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AMS-dating of Late Pleistocene and Holocene syngenetic ice-wedges

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Abstract

We discuss the ^{14}C dating (both conventional and AMS) of Siberian permafrost sediments and ice-wedge ice. Direct dating of Late Pleistocene and Holocene syngenetic ice-wedges was done on organic material included in the ice. The time of ice formation (in ^{14}C years) is 21,000–14,000 BP for Seyaha, and 7100 BP for Shchuch'ya. The AMS dates show that the ice-wedges stratification is normal, i.e., the older ice is located below the younger. The ^{14}C dates yield for the first time a timescale (in ^{14}C years) for paleoclimatic indicators (oxygen and hydrogen isotope ratios from the ice).

Keywords: AMS ^{14}C-dating; Syngenetic ice-wedges; Late Pleistocene; Holocene

1. Introduction

Here we present direct ^{14}C dating of Late Pleistocene and Holocene ice-wedges by AMS, showing a clear age stratification of the ice-wedges. We investigated two sites in the Siberian permafrost. The first site is located near the Seyaha settlement in the central part of Yamal Peninsula, at the coast of the Ob Bay (70°N, 72°E). The second site is located in the Shchuch'ya River valley, in the southern part of Yamal Peninsula (67°10′N, 69°5′E).

Large syngenetic ice-wedges result from repeated frost cracking and melted snow water, filling the frost cracks under conditions of slow, continuous sedimentation. Simultaneous accumulation of sediments and ice leads to a vertical stratification of the ice, i.e., the lower part of the ice-wedge is older than the upper part.

Both the structure and composition of syngenetic ice-wedges have been preserved from their time of formation until today. The $\delta^{18}O$ and δD values in modern ice-wedges correlate well with mean winter temperatures: the ice formed from the melt water, which penetrates into the frost cracks in early spring, and which had its origin from winter precipitation. Based on $\delta^{18}O$ measurements collected for many ice-wedges from the permafrost zones in Northern Eurasia and Northern America

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and meteorological data, an empirical relation between $\delta^{18}O$ values of the ice and winter temperatures could be deduced [1]. Assuming that the relationship derived from modern ice-wedges can also be applied to Late Pleistocene and Holocene conditions, therefore, $\delta^{18}O$ and δD values in ancient ice-wedges enable the reconstruction of paleotemperatures. Radiocarbon dating of organic material yields a timescale (in BP) for such paleotemperature records.

2. The Seyaha cross-section

A multistage ice-wedge complex (Fig. 1) with a depth of 22–24 m is exposed for a length of more than 4 km along the Ob Bay coastline near the Seyaha settlement. Three characteristic structural parts can be observed. In the bottom part (the lowest 11 m), the ice-wedges are the 3 m wide. The host sediment is laminated peat with moss and plant remains and a small admixture of sandy loam. The middle part (8–9 m) contain narrow (1–1.5 m width) ice-wedges penetrated into the ice-wedge body of the lower part. This ice contains mineral inclusions. The host sediments are laminated and contain little organic material. The uppermost 2–3 m of the section contain narrow 1.5 m wide ice-wedges penetrated into the ice-wedge body of the middle stage. These ice-wedges contain vertical inclusions of sand. Good preserved, very thin and not re-deposited foraminifera were found here.

The host sediments have been radiocarbon dated conventionally in the past. The dates in the middle part are all around 22,000 BP. The bottom of the cross-section is dated about 30,000 BP. There is one older date: 36,800 +3200/−2100 (Hel-3950). But a well preserved *Betula nana* twig, later dated by AMS, yields 31,200 ± 90 BP (Hela-201). We consider this AMS date more reliable, because contamination with allochthonous material can be excluded here. We therefore conclude that the lowest layer of peat started to form about 30,000–31,000 BP. When we have only dates of organic material from the host sediments surrounding the ice-wedges, we assume that ice-wedges at the bottom of the cross-section began to grow about 27,000 BP [1,2] due to underestimating the contribution of older, reworked carbon in permafrost

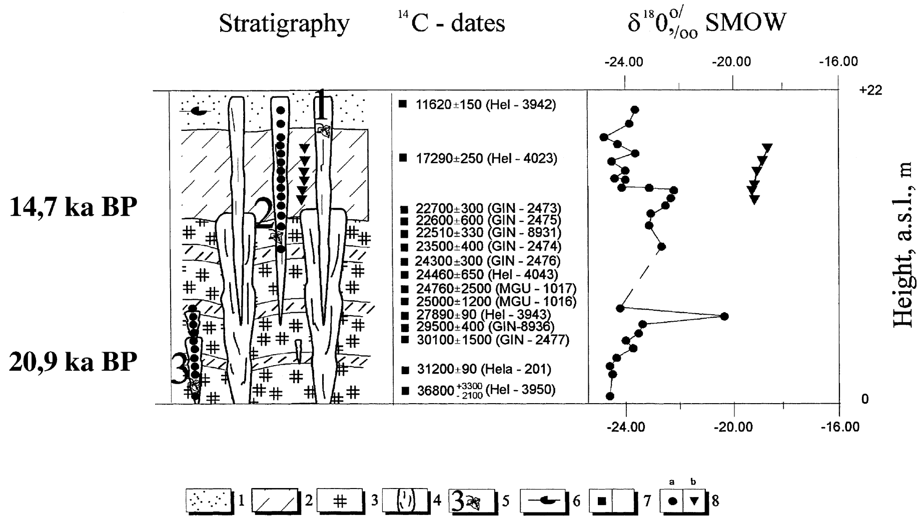

Fig. 1. Relations between age of syngenetic sediments with ice-wedge complexes near the Seyaha settlement: (1) sand; (2) sandy loam with small content of allochthonous organic; (3) horizons enriched with autochthonous and allochthonous organic; (4) syngenetic Late Pleistocene large ice wedges; (5) AMS-samples from syngenetic Late Pleistocene ice wedges; (6) site of marine foraminifers finds; (7) radiocarbon dates of rootlets and dispersed plant materials; (8) oxygen-isotope ratio: (a) – of ice wedge, (b) – of segregated ice (ice lenses in host sediments).

conditions and an indefinite depth of frost cracking at that time.

By means of AMS, the ice-wedges themselves can now be dated directly by their organic remains found in the ice. In 1996 samples of ice (10 kg each) from three different levels of the ice-wedges were collected (see Fig. 1; AMS sampling locations are indicated by the numbers 1–3). The micro-organic material was extracted, pre-treated by the usual acid–alkali–acid method, combusted to CO_2 [3] and subsequently reduced to graphite and measured by the Groningen AMS facility [4].

The results of the AMS measurements are shown in Table 1. The dates show that the ice-wedges began to form about 21,000 BP. Now that we have direct dates of the lower ice-wedge ice ranging from 14,000 to 21,000 BP, we are able to deduce that some of the host sediment samples (GIN-2473, 2474, 2475 – see Fig. 1) must have been contaminated by old carbon. There is one sample (GIN-2476) from the same collection containing autochthonous organic material, yielding a more consistent result. From the upper AMS dates (nos. 1 and 2, Table 1), the alkaline extracts are older than the organic component. The AMS dates of both the alkaline extract and the micro-organic material of the lowest sample are almost identical. These differences can be explained by the formation process of ice-wedges of the second and third stages in open beach conditions. They can be contaminated with fine organic dust blowing into frost cracks from neighboring exposures of old sediments. Some organic material penetrated into the frost cracks came from the sand with a high concentration of ancient organic material. The natural conditions for ice-wedge formation at the lowest stage were less suitable for contamination of frost cracks by ancient organic material, because there was of tundra vegetation and peat covering the sea coast. Only contemporaneous organic material could penetrate into the frost cracks at that time.

The large ice-wedges were sampled for $\delta^{18}O$ analysis with a vertical resolution of about 2–3 samples per m. The results (27 samples) are plotted at the right part of Fig. 1. The $\delta^{18}O$ values in the ice-wedges range from -25.0 to $-20.4‰$. The δD values (10 samples) range from -189 to $-153‰$. Modern ice-wedges are isotopically heavier: the $\delta^{18}O$ values in modern ice-wedges range from -16.6 to $-18.0‰$, the δD values are about $-130‰$. The $\delta D/\delta^{18}O$ relation is close to the global Meteoric Water Line (MWL), which is evidence for the atmospheric origin of the precipitation. The deuterium excess for Late Pleistocene ice-wedge ice is slightly larger than for modern ice, showing changes in evaporation conditions during the period 21,000–11,000 BP.

By using the empirical relation between mean winter temperature and $\delta^{18}O$ in ice-wedge ice, we deduce that the mean winter temperature during 22,000–14,000 BP has been 6–9°C colder than at present.

3. The Shchuch'ya cross-section

In the Shchuch'ya valley, thick syngenetic ice-wedges are found in a 5.0–5.5 m thick peat profile

Table 1
AMS-^{14}C measurements for ice-wedge complexes, Yamal Peninsula, Russia

N	Field no of samples	Depth (m)	Material	Lab code	^{14}C age, years (BP)
The Seyaha Late Pleistocene ice-wedges					
1	363-YuV/27	1.8	Micro-organic	GrA-10538	14,550 ± 100
1a			Alkaline extract	GrA-9847	19,920 ± 130
2	363-YuV/87	12.0	Micro-organic	GrA-10539	14,720 ± 100
2a			Alkaline extract	GrA-9848	23,620 ± 160
3	363-YuV/125	20.6	Micro-organic	GrA-10536	20,960 ± 140
3a			Alkaline extract	GrA-10535	21,440 ± 140
The Shchuch'ya Holocene ice-wedges					
4	364-YuV/168	3.5	Moss	Hela-262	7150 ± 75

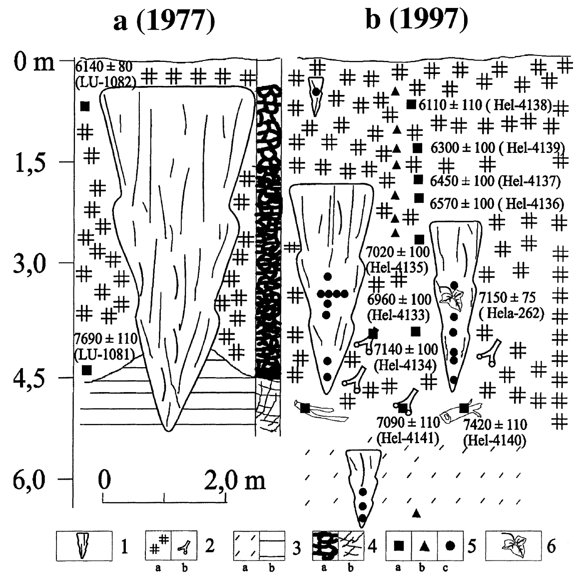

Fig. 2. Relations between age of syngenetic peat with Holocene ice-wedge complexes Shchuch'ya River valley, near Edem'yaha Creek: (1) Ice-wedges ice; (2) Organic material: (a) – peat, (b) – wood; (3). Inorganic sediments: (a) – sandy loam, (b) – clay; (4) Structure forming ice content: (a) – with very high iceness, (b) – with less iceness; (5) Samples: (a) – for conventional radiocarbon dating, (b) and (c): for oxygen-isotope and deuterium analyses ratio: (b) – of segregated ice (ice lenses in host sediments), (c) – of ice wedge ice; (6) AMS-samples from syngenetic Holocene ice wedges.

(Fig. 2). About 1.5-m thick wood trunks and lacustrine sandy loam are at the base of the wedge. The ^{14}C ages of the wood and root samples range between 7000 and 7400 BP. The peat growth between 6100 and 7000 BP corresponds to the Holocene climatic optimum [5]. The ice-wedges are contemporaneous with this wood and peat horizons. Evidence for this is their large vertical extension, the cyclic vertical structural characteristics of the ice in the peat, a decrease in peat thickness going from the center to the margin of polygons, the raised bottom of the peat from central part of the peat into the ice, and the presence of ice-wedges in the lacustrine sandy loam.

Two radiocarbon dates have been obtained in 1977 (Fig. 2(a)). Later, a larger number of dates has been obtained for this thick peat in 1997 (Fig. 2(b)); one AMS date for a moss sample has been measured directly from the syngenetic ice-wedge. The beginning of the peat formation at this site took place 7600–7200 years ago, which is in agreement with the radiocarbon dates. The end of the peat accumulation is dated about 6100 years ago. This shows that about 5 m of peat accumulated during a period of 1000–1100 years.

AMS dating of moss from the ice-wedge body allows refining the age determination of the ice-wedge ice, which coincided with peat accumulation which began 7100–7200 years ago, and also to establish the depth of frost cracking and melt water penetration into ice-wedges at a depth of about 1–1.5 m (close to the present time). This is probably caused by temperate winters during the Holocene optimum. However, it is important to note that ice-wedge formation processes in the Shchuch'ya River valley were intense during the Holocene optimum.

The stable isotope ratios δD and $\delta^{18}O$ of the ice-wedges and ice structural elements (such as ice lenses and schlieren) are used for the reconstruction of palaeotemperature records. For segregated ice (ice lenses in the host sediment), the $\delta^{18}O$ values range from -14.22 to $-10.80‰$, which is isotopically heavier than the Holocene ice-wedges with values ranging from -20.3 to $-17.39‰$. For deuterium, these values are -110.4 to $-97.9‰$, and -151.0 to $-139.6‰$, respectively. The deuterium excess varied from +0.24 to +5.46‰ in segregated ice and from +4.74 to +8.02‰ in ice-wedges. In modern ice-wedge ice, $\delta^{18}O = -18.2‰$, $\delta D = -135.7‰$ and the deuterium excess is +9.9‰, i.e., the deuterium excess values for the Holocene optimum ice-wedge ice is very close to modern values. In general, the deuterium excess is higher in ice-wedge ice and lower in segregated ice. This is an indication for a different origin of ice: the ice-wedge ice originates from the atmosphere, whereas segregated ice is formed from active layers of water (melting during the summer, at the top of the permafrost).

4. Discussion and conclusions

By dating small samples by means of AMS it is very difficult to assess that the sample represents autochthonous material. Nelson et al. [6] marked that it is very important that all size fractions of organic sediments from Arctic coastal plain are likely to be contaminated by re-deposited organic carbon, even after cleaning. Only autochthonous objects such as plants in situ, fossil rodent burrows, etc. are suitable for AMS dating. The narrow range of the oxygen isotope data within large ice-wedge and the good correlations among ice-wedges [7] suggest some homogenization of annual variations within sites. Some homogenization by partial melting and percolation may also occur.

The stable isotope ratios of the ice-wedges reflect temperature variations, allowing comparison of different cryosphere proxies: i.e. syngenetic ice-wedges, Greenland ice cores, cores of Canadian islands ice caps, cores of mountain glaciers, etc. [8–10]. The results are important as an indicator for global and contemporaneous climatic variations for the period 22,000–14,000 BP.

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