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# First direct dating of Late Pleistocene ice-wedges by AMS

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## Abstract

We present the first direct dating by <sup>14</sup>C-accelerator mass spectrometry of three Late Pleistocene syngenetic ice-wedges from the Seyaha cross-section. They are representative of permafrost with multistage ice-wedges from the North of Western Siberia. The most important result is the clear vertical age stratification of the ice, i.e. the old ice is located beneath the young. This shows that a timescale can be assigned to these ice-wedges penetrating down into the permafrost. The age of the ice shows a depth of not more than 3–5 m for frost cracking; water penetrated into the ice-wedges at that depth. The lower part of the ice-wedges from the Seyaha cross-section has been dated between 21 000 and 14 000 BP. © 2000 Elsevier Science B.V. All rights reserved.

*Keywords:* accelerator mass spectrometry dating; ice wedges; Pleistocene; paleoclimatology

## 1. Introduction

Syngenetic ice-wedges, a type of ground glaciation, occur throughout areas covered with permafrost. Ice from such ice-wedges forms a unique archive, preserving many features of the past environment. The analysis of the constituents collected in the ice provides new information about the history of the climatic system.

Syngenetic ice-wedges as old as 40 000–50 000 years are available for investigation in natural exposures along sea shores, river or lake banks and

in quarries [1,2]. This allows detailed and clean sampling of the ice, independent of its age. Syngenetic ice-wedges can be dated either by conventional dating of bulk organic material from the host sediments surrounding the ice, or (almost) directly by accelerator mass spectrometry (AMS) dating of organic micro-remains, which were transported by aerosols and trapped in the ice-wedge ice. Earlier attempts to date macro-organic remains directly from ice-wedges yielded conflicting results [2].

The peculiarities of ice-wedge dating result from their formation process [1]. The ice-wedges result from the filling of frost cracks with snow-melt water, consisting of many vertical veins. Syngenetic ice-wedges form under conditions of slow, continuous sedimentation accompanied by re-

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peated frost cracking. Subaqueous and subaerial stages of the wedges can be distinguished by their sedimentation conditions. The subaqueous stage corresponds to a relatively short period (about 1000 years) of a high accumulation rate and the subaerial stage corresponds to a relatively long period (more than 5000 years) of a low accumulation rate. The growth of ice-wedges is a fluctuating process, which is slower during subaqueous deposition of sand, sandy loam or loam and faster in subaerial conditions during accumulation of peaty sediments or peat. The  $^{14}\text{C}$  dates of the host sediments are almost all from such subaerial stage sediments and rarely from the subaqueous stage.

Direct dating of ice-wedges gives information about the exact depth of frost cracking. This can be done by dating small amounts of organic material by means of AMS [1,3]. Here we report on such a study for a representative ice-wedge cross-section: Seyaha in the North of Western Siberia.

## 2. The Seyaha cross-section

The site at the Seyaha Settlement on the east coast of Yamal Peninsula (70°N, 72°E) was investigated by the authors in 1978, 1980 and 1996. The exposure extends more than 4 km along the coastline of the Ob Bay. This sequence with a depth of 22–24 m is especially valuable for paleo-geographical reconstruction thanks to the abundance of multistage ice-wedges. The sediments accumulated continuously during almost 20 000 years: from 30 000 to 11 000 BP (according to  $^{14}\text{C}$  dates of the host sediments). Three characteristic parts can be observed in the geocryologic structure of the section (Fig. 1).

The lowest 11 m is characterized by 3 m wide ice-wedges of pure ice. This part of the sediment formed when the lower coastal parts of the Ob Bay were inundated, as indicated by the structure of these layers, with organic inclusions. The host sediments accumulated in alternating subaqueous–subaerial conditions, they are laminated and contain organic material such as rootlets, stems and leaves (subaerial layers) with sandy

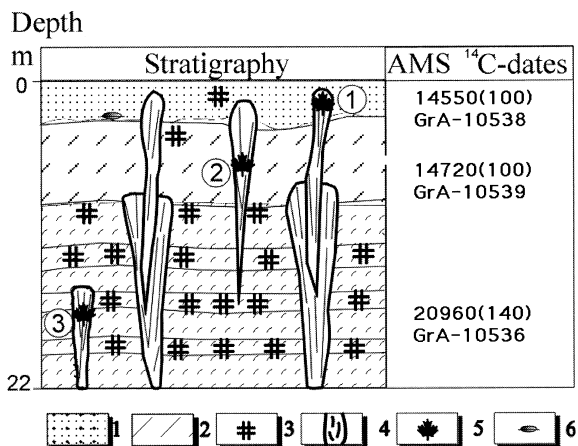


Fig. 1. Syngenetic sediments with ice-wedge complexes near the Seyaha settlement. The AMS dates are indicated. Sample No. 1 is for re-deposited material (see text). Legend: (1) sand; (2) loamy sand with small content of allochthonous organic material; (3) horizons enriched with autochthonous and allochthonous organic material; (4) syngenetic Late Pleistocene large ice-wedges; (5) AMS-samples of non re-deposited micro-organic remains from syngenetic Late Pleistocene ice-wedges (numbers correspond with Table 1) and (6) marine foraminifera.

loam admixture (subaqueous layers). The main part of the organic material consists of moss remains of *Drepanocladus fluitans* (Hedw.) Warnst., *Tomentipnum nitens*, *Paludella squarrosa*, *Scorpidium scorpioides*, herbs *Eriophorum vaginatum*, *Carex caespitosa*, *Carex rostrata*, *Carex inflata* and also single remains of shrubs *Oxycoccus* sp. and *Ledum palustre* L. In addition, organic laminae contain a small amount of mineral admixture.

The middle 8–9 m of the section contains 1–1.5 m wide ice-wedges. These wedges also penetrate into the ice-wedge body of the lower stage and show vertical layers containing mineral inclusions. The host sediments are laminated but have a low organic content, because we believe that this part of the sediment accumulated during a period of higher water levels of the Ob Bay.

The uppermost 2–3 m consists of laminated yellow sand (subaqueous layers). This part of the sediment is assumed to have formed during a more inundated period. This conclusion is shown by both structural features of the deposit and from the presence of well-preserved and not

re-deposited sub-saline foraminifera: *Elphidium subclavatum* Gudina, *Pninaella pulchela* Parker, *Protelphidium parvum* Gudina, *Discorbis* sp., *Miliolinella* cf. *subrotunda* (Montagu), *Discorbis deplanatus* Gudina, *Globulina glacialis* Gushman et Ozawa, etc. The uppermost part of the section contains 1.5 m wide ice-wedges; these penetrate into the ice-wedge body of the middle stage. These ice-wedges also contain vertical inclusions of sand.

Previous work on the chemical composition of ice from ice-wedges and segregated ice (ice lenses in the host sediments) shows a varying influence of the Ob Bay for different sedimentation regimes. For a more detailed description we refer to [1].

### 3. Results and discussion

The age of Late Pleistocene syngenetic ice-wedges in the Seyaha cross-section has been determined in two ways, by conventional radiocarbon dating and by AMS dating.

#### 3.1. Conventional dating of host sediments

Radiocarbon dating of organic material from the host sediments was done in two stages. At first, a series of six radiocarbon dates ranging

from 30 000 to 22 000 BP from the host sediment were obtained from the Institute of Geology, Moscow (laboratory code GIN) in 1982 [4]. The lower part of the section was dated, which consisted of laminated organic material with sandy loam. Later, the lower part of the section was re-dated and also several very important dates from the host sediment of the upper part were obtained in 1996–1997 from the University of Helsinki (laboratory code Hel). There is a good agreement between radiocarbon dates from the same horizons, which have been obtained in 1980 and in 1997 (after the field seasons 1979 and 1996). For example, the date of  $30\,100 \pm 1500$  BP (GIN-2477) was obtained at 21 m depth at the basement of the ice-wedge complex and the date of  $29\,500 \pm 400$  BP (GIN-8936) was obtained 17 years later at a depth of 20 m (Table 1). The date of  $22\,600 \pm 600$  BP (GIN-2475), from the depth of 10 m, is very close to the date of  $22\,510 \pm 330$  BP (GIN-8931), obtained 17 years later from a depth of 11 m [3]. The dates are very consistent in spite of the possible presence of allochthonous components in the sediments. In particular, the bottom and top of the lowermost 11 m of the laminated sediment are well dated. The bottom section was first dated to about 30 000 BP. One AMS date of a *Betula nana* twig from the same sample gave an age of

Table 1  
<sup>14</sup>C dates for the Seyaha ice-wedge complex, Russia: dating of the host sediment

Sample	Depth (m)	Material	Laboratory code	<sup>14</sup> C age (yr BP)
363/55	0.8	peat	Hel-3942	11620 ± 90
363/77	3.2	peat	Hel-4023	17290 ± 250
279/10	8.6	peat	GIN-2473	22700 ± 300
279/13	10.0	peat	GIN-2475	22600 ± 600
363/207	11.0	peat	GIN-8931	22510 ± 330
363/111	12.0	peat	Hel-4046	22850 ± 440
279/16	12.0	peat	GIN-2474	23500 ± 400
363/206	12.0	peat	Hel-4043	24460 ± 650
363/62	12.2	peat	Hel-4056	25300+900
363/112	15.2	peat	Hel-3943	27890 ± 90
279/23	16.2	peat	GIN-2476	24300 ± 300
363/212	20.5	peat	GIN-8936	29500 ± 400
279/28	20.9	peat	GIN-2477	30100 ± 1500
363/211	20.9	twig	Hela-201	31200 ± 900
363/208	20.9	peat	Hel-3950	36800+3300/–2100

31 000 BP (Hela-201). This confirms that the lowermost 11 m layer began to form about 30 000 BP. The dates for samples taken from different sites of the 4 km long exposure along the Ob Bay coastline from the same depth suggest the chronology. Five dates from 11 m depth were obtained, ranging from 22 300 to 22 800 years BP.

The radiocarbon dates of the peat (Table 1) show that the 11 m of sediment at the bottom of the cross section accumulated during ca. 7500 years. The accumulation rate was about 1.3 m per 1000 years.

The accumulation rate and age of the sediments can be used to obtain a timescale for the  $^{18}\text{O}$  curves of the ice-wedge ice [1,4,5]. However, a more accurate age can be obtained by direct AMS radiocarbon dating of organic material extracted from ice-wedge ice. When only dates of organic material from host sediments surrounding ice-wedges were available, we had assumed that ice-wedges at the bottom of the cross-section began to grow about 27 000 years ago [1,4]. We conclude that we have underestimated the possibility of re-deposition of old organic material under syngenetic permafrost conditions.

### 3.2. Direct AMS dating of ice-wedge ice

In 1996, large samples of ice from three different levels of ice-wedges were collected. Extracted organic material was radiocarbon-dated using AMS. Up to 10 kg of ice was sampled and thawed in a closed bottle near the sampling site. After settling during 48 h, the water was discharged and the residue collected.

The ice-wedges themselves were dated by small organic remains obtained from the ice. The mate-

rial was pre-treated by the usual acid–alkaline–acid method [6], combusted to  $\text{CO}_2$  and subsequently reduced to graphite and measured by AMS [7] in Groningen (laboratory code GrA).

The AMS dates show that ice-wedges began to form about 21 000 BP (sample No. 3 in Fig. 1). From these direct dates of ice-wedge ice from 21 000 to 14 000 BP we are able to deduce that the 1980 host sediment samples No. 10, 13 and 16 (GIN-2473, 2474, 2475) must have been contaminated by older organic material. Sample No. 23 (GIN-2476) from the same collection contained autochthonous organic material, yielding a more consistent result. It is likely that contemporaneous ice-wedge ice is found 3–5 m lower, because water penetrated into ice-wedges at that depth (the depth of frost cracking at that time).

From the AMS dates for the deepest samples (see Fig. 1, No. 2 and 3), we conclude that the ice-wedge vertical accumulation rate was about 1.2–1.3 m per 1000 years. The soluble alkaline extracts are older than the organic component for samples 1 and 2 (Table 2). These differences can be explained by the formation of ice-wedges of the higher stages 2 and 3 in open beach conditions. The ice-wedges could have been contaminated with fine organic dust, which blew into frost cracks from neighboring exposures of ancient sediments. Some organic material, which penetrated into the frost cracks may have come from the sand with a high concentration of ancient organic material. Evidence for this suggestion is the high concentration of re-deposited pollen and spores older than Pleistocene in the upper part of the section. However, the AMS dates of both the alkaline extract and the organic material of the lowest sample (No. 3) are almost identical.

Table 2

$^{14}\text{C}$  dates for the Seyaha ice-wedge complex, Russia: direct dating of the ice-wedge

No.	Sample	Depth (m)	Material	Laboratory code	$^{14}\text{C}$ age (yr BP)
(1)	363/27	1.8	micro-organic	GrA-10538	14550 ± 100
(1a)			alkaline extract	GrA-9847	19920 ± 130
(2)	363/87	12.0	micro-organic	GrA-10539	14720 ± 100
(2a)			alkaline extract	GrA-9848	23620 ± 160
(3)	363/125	20.6	micro-organic	GrA-10536	20960 ± 140
(3a)			alkaline extract	GrA-10535	21440 ± 140

The natural conditions during ice-wedge formation at the lowest stage were less affected by contamination because during that time there was tundra vegetation and peat covering the seacoast. This young organic material penetrated into the frost cracks at these times, which explains why the dates of both fractions for sample No. 3 are identical.

Up to now, ice-wedges have been dated by  $^{14}\text{C}$  dating the surrounding host sediments. The correlation between these dates and  $^{18}\text{O}$  data of the ice, yielding paleoclimate information, is difficult, for example, if the depth of frost cracks is different for the different epochs.

Whether the  $^{14}\text{C}$  dates of micro-organic material included in the ice-wedge are correct, depends on whether they have an autochthonous or allochthonous origin [9]. The dates of alkali-soluble fractions of the  $^{14}\text{C}$  sample are older, apparently because old organic material is re-deposited into the initial cracks. For the Seyaha cross section presented in this study, it is possible to select samples with a high content of autochthonous material.

The AMS dates are crucial for the investigation of the changes of levels in the Ob Bay during the late Pleistocene. The upper half of the section accumulated between ca. 11 000 and 19 000 BP. The conventional date at 17 000 BP represents the time of the deepest regression [8]. At 11 000 BP the subaqueous stage terminated. It may be possible to verify our dating of ice in the ice-wedges by AMS dating of  $\text{CO}_2$  trapped in the ice [10].

#### 4. Conclusions

For the first time, we have directly dated ice-wedges by  $^{14}\text{C}$ -AMS, using micro-remains of organic material extracted from the ice. Syngenetic ice-wedges formed by the penetration of melt water in frost cracks in the ice-wedges, contemporaneously with sediment accumulation. The older ice is located below the younger, confirming stratigraphy. Our data show a good perspective for dating Late Pleistocene syngenetic ice-wedges by means of radiocarbon measurements. The time of

formation of ice-wedges, determined by direct (AMS) and indirect ice dating (host sediments which can be dated by conventional  $^{14}\text{C}$ ) is consistent. We can apply these methods to other important cross sections in the permafrost. In combination with stable isotope ( $^{18}\text{O}$ ,  $^2\text{H}$ ) analysis of the ice it now becomes feasible to reconstruct chronologies for winter paleotemperatures of ground ice.

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