012; Luterbacher et al., 2004; Mann et al., 1998; Maasch et al., 2005].

There are two key periods in the last 3 ka: the Medieval Warm Period (MWP) and the Little Ice Age (LIA). There are no universally accepted precise definitions for the duration of the LIA or the MWP. The MWP varied both spatially and temporally. The MWP is dated to about 800–1200 AD [Maach et al., 2005].

The span from 820 to 1050 AD was the warmest period with the average annual temperatures 0.6 °C higher than the modern temperatures, i.e. mean annual temperatures were only slightly higher than the modern ones in many parts of the world [Maach et al., 2005]. In Arctic Canada, the MWP is dated to 1375–1575 AD; it was 1.2 ± 0.6 °C cooler than today, and only slightly (0.1 ± 0.2 °C) warmer than the average for the last millennium in northeast Baffin Island [Thomas, Briner, 2009].

The transition from the MWP to the LIA was one of the most rapid global climatic events [Maach et al., 2005]. It occurred not only as a rapid temperature change, but also as changes in the atmospheric circulation and oceanic circulation. The culmination of the MWP is dated to approximately 1400 ± 40 AD, and its onset is dated to 1220 ± 40 AD [Moberg et al., 2005]. The LIA is characterized by a global decrease of 0.5–1.0 °C of the average air temperature and a lowering of the snowline by 100 m relative to its modern position [Maasch et al., 2005]. The LIA contains a coldest period called the Maunder minimum, the period of long-term decreasing solar spots [Eddy, 1976] from approximately 1645 to 1715 AD. Data from a varved proglacial lake sediments on northeast Baffin Island, Arctic Canada, [Thomas, Briner, 2009] show that the LIA (1575–1760 AD) was 1.5 ± 0.2 °C cooler than today and 0.2 ± ± 0.2°C cooler than the last millennium. January temperature reconstructions of both Northern and Southern Norway based on numerous studies in Scandinavia examining pollen and plant macrofossils in lake sediment cores, show that the LIA was the coldest period in the last 3 ka [Lilleøren et al., 2012].

Recent studies have shown that ice wedges in flood plains and peat bogs actively grew during the last 3–2 ka, e.g., within the floodplain near Fairbanks [Hamilton et al., 1983] and in the Da Hinggan Mountains, northeastern China [Yang, Jin, 2011]. This motivates us to consider in detail the palaeo-geocryological history of the Late Holocene based on a comparison of isotope data of ice wedges from the Yamal Peninsula and Svalbard, which have common morphological and genetic characteristics, but developed in rather different climatic conditions.

Ice wedges are the object to provide proxy-data for palaeoclimatic and palaeoenvironmental reconstructions. The origin of the ice infilling a crack can be attributed not only to unmodified winter snow, but also to hoarfrost accretion during winter and melting snow in spring, that subsequently refreezing in the crack. As a rule, wedge ice accumulates from

Table 1. $\delta^{18}O$ values for samples of recent syngenetic ice wedges and temperature parameters for Yamal Peninsula and adjacent regions and Russian Arctic Islands (from [Vasil'chuk, Kotlyakov 2000] with additions)

Ice wedge location	Latitude, Longitude	$\delta^{18}O$, ‰	FDD	$T_{m.w}$	$T_{m.J}$	$T_{gr.m.an}$
Yamal Peninsula						
Neromoyakha River	67°57´N, 66°20´E	−15.0	−3700	−15	−22	−10
Shchuch'ya River	66°57´N, 68°22´E	−18.2	−4000	−16	−24	−8
Seyakha settlement	71°10´N, 72°30´E	−18.0	−4173	−16	−23	−9
Vorkuta region						
Vorkuta	67°30´N, 62°02´E	−16	−2500	−12	−21	−6
Amderma	69°45´N, 61°40´E	−15.2	−3086	−13	−19	−7
Arctic Islands						
Henrietta Island	77°06´N, 156°30´E	−15.3	−5330	−17	−27	−12
Kotelny Island	75°27´N, 140°50´E	−18.1	−5400	−20	−29	−14
Novaja Sibir Island	75°03´N, 148°28´E	−18.0	−5500	−20	−30	−14
Chetyrehstolbovy Island	70°47´N, 161°36´E	−20.0	−5143	−19	−30	−13
Ayon Island	69°47´N, 168°39´E	−20.0	−5047	−20	−29	−12

FDD – cumulative freezing degree days; $T_{m.w}$ – mean winter air temperature (average temperature during period when mean days air temperature are lower than 0 °C), °C; $T_{m.J}$ – mean January air temperature, °C; $T_{gr.m.an}$ – mean annual ground surface temperature °C.

melting snow in spring. The isotope values of ice wedges correspond to the total winter isotope signal. Vasil'chuk [1993] established close relationship between oxygen isotope values ($\delta^{18}O$) in recent ice wedges and winter air temperatures (Table 1) that is described by the equations:

$$t_{mean\ winter} = \delta^{18}O_{ice\ vein}\ (\pm 2\ °C)$$

$$t_{mean\ January} = 1{,}5\ \delta^{18}O_{ice\ vein}\ (\pm 3\ °C).$$

Stable isotope study of ice wedges, both syngenetic and epigenetic, allows reconstructing the winter palaeotemperatures. However, syngenetic ice wedges are best for this purpose because it is possible to evaluate their age using ^{14}C dates of the host sediments. Sampling across the horizontal extent of ice wedges provides comprehensive information for reconstructions [Vasil'chuk, 2006, 2013; Yang and Jin, 2011].

Syngenetic ice wedges formed actively during the last 3 ka in various permafrost landforms: within floodplains and marshes, peatbogs, and in loess and slope sediments. Ice wedges are characterized by assumed symmetric isotope profiles that indicate symmetrical growth and frost cracking at relatively fixed intervals.

The aim of the paper is to study the oxygen-isotope composition of the Late Holocene ice wedges from the Erkutayakha River valley in the Southern Yamal Peninsula and from the Adventdalen valley in Svalbard and to reconstruct the winter palaeotemperatures for the last 3 thousand years.

STUDY AREAS

Erkutayakha River valley, Southern Yamal Peninsula

The Erkutayakha River valley is located in the Southern Yamal Peninsula (Fig. 1). This is the area of continuous permafrost with thickness of 100 m. The thickness of the active layer is about 95–100 cm [Trofimov et al., 1989]. The climate of the region is subarctic with long

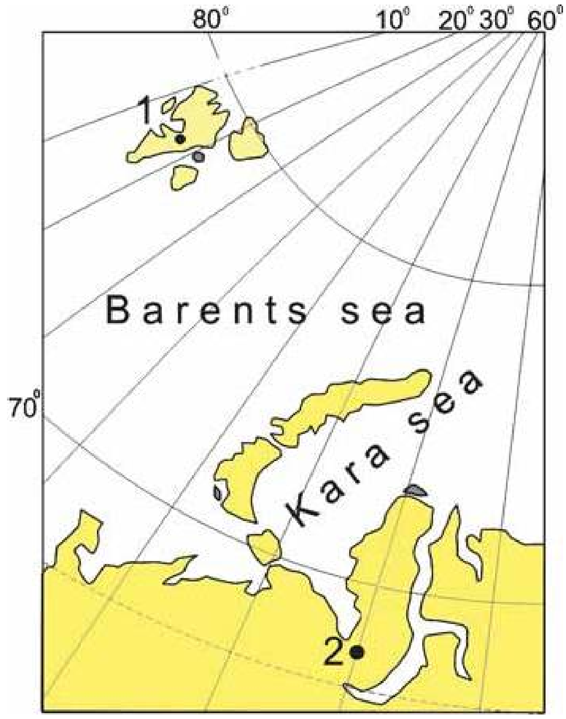

Fig. 1. Map showing the locations of the study sites:
1 – Svalbard, 2 – Yamal.

severe winters and very short summers (no longer than 50–60 days). The warmest months are July and August with mean monthly temperature ranging from 5 to 7 °C, while the coldest months are January and February with mean air temperature ranging from –22 to –24 °C. Mean annual air temperature fluctuates between –8 and –10 °C, and the surface ground temperature is close to the same values: –8 to –10 °C [Vasil'chuk, 2006].

Most of the ice wedges on the Southern Yamal Peninsula occur within floodplains. The Holocene syngenetic floodplain with ice wedges was studied on the left bank of the Erkutayakha River. The height of the floodplain is about 2.5–3 m. The polygons with open frost cracks are more distinct in drier areas. In the cross-section of the floodplain, were revealed (Fig. 2, A):

0–0.2 m – unfrozen brown peat with stems, roots, and some peat layers 2–3 cm thick;

0.2–0.7 m – grey sand with massive cryostructure;

0.7–1.5 m – peaty and stratified sand with massive cryostructure and lenses of ice.

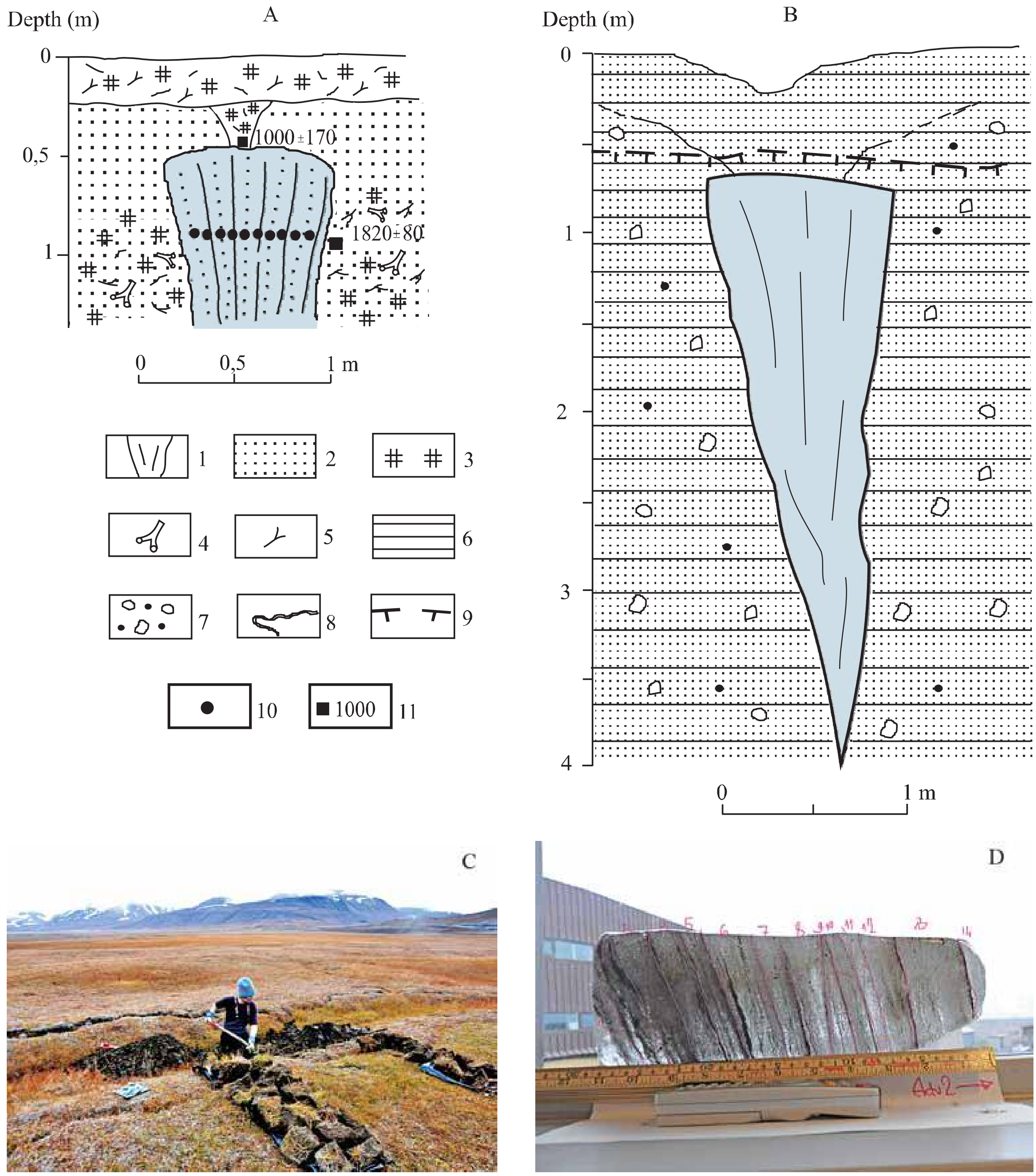

Fig. 2. Studied ice wedges:

A – Erkutayakha River floodplain, Yamal Peninsula, B – D – Adventdalen valley, Svalbard; B – sketch of a typical ice wedge in the Adventdalen valley (from [Matsuoka, Hirakawa, 1993]; C – the study site in the Adventdalen valley; D – internal structure of the ice wedge ice in the Adventdalen valley.

1 – ice wedge; 2 – sand; 3 – peat; 4 – twigs; 5 – roots; 6 – clay; 7 – gravel; 8 – clayey layers; 9 – base of active layer; 10 – sampling of ice wedge; 11 – ^{14}C dates.

At the depth of 0.4 m, an ice wedge was exposed. It consisted of about 160 individual ice veins. The ice was clear without admixtures. A ground peaty vein adjoined the top of the ice wedge (see Fig. 2, A).

Adventdalen valley, Svalbard

The Adventdalen valley is located in the central part of Svalbard and extends from east to west towards the fjord (see Fig. 1). It is a wide U-shaped valley, 3.5 km wide and 27 km long. The Adventdalen area is one of the driest parts of Svalbard; the average amount of precipitation is only about 190 mm.

The area is characterized by considerable temperature fluctuations during winter due to its maritime location. Mean air temperature of the coldest winter month is around –15 °C, mean air temperature of the warmest summer month is around 6 °C. Mean annual air temperature varies from –4 °C to –6 °C [Christiansen et al., 2013]. This is the area of continuous permafrost with thickness about 100 m thick. The thickness of the active layer is about 80–115 cm.

Ice wedges are widespread in Svalbard primarily in the lower parts of large valleys (e.g. Reindalen and Adventdalen valleys, Fig. 3) [Vtjurin, 1989; Matsuoka, Hirakawa 1993; Christiansen, 2005]. Thermal observations at the polygons in Adventdalen, where mean annual ground temperature at the bottom of the active layer was about –6 °C, showed that frost cracking was particularly active when mean daily air temperature dropped down to –20 °C and ground temperature at the bottom of the active layer decreased to –15 °C [Christiansen, 2005].

Ice wedges studied in the Adventdalen valley (78° 12´05´´ N, 15° 50´04´´ E) are located on

Fig. 3. Ice-wedge polygons in the central part of Svalbard.

the outer part of a large alluvial fan covered by aeolian deposits. The studied ice wedge, 2.5 m wide at the top, was exposed down to 3–3.5 m (see Fig. 2, B, C). About 345 elementary veins have been counted in the ice wedge.

According to Matsuoka and Hirakawa [1993], each ice vein cracks and acquires a new annual elementary vein every 6–7 years. Considering the amount of elementary veins, we may assume that the studied ice wedge has been growing during for the last 2500 years.

MATERIALS AND METHODS

11 samples of the ice wedge from the Erkutayakha site and 65 samples of the ice wedge from the Adventdalen site were sampled for isotope analysis. Both ice wedges were sampled horizontally in the top part using a chain saw to get large ice samples from across the entire ice wedges.

The ice samples were kept at a freezing temperature of –19.5 °C and then they were analyzed in the laboratory at –5 °C. The mineral admixtures were scrapped out. All ice samples were described on a light table, photographed in transmitted light, and further sawn up with a handsaw to obtain samples with widths from 0.7 to 2 cm (see Fig. 2, D). The ice samples were thawed at 7 °C and then poured into 50 ml plastic vials.

The oxygen stable isotope analysis was carried out in the Stable Isotope Laboratory of the Geography Department at Lomonosov Moscow State University, using a Delta-V mass spectrometer equipped with a standard gas bench. Oxygen isotope ratio was determined using equilibration techniques: samples for $\delta^{18}O$ analysis were equilibrated with CO_2 for 24 hours. For the measurements, international standards V-SMOW and international laboratory standards of the IAEA, as well as of the isotope laboratory of the Austrian Institute of Technology, were used. The precision of the measurements is 0.1‰.

The oxygen isotope composition of the ice wedge from the Erkutayakha site was determined by D. Rank and W. Papesch in the Arsenal Scientific Research Center in Vienna and by E. Soninnen in the Isotope Laboratory of the University of Helsinki, Finland. The organic matter from the floodplain was ^{14}C dated in the Geology Institute of RAS and in the radiocarbon laboratory of the University of Helsinki. ^{14}C AMS dates of ice wedges from the Adventdalen valley published by Jeppesen [2001] and Vittinghus et al. [2008] were used.

RESULTS

Oxygen stable isotope variations

The $\delta^{18}O$ values in the ice wedge from the *Erkutayakha River valley* varied from –18.0 to –20.63‰ (Table 2, Fig. 4). A segregated ice lens from the host sediment had higher $\delta^{18}O$ values – from –15 to –19.8‰.

The relatively narrow range of $\delta^{18}O$ (2.63‰) values indicates rather stable winter conditions during ice-wedge growth. The $\delta^{18}O$ value of a recent ice vein from floodplain sediments is –16.1‰ (see Table 2).

Table 2. $\delta^{18}O$ values in the ice wedge from the Erkutayakha River valley, Yamal Peninsula (site no 375–YuV)

Field no.	Depth, m	Distance from left contact zone, cm	$\delta^{18}O$, ‰
Holocene ice wedge in floodplain outcrop			
375-YuV/26*	1.0	0–7	–18.8
375-YuV/4*	1.0	10	–19.0
375-YuV/27*	1.0	10–14	–18.7
375-YuV/28*	1.0	14–28	–19.0
375-YuV/30*	1.0	28–40	–19.6
375-YuV/30**	1.0	28–40	–19.7
375-YuV/7*	1.0	40	–19.8
375-YuV/7**	1.0	40	–19.0
375-YuV/8*	1.0	40	–20.0
375-YuV/9*	1.0	40	–20.2
375-YuV/9**	1.0	40	–19.5
375-YuV/10*	1.0	40	–20.6
375-YuV/31*	1.0	40–50	–20.4
375-YuV/32*	1.0	50–54	–19.9
375-YuV/33*	1.0	54–64	–20.3
375-YuV/33**	1.0	54–64	–20.2
375-YuV/34**	1.0	64–70	–19.0
375-YuV/35*	1.0	70–80	–18.3
Recent ice vein in floodplain sediments			
375-YuV/36*	0.3	–	–16.1

* – isotope measurements made by D. Rank and W. Papesch in the Arsenal Scientific Research Center, Vienna,
** – isotope measurements made by E. Sonninen at the isotope laboratory of the University of Helsinki.

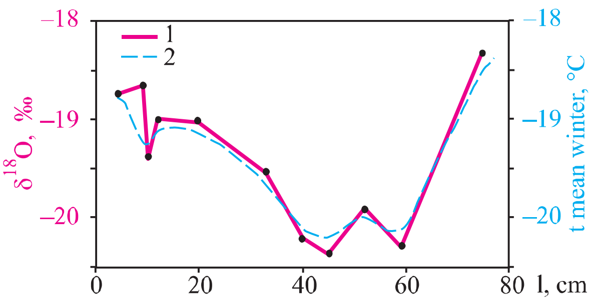

Fig. 4. $\delta^{18}O$ variations along the horizontal profile of the ice wedge, the Erkutayakha River valley, Yamal Peninsula, (1) and reconstructed mean winter air temperatures (2) based on Vasil'chuk's equations [1993]. *l* – distance from the left contact zone.

The $\delta^{18}O$ values in the presently growing parts of the ice wedge in the Southern Yamal Peninsula vary from –16 to –18‰ (see Table 2). These ice wedges occurred at the upper part of floodplain which formed 2–3 ka BP; thus, in the middle and early Holocene, the ice wedges in the Southern Yamal Peninsula were active also [Vasil'chuk et al., 2000]. In recent ice wedges on the islands of the Arctic Ocean, $\delta^{18}O$ values vary from –18 to –20‰ (see Table 1).

The $\delta^{18}O$ values in the ice wedge in the *Adventdalen valley* range from –12.2‰ to –15.4‰ (Table 3, Fig. 5) that correspond to the earlier obtained oxygen isotope data for ice wedges in the Adventdalen valley: $\delta^{18}O$ values vary from –11.5‰

Table 3. $\delta^{18}O$ values in the ice wedge from the Adventdalen valley, Svalbard

Distance from left contact zone, cm	$\delta^{18}O$, ‰	Distance from left contact zone, cm	$\delta^{18}O$.,‰	Distance from left contact zone, cm	$\delta^{18}O$, ‰
0.9	–12.3	59.2	–13.9	165	–14.1
1.8	–12.7	62	–14.1	169	–14.1
3.6	–14.1	77.4	–13.3	179	–12.3
5.4	–14.2	82.2	–14.7	185	–13.4
7.2	–14.1	87	–14.0	189	–12.2
9	–14.5	89	–13.2	193	–14.6
12	–15.4	91.8	–13.7	197	–14.1
14.4	–14.9	96.6	–14.3	211	–14.1
16.4	–15.0	99	–14.2	213	–14.1
19.8	–14.9	103	–13.0	219	–13.9
21	–14.7	110	–13.9	222	–13.4
23	–14.8	114	–14.1	225	–14.9
25	–14.5	118	–14.1	229	–14.7
27	–14.4	126	–12.9	234	–13.9
30	–13.8	128.5	–12.3	238	–14.2
32	–13.8	131	–13.5	245	–13.3
34	–14.2	134	–13.5	249	–13.4
36	–13.5	137	–13.5	252	–13.1
40	–13.7	147	–13.5	263	–13.5
43	–14.0	151	–13.9	264	–13.5
50.8	–14.8	155	–14.0	265	–13.6
56.4	–14.4	159	–12.5		

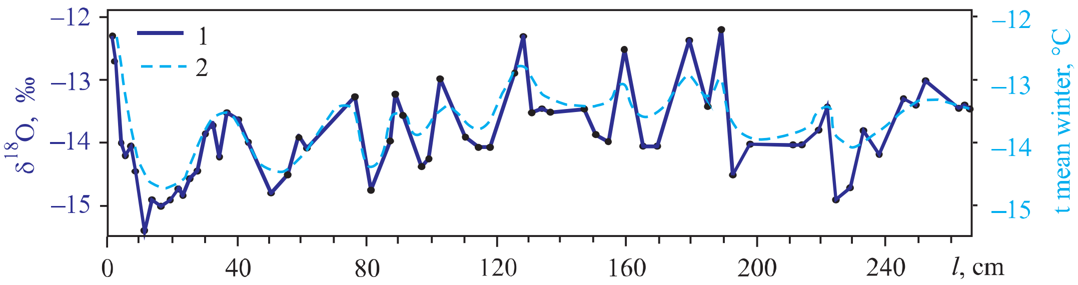

Fig. 5. δ18O variations along the horizontal profile of the ice wedge, the Adventdalen valley, Svalbard (1) and reconstructed mean winter air temperatures (2) based on Vasil'chuk's equations [1993]. *l* – distance from the left contact zone.

Fig. 6. The Late Holocene ice wedge studied by Jeppesen [2001] in the Adventdalen valley.

to –15.5‰ [Jeppesen, 2001] and from –10.5‰ to –14.8‰ [Vittinghus et al., 2008] (Fig. 6, 7). The oxygen isotope composition of modern precipitation collected in Longyearbyen is characterized by $\delta^{18}O$ values from –5‰ to –30‰ [Ole Humlum, pers.comm].

These dates were obtained in the Geology Institute of RAS. ^{14}C age of the roots often is younger than in host sediment, due to the development of the root system only after sedimentation. However, the roots in permafrost may be quite reliable material for ^{14}C dating of syngenetic sediments with ice wedges [Vasil'chuk et al., 2001] due to excellent preservation and the barrier function of permafrost blocking root growth below the active layer. ^{14}C age of 1820 ± 100 yr BP (Hel-4492) (cal. 1747 ± 119) for moss sampled at a depth of 1.0 m was obtained in the Radiocarbon Laboratory of Helsinki University, that confirms the validity of the dates obtained.

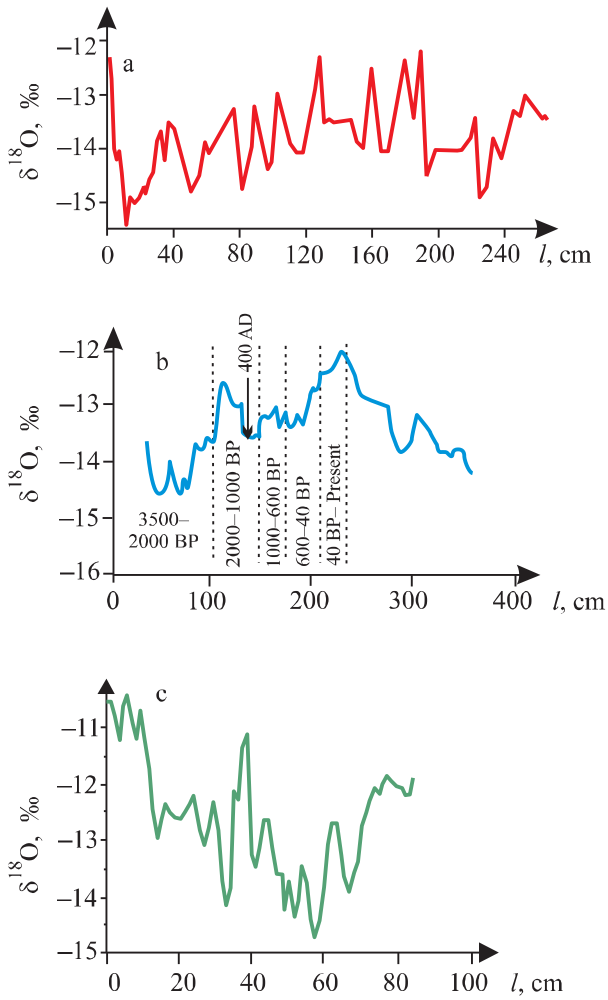

Fig. 7. Comparison of variations of δ18O values across the Late Holocene ice wedges from the Adventdalen valley with the distance from the left contact:

a) This study, b) From Jeppesen [2001],

c) From Vittinghus et al. [2008].

Table 4. ^{14}C AMS ages of organic matter from the ice wedges and host sediments from the Adventdalen valley, Svalbard

Depth, m	Dated material	cal.^{14}C age, BP*	Author
1.5	Peat	1618	[Jeppesen, 2001]
1.5	Peat	1766	
1.9	Peat	2018	
1.9	Peat	2166	
2.6	Peat	2710	
2.6	Peat	3680	
0.5	Organic material (Salix leaves) from outer part of the ice wedge	2900	
1.0	Organic matter from the ice wedge	2150	[Christiansen, 2005]
1.0	Organic matter from the ice wedge	1980	

^{14}C DATING AND AGE OF ICE WEDGES

The radiocarbon dating revealed a relatively young age of the floodplain sediments in the Erkutayakha River valley (see Fig. 2, A). The ^{14}C age of the peat from the ground vein above the ice wedge at a depth of 0.3 m is 1000 ± 170 yr BP (GIN-10632) (cal. 916 ± 167), while roots at a depth of 1.0 m were dated to 1820 ± 80 yr BP (GIN-10986) (cal. 1748 ± 97).

We suggest that roots are the "in situ" position because of the ages of the roots and the moss remains are close. We assume that about 1000 yr BP, the Erkutayakha River floodplain transitioned to subaerial regime of accumulation and ice wedges started to grow (so we think that the lower part of the studied ice wedge is actually epigenetic as it would not have been able to form when the site was flooded.

Radiocarbon dating of ice wedges in the *Adventdalen valley* has shown their Late Holocene age. The leaves of *Salix* found "in situ" in the outer part of ice wedge 160 cm wide at the top were ^{14}C AMS dated to 1980–2150 cal yr BP [Vittinghus et al., 2008].

^{14}C AMS dating of plant remains found directly in another ice wedge and in ice-wedge polygon sediments indicate that the oldest ice wedges grew syngenetically from app. 3.7 cal ka BP [Jeppesen, 2001]. Most of the AMS ^{14}C dates of peat or organic material from the ice-wedge host sediment ranges from 3.5 to 2 ka BP (Table 4).

AMS ^{14}C ages of plant fragments in the ice-wedge polygon sediments in the Adventdalen indicate that floodplain accumulation started from 3.3–3.9 cal ka BP [Oliva et al., 2014], supporting the assumption that ice wedges were formed since then, as these AMS ^{14}C dates provide direct maximum ages for syngenetic ice wedges.

The ^{14}C dated oxygen isotope diagram of the Holocene ice wedge from the Lena River Delta in the Siberian Arctic published by Meyer et al. [2015] became a good reference point for chronological binding of the oxygen isotope diagram of the Adventdalen ice wedge. ^{14}C AMS dates of 40 samples of ice provided a reliable dating of the isotope curve for the last 7 ka.

Comparison of the fragment of the isotope curve for the last 2–3 ka for the ice wedge from the Lena River Delta with the isotope curve for the Adventdalen ice wedge has shown satisfactory correlation of the isotope maxima and minima (Fig. 8).

It should be noted that the similarity of the isotope value ranges for the last 2–3 ka: in the ice wedge from the Lena River Delta, $\delta^{18}O$

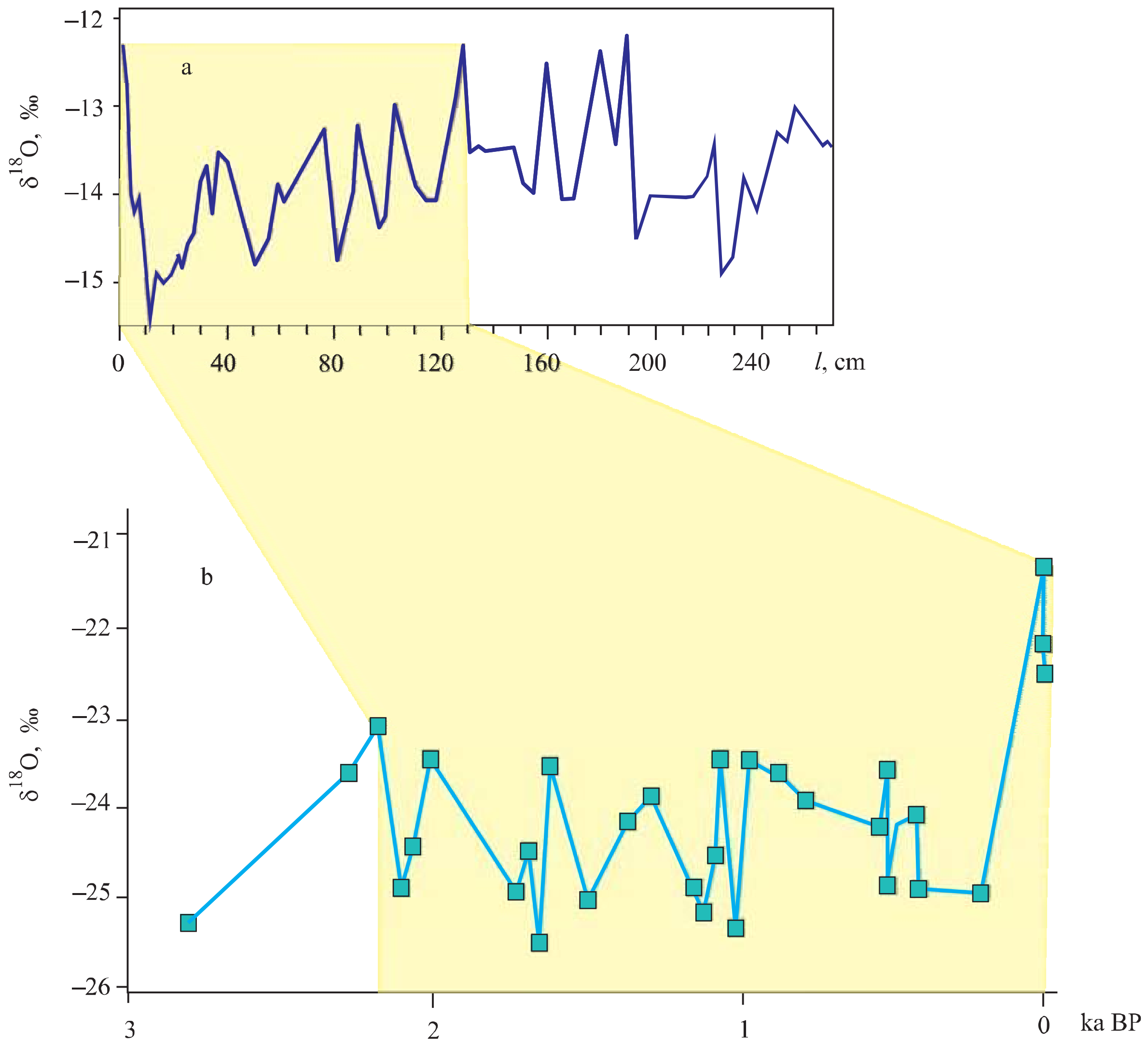

Fig. 8. Comparison of the oxygen isotope curve of the ice wedge from the Adventdalen valley, Svalbard, indirectly dated to the last 3 ka (a), with the ^{14}C dated fragment of the oxygen isotope curve of the ice wedge from the Lena River Delta, Siberian Arctic (b, from [Meyer et al., 2015]). Yellow area marks the fragments of the isotope curves that we assume have an approximately similar age.

values vary from –25.7 to –21.4‰, with 6 minima and 8 maxima; in the Adventdalen ice wedge, $\delta^{18}O$ values vary from –12.2 to –15.4‰, with 5 minima and 7 maxima.

DISCUSSION

Oxygen isotope composition of ice wedges and palaeotemperature reconstructions

^{14}C dating of ice wedges and host sediments as well as the amount of elementary veins in the ice wedge from Adventdalen allows us to consider that both studied ice wedges grew in the Late Holocene during the last 3–3.5 ka.

The difference of the oxygen isotope composition of the two ice wedges reflects the fact that winter conditions on Svalbard during the Late Holocene were less severe but more variable due to the marine environment, compared with continental climatic conditions of the Southern Yamal Peninsula, where winter temperatures were consistently lower.

Comparison of both ice-wedge isotope curves may be carried out by matching the most evident extreme peaks. These are the MWP dated from 1000 up to 700 years BP, and the Maunder minimum dated about 200 years BP [Isaksson et al., 2003]. We have selected the part from the Adventdalen ice wedge isotope curves, which is most similar to that of the ice wedges in the Erkutayakha valley. We suppose that fragment 0–20 cm of the isotope curve of the ice wedge from the Erkutayakha River (Fig. 9) corresponds to the end of the MWP. The interval 20–80 cm corresponds to the subsequent transition period to the LIA and as this interval is characterized by two minima divided by a low positive peak and possibly the subsequent maximum of modern warming at the Yamal Peninsula curve at the interval 20–80 cm (see Fig. 9). Obviously, in this period, the ice wedges grew more intensely due to a more intensive frost cracking.

On the isotope curve for the Adventdalen ice wedge, the MWP interval is more expressive and possibly corresponds to the interval between 180 and 200 cm from the left contact zone (see Fig. 9). A subsequent transition period and the LIA show the same contrast as in the Yamal Peninsula.

Based on the oxygen isotope records of the ice wedges it is possible to reconstruct mean winter temperatures for the last 3 ka using the equations of Vasil'chuk [1993]. In the Southern Yamal Peninsula, mean winter air temperatures varied from –18 to –21 °C; in Svalbard, they varied from –12 to –15 °C.

Thus, the range of the mean winter temperatures values does not exceed 3 °C

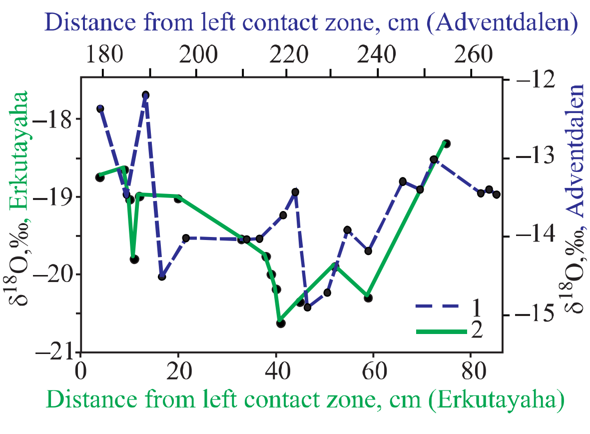

Fig. 9. Relation between the $\delta^{18}O$ curve fragments and the distance from the left contact zone from the ice wedges in the Adventdalen valley (1) and Erkutayakha valley (2).

for both sites. However, there is a difference between extremely maritime Svalbard and the much more continental Yamal Peninsula with more contrasting winter temperature oscillations during the MWP in Svalbard.

Oxygen isotope composition of Late Holocene ice wedges in the Northern Hemisphere

Comparison of the isotope data of the ice wedges from the Yamal Peninsula and Svalbard with published isotope data for ice wedges in the Northern Hemisphere formed during the last 3 ka, shows that the variations of the isotope values are rather moderate, but nevertheless noticeable. The Maunder minimum of the LIA (200 years BP) is characterized by relatively low isotope values, whereas the MWP (from 1000 to 700 years BP) is characterized by relatively high isotopic values.

Hamilton et al. [1983] have dated ice wedges in the floodplain near Fairbanks, Alaska, and concluded that the ice wedges actively formed during last 2–3 ka. They actively grew in the last 300–400 years despite a rather high mean annual air temperature (about –3.5 °C), and an even high ground temperature (mean annual values are up to –0.5, –1 °C higher than modern values). The ice wedge studied near the Vault Creek Tunnel, Fairbanks area, [Meyer et al., 2008] directly dated to 3.6 ka ^{14}C BP, shows a mean $\delta^{18}O$ value of –21.8‰. This is a typical isotope signature for Holocene ice wedges.

In the Da Hinggan Mountains, northeastern China, Yang and Jin [2011] studied ice wedges and found that they were formed from 1.6 to 3.3 ka BP. The isotope curve based on 16 samples collected along a horizontal profile at a depth of 1.3–1.4 m shows the range of $\delta^{18}O$ values from –20.9 to –17.8‰. There are three short cold periods in the isotope curve: 2.8, 2.3, and 1.9 ka BP, corresponding to a decrease of the mean air temperature of 2.1, 1.1, and 1.3 °C, respectively. The scale of the temperature variations in the Da Hinggan Mountains is similar to the Yamal Peninsula and Svalbard.

Late Holocene Northern Hemisphere palaeotemperatures from proxy data and their correlation with the studied ice-wedge isotopic data

Analysis of the Late Holocene palaeoclimatic reconstructions for the Northern Hemisphere shows relatively good correspondence of the regional and local scale and chronology of the major palaeoclimatic fluctuations with global changes during the last 2 ka.

Reconstruction of summer temperatures for Baffin Bay by varves from Big Round Lake (the thickness of varves correlates with average air temperature from July to September) demonstrated that mean summer air temperature during the LIA (1575–1760 years AD) was approximately 1.5 °C below the modern values (average temperature for 1995–2005 AD) and 0.2 °C below the average temperature for the last 1000 years [Thomas, Briner, 2009].

Ljungqvist et al. [2011] analyzed spatio-temporal patterns of centennial temperature variability over the Northern Hemisphere land areas for the last twelve centuries based on 120 proxy records (ice-cores, pollen, marine sediments, lake sediments, tree rings, speleothems, and historical documentary data). These data include the Lomonosovfonna ice core from Svalbard and tree rings from the Southern Yamal Peninsula and nearby Polar Ural mountains. The temperatures from 800 to 1100 AD were generally above the long-term mean, gradually cooling to below the mean during 1500–1800 AD, with maximum cooling at 1600–1700 AD. The warming of 1900–2000 AD raised the centennial mean back to a level comparable to that of 800–1100 AD. The resulting maps showing gridded, weighted, centennial proxy anomalies derived from 120 proxy records reveal remarkable large-scale spatial coherency of warm and cold conditions over the Northern Hemisphere land areas for the past twelve centuries [Ljungqvist et al., 2011].

An evident cool period in Southern Yamal Peninsula and Svalbard is dated to 1500–1800 AD. The temperatures of this period, according to Ljungqvist et al. [2011], were 0.5–1 °C below the long-term mean, and during the coldest part of the LIA – 1.5 °C below the long-term mean (Fig. 10, D). The reconstructed palaeotemperature based on the ice-wedge isotope values from Adventdalen valley dated to this period is characterized by low mean winter values (–14.2 °C, –14.5‰). Possibly the lowest values of mean winter temperature (–20.3 °C) reconstructed from the ice wedge from Erkutayakha valley are also dated to the coldest time of the LIA (Fig. 10, F, G).

According to Ljungqvist et al. [2011], warm anomalies in the Northern Hemisphere occurred from 800–1200 AD in the Medieval warming and about 1400 AD, when temperatures were from 0.5 to 2 °C above the long-term mean (see Fig. 10, D). These warm peaks correspond to higher mean winter temperatures, based on $\delta^{18}O$ values from contact zones of ice wedges (see Fig. 10, E, F): –19.5 °C (Erkutayakha River valley) and –12.3 °C (Adventdalen valley). A warm anomaly of the 20th century is noted in many regions of the Northern Hemisphere including the Yamal Peninsula and Polar Ural [Ljungqvist et al., 2011].

This warming is matched with the palaeotemperature curves of the ice wedge from the Adventdalen valley by mean winter temperatures close to Medieval warm values. The 20th century warming is not identified on the palaeotemperatures curve of the ice wedge from the Erkutayakha valley, most probably due to the relatively coarse sampling space of this ice wedge. However, the isotope value ($\delta^{18}O$ = –16.1‰) of modern ice veins in the study site corresponds to a mean winter temperature value of –16 °C, allowing us to assume that the present mean winter temperatures are almost 2 °C above those of the Medieval warm period.

There is a clear correspondence in the range of mean annual air temperature variations of 2–2.5 °C over the Northern Hemisphere

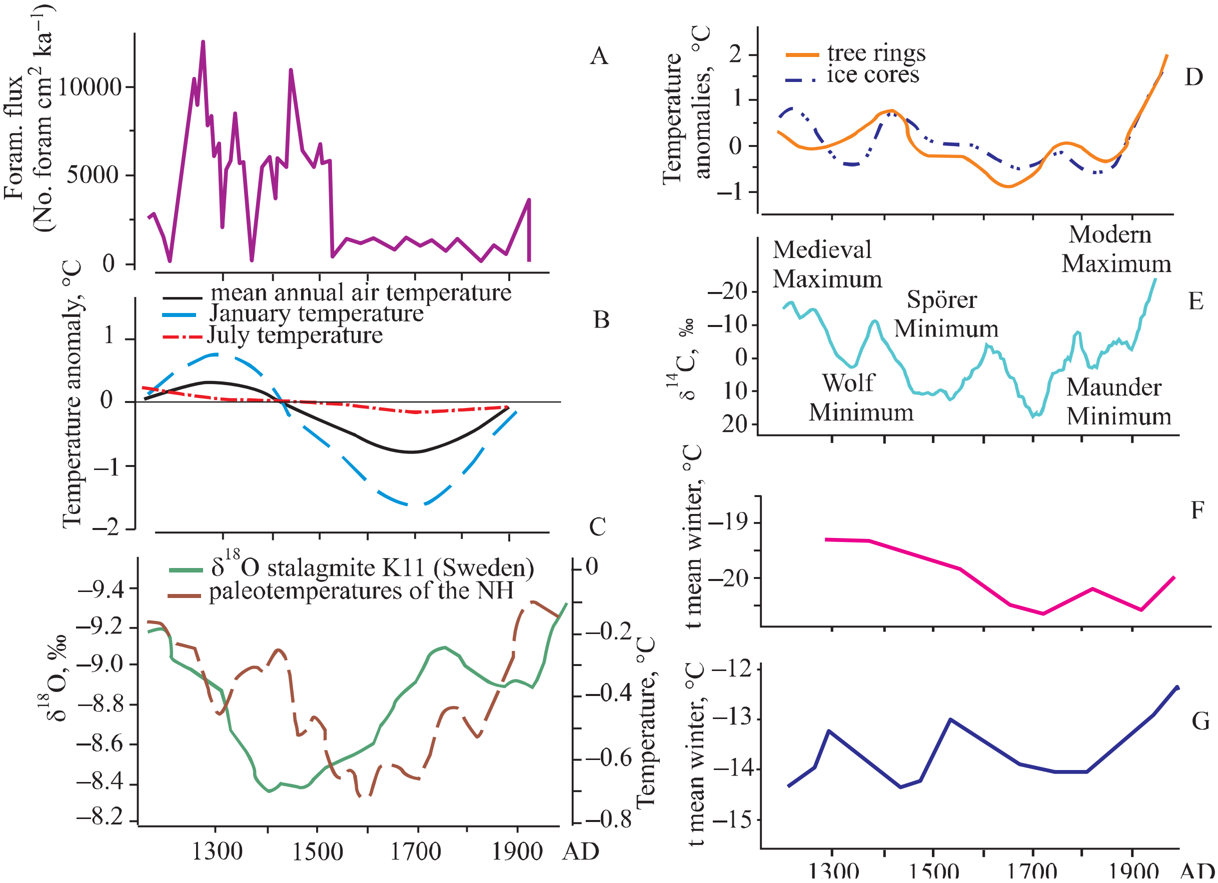

Fig. 10. Comparison of the Late Holocene Northern Hemisphere air temperature proxy records with the reconstructed palaeotemperature proxy from the ice wedges from the Yamal Peninsula and Svalbard:

(A) Benthic foraminiferal specimen flux in Hinlopen Trough (northern Svalbard), after Jernas et al. [2013].

(B) Anomalies of mean annual air temperature, January and July temperatures relative to present temperatures for northern Norway, after Lilleoren et al. (2012).

(C) Comparison between the $\delta^{18}O$ record of stalagmite K11 (northwestern Sweden) and the low-frequency component (480 yr scales) of the NH air temperature reconstruction by Moberg et al. [2005] after Sundqvist et al. [2010].

(D) Mean time-series of centennial temperature proxy anomalies reconstructed from tree rings and ice cores after Ljungqvist et al. [2011].

(E) Solar activity events recorded in the sunspot record for the last 1100 years; minima in $\Delta^{14}C$ correspond to maxima in sunspot number and maxima in $\Delta^{14}C$ lead minima in sunspot number. The radiocarbon signal in the Earth's atmosphere is response to changes in solar activity. The cycles in sunspot minima ($\Delta^{14}C$ maxima) with periodicities of about 200 years are referred to as Suess Cycles.

(F) Mean winter temperature reconstruction for the Erkutayakha River valley, Yamal Peninsula. This curve is not precisely dated; dating is made only by comparison of ^{14}C dates from the surrounding sediments.

(G) Mean winter temperature reconstruction for the Adventdalen valley, Svalbard. This curve is not precisely dated; dating is made only by AMS-dating of the adjacent ice wedges.

land areas during the past 1200 years, presented by Ljungqvist et al. [2011] and the reconstructed air temperature variations based on the isotope data from ice wedges in Svalbard and the Yamal Peninsula, where the range of mean winter air temperatures is also 2.5–3 °C. To understand the correlation of the temperature trends, we compared the isotope curves of a 4000-year-old stalagmite K11 with ice wedges of Svalbard and the Yamal Peninsula.

Two main temperature anomalies during the past 2000 years were noted by Sundqvist et al. [2010]. They studied the isotope composition of a 4000-year-old stalagmite, K11 from Korallgrottan in northwestern Sweden, and hypothesized that the interval of high $\delta^{18}O$

values (–8.5‰) in the stalagmite at 1300–1700 AD was driven by cooler and drier conditions, while the depleted isotopic values ($\delta^{18}O$ around –9.5‰) in 800–1000 AD were driven by warmer conditions. This suggests a negative relationship between calcite $\delta^{18}O$ and air temperature.

The K11 stalagmite $\delta^{18}O$ record shows an overall rather similar evolution of low-frequency (Fig. 10, C) temperature changes to that in the Northern Hemisphere temperature reconstruction by Moberg et al. [2005]. The main difference is that the observed warm peak in Medieval times and the LIA maximum cooling in K11 precede that in the hemispheric temperature record by 100–150 years. However, this apparent time-lag may, at least to some extent, be explained by uncertainties in the stalagmite age model, which is sensitive to the detrital correction at young ages [Sundqvist et al., 2010]. This MWP peak chronologically coincides with the warm peaks of the reconstructed palaeotemperature curves from the ice wedges from Svalbard and the Yamal Peninsula. The cooling peak on the stalagmite isotope curve ($\delta^{18}O$ around –8.5‰) was dated to about 1400 AD. This is, on average, 50–150 years earlier, than on the palaeotemperature curves of these ice wedges (see Fig. 10, C, E, F).

The LIA maximum cooling, identified in the studied ice wedges, practically coincides in scale and chronology with the cooling peak noted by Lilleøren et al. [2012]. They studied the regional distribution of mountain permafrost in Norway during the Holocene based on modelling of ground temperatures and long-term observations of modern ground temperatures in boreholes.

It was found that in all the boreholes, the coldest simulated permafrost occurred during the LIA, and the largest areal distribution of Holocene permafrost in Norway was in the LIA (see Fig 10, B).

During this period, the mean annual air temperatures were 0.8 °C below the present, while mean winter temperatures were 1.2–1.8 °C below the present. The MWP on the palaeotemperature curve is dated to 1000–1100 AD, and mean annual air temperatures were 0.5 °C above the present [Lilleøren et al., 2012], which also chronologically corresponds to the warm peaks on the reconstructed palaeotemperature curves of the ice wedges from Svalbard and Yamal Peninsula.

Palaeoenvironmental conditions on the northern and western continental shelves of Svalbard during the past 2000 years were studied by Jernas et al. [2013], who analyzed two marine sediment cores from the Kongsfjorden Trough (western Svalbard) and Hinlopen Trough (northern Svalbard) with respect to benthic foraminifera and lithology. Superimposed on the long-term trend, five centennial-scale main intervals were isolated at both sites, reflecting variations in the advection of Atlantic water onto the Svalbard shelf, and resulting in variations of climatic conditions in Svalbard. From AD 300 to 700, a diminished inflow of Atlantic water and, most probably, an enhanced inflow of cold and fresher Arctic water took place, followed by a renewed seasonal inflow of chilled, more saline waters of Atlantic origin and an overall diminished influence of Arctic water from AD 700 to 1200. Enhanced inflow of Atlantic water to the Hinlopen Trough from AD 1200 to 1500 led to maxima in foraminiferal fluxes (see Fig. 10, A) and the development of oceanic fronts. In this period, increases in ice rafting reflect either growth or surges of glaciers on Svalbard [Jernas et al., 2013] caused by an increase of humidity due to the influence of Atlantic water. The period AD 1200–1500 may be considered as the maximum influence of Atlantic water, which could be represented by positive peaks in the reconstructed palaeotemperature curves from the ice wedges from Svalbard and the Yamal Peninsula (see Fig. 10, E, F). From AD 1500 to 1900, particularly harsh conditions prevailed in the Hinlopen area owing to larger sea-ice cover and reduced inflow of Atlantic water, which led to minima in the foraminiferal fluxes (see Fig. 10, A).

This cold period of the LIA chronologically coincides with the cool peaks marked on the reconstructed palaeotemperature curves from the ice wedges from Svalbard and the Yamal Peninsula.

Comparison of the reconstructed palaeotemperatures from the Svalbard and Yamal Peninsula ice wedges with the results of the palaeoclimatic review shows that the most evident events are the MWP (800–1200 AD) and the LIA (1600–1800 AD).

CONCLUSIONS

1. Thick syngenetic ice wedges in the upper profile of the high floodplains in the Erkutayakha River valley in the Southern Yamal Peninsula and in the Adventdalen valley in Svalbard, separated by a distance of 2000 km, have been compared with respect to isotope values. These ice wedges developed during the last 2–3 ka and are continuing to grow at present.

2. Ice wedges that have been studied in different permafrost regions (i.e. Alaska, Siberia, Northern China, Yakutia and Chukotka) dated about 2–3 ka BP that implies an active ice-wedge growth during the Late Holocene.

3. For ice wedges formed during 2–3 ka in the subarctic Northern Hemisphere permafrost zone, variations of $\delta^{18}O$ values do not exceed 2–3.5‰ even for ice wedges located in significantly different climatic and geocryological conditions. In the ice wedge from Erkutayakha River valley in Southern Yamal Peninsula, the $\delta^{18}O$ values vary by 2.6‰ (from –18.0 to –20.6‰), and in the ice wedge from Adventdalen valley, the $\delta^{18}O$ values vary by 3.2‰ (from –12.2 ‰ to –15.4‰).

4. During the last 2–3 ka in the subarctic permafrost, changes of mean winter air temperatures did not exceed 3 °C; these changes have been also confirmed by comparison with proxy data (dendrochronological, palynological, and microfaunistic) in different regions of the Northern Hemisphere.

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REFERENCES

1. Buntgen U., Esper A.J., Frank D.C., Nicolussi K., Schmidhalter M. (2005). A 1052-year tree ring proxy for Alpine summer temperatures // Climate Dynamics. N 25. pp. 141–153.

2. Christiansen H.H. (2005). Thermal regime of ice-wedge cracking in Adventdalen, Svalbard // Permafrost and Periglacial Processes. N 16. pp. 87–98.

3. Christiansen H.H., Humlum O., Eckerstorfer M. (2013). Central Svalbard 2000–2011 Meteorological Dynamics and Periglacial Landscape Response // Arctic, Antarctic and Alpine Research. N 45. pp. 6–18.

4. Eddy J.A. (1976). The Maunder Minimum // Science. Iss. 192. pp. 1189–1202.

5. Goosse H., Renssen H., Timmermann A., Bradley R.S., Mann M.E. (2006). Using paleo-

climate proxy-data to select optimal realizations in an ensemble of simulations of the climate of the past millennium // Climate Dynamics. N 27. pp. 165–184. doi: 10.1007/s00382-006-0128-6.

6. Hamilton T.D., Ager T.A., Robinson S.W. (1983). Late Holocene ice wedges near Fairbanks, Alaska, U.S.A.: environmental setting and history of growth // Arctic and Alpine Research. N 15. pp. 157–168.

7. Isaksson E., Hermanson M., Hicks S., Igarashi M., Kamiyama K., Moore J., Motoyama H., Muir D., Pohjola V., Vaikmäe R., van de Wal R.S.W., Watanabe O. (2003). Ice cores from Svalbard–useful archives of past climate and pollution history // Physics and Chemistry of the Earth, Parts A/B/C. N 28. pp. 1217–1228.

8. Jeppesen J.W. (2001). Palaeoklimatiske indikatorer for central Spitsbergen, Svalbard. Eksemplificeret ved studier af iskiler og deres vaertssediment. Master's thesis, University of Copenhagen. UNIS. Svalbard. 35 pp.

9. Jernas P., Kristensen D.K., Husum K., Wilson L., Koç N. (2013) Palaeoenvironmental changes of the last two millennia on the western and northern Svalbard shelf // Boreas. Vol. 42. pp. 236–255. doi: 10.1111/j.1502-3885.2012.00293.x.

10. Jones P.D., Mann M.E. (2004). Climate over past millennia // Reviews of Geophysics. Vol. 42. RG2002. doi:10.1029/2003RG000143.

11. Ljungqvist F.C., Krusic P.J., Brattström G., Sundqvist H.S. (2011). Northern Hemisphere temperature patterns in the last 12 centuries // Climate of the Past Discussions. N 7. pp. 3349–3397. doi:10.5194/cpd-7-3349-2011.

12. Lilleøren K.S., Etzelmüller B., Schuler T.V., Gisnås K., Humlum O. (2012). The relative age of mountain permafrost–estimation of Holocene permafrost limits in Norway // Global and Planetary Change. Iss. 92–93. pp. 209–223.

13. Luterbacher J., Dietrich D., Xoplaki E., Grosjean M., Wanner H. (2004) European seasonal and annual temperature variability, trends and extremes since 1500 AD // Science. Iss. 303. pp. 1499–1503.

14. Maasch K.A., Mayewski P.A., Rohling E.J., Stager J.C., Karlén W., Meeker L.D., Meyerson E.A. (2005). A 2000-year context for modern climate change // Geografiska Annaler. N 87A. pp. 7–15.

15. Mann M.E., Bradley R.S., Hughes M.K. (1998). Global-scale temperature patterns and climate forcing over the past six centuries // Nature. Vol. 392. pp. 779–787.

16. Matsuoka N., Hirakawa K. (1993). Critical polygon size for ice-wedge formation in Svalbard and Antarctica // Proceedings of the Sixth International Conference on Permafrost. Beijing, China. South China University of Technology Press, Wushan, Guangzhou. N 1. pp. 449–454.

17. Meyer H., Yoshikawa K., Schirrmeister L., Andreev A. (2008). The Vault Creek Tunnel (Fairbanks Region, Alaska): A Late Quaternary Palaeoenvironmental Permafrost Record // Pro-

ceedings of the Ninth International Conference on Permafrost. Kane DL, Hinkel KM (eds). Institute of Northern Engineering, University of Alaska Fairbanks. N 2. pp. 1191–1196.

18. Meyer H., Opel T., Laepple T., Dereviagin A.Yu., Hoffmann K., Werner M. (2015). Long-term winter warming trend in the Siberian Arctic during the mid- to late Holocene // Nature Geoscience. Letters. Published online: DOI: 10.1038/NGEO2349.

19. Moberg A., Sonechkin D.M., Holmgren K., Datsenko N.M., Karlen W. (2005). Highly variable Northern Hemisphere temperatures reconstructed from low- and high resolution proxy data // Nature. Vol. 433. pp. 613–617.

20. Oliva M., Vieira G., Pina P., Pereira P., Neves M., Freitas M.C. (2014). Sedimentological characteristics of ice-wedge polygon terrain in Adventdalen (Svalbard). Environmental and climatic implications for the Late Holocene // Solid Earth Discussions. N 6. pp. 1191–1225.

21. Sundqvist H.S., Holmgren K., Moberg A., Spötl C., Mangini A. (2010). Stable isotopes in a stalagmite from NW Sweden document environmental changes over the past 4000 years // Boreas. N 39. pp. 77–86. doi: 10.1111/j.1502-3885. 2009.00099.x.

22. Thomas E.K., Briner J.P. (2009). Climate of the past millennium inferred from varved proglacial lake sediments on northeast Baffin Island, Arctic Canada // Journal of Paleolimnology. N 41. pp. 209–224.

23. Trofimov V.T., Baulin V.V., Vasil'chuk Y.K., Grechishchev S.E. (1989) Geokriologija SSSR. Zapadnaja Sibir. (Geocryology of Russia. Western Siberia) Izd-vo Nedra. Moskva. 454 s (In Russian).

24. Vasil'chuk Y.K. (1993). Northern Asia cryolithozone evolution in Late Quaternary // Proceedings of the Sixth International Conference on Permafrost. Beijing, China. South China University of Technology Press, Wushan, Guangzhou. Vol. 1. pp. 945–950.

25. Vasil'chuk Y.K. (2006). Povtorno-zhil'nye l'dy: geterociklichnost', geterogennost', geterohronnost'. (Ice wedge: heterocyclity, heterogeneity, heterochroneity). Izd-vo MGU. 404 s (In Russian).

26. Vasil'chuk Y.K. (2013). Syngenetic ice wedges: cyclical formation, radiocarbon age and stable-isotope records // Permafrost and Periglacial Processes. N 24. pp. 82–93.

27. Vasil'chuk Y.K., Kotljakov V.M. (2000). Osnovy izotopnoj gljaciologii i geokriologii. (Principles of isotope geocryology and glaciology) Uchebnik. Izd-vo MGU. 616 s (In Russian).

28. Vasil'chuk Y.K., Vasil'chuk A.C., Rank D., Kutschera W., Kim J.-C. (2001). Radiocarbon dating of $\delta^{18}O$-δD plots in Late Pleistocene ice-wedges of the Duvanny Yar (Lower Kolyma River, northern Yakutia) // Radiocarbon. N 43. pp. 541–553.

29. Vasil'chuk Y.K., van der Plicht J., Jungner H., Vasil'chuk A.C. (2000). AMS-dating of Late Pleistocene and Holocene syngenetic ice-wedges // Nuclear Instruments and Methods in Physics Research. Section B: Beam Interactions with Materials and Atoms. Vol. 172. pp. 637–641.

30. Vittinghus H., Christiansen H.H., Meyer H., Elberling B. (2008). Hydrogen and oxygen isotope studies from an ice wedge in Svalbard // Extended Abstracts of the Permafrost Ninth International Conference. University of Alaska. Fairbanks, USA. pp. 333–334.

31. Vtjurin B.I. (1989). Podzemnye l'dy Shpitsbergena (Underground ice of Svalbard) // Materialy gljaciologicheskih issledovanij. Vyp. 65. s. 69–85 (In Russian).

32. Yang S., Jin H. (2011). $\delta^{18}O$ and δD records of inactive ice wedge in Yitulihe, Northeastern China and their paleoclimatic implications // Science China. Earth Sciences. N 54. pp. 119–126.

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