RADIOCARBON DATING OF $\delta^{18}O$-δD PLOTS IN LATE PLEISTOCENE ICE-WEDGES OF THE DUVANNY YAR (LOWER KOLYMA RIVER, NORTHERN YAKUTIA)

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ABSTRACT. The Duvanny Yar cross-section located in the Lower Kolyma River valley of Northern Yakutia (69°N, 158°E, height above the Kolyma River level 55 m), has been studied and dated in detail by radiocarbon. The sequence mainly consists of sandy loam sediments with large syngenetic ice wedges. Their width at the top is 1–3.5 m. Allochthonous organic material occurs in high content, concentrating as 0.5–0.7 m lenses. Shrub fragments, twigs, and mammoth bones are accumulated in peaty layers. Through interpolation based on a series of ^{14}C dates, dating of the host sediments provides an approximate age for the ice wedges. The ^{14}C dates of various types of organic material are sometimes very close, but not all in agreement. Therefore, the dates do not accurately show the age of the $\delta^{18}O$ and δD plots. A new approach is developed to a ^{14}C dating strategy of syncryogenic sediments with high admixture of allochthonous organic material. The main purpose of this study is to consider detection of inversions or disturbances in the syngenetic permafrost sediment at the Duvanny Yar cross-section by ^{14}C date series. Direct accelerator mass spectrometry (AMS) dating of the ice confirmed the relatively young age of ice wedges.

INTRODUCTION

The Duvanny Yar is a well-known cross-section containing numerous evidences of the Late Pleistocene Siberian paleoenvironment. It has been studied repeatedly and several series of radiocarbon dates have been obtained. The dates reflect different space cross-sections of the Duvanny Yar ice-wedge complex. We also present stable isotope study of ice-wedge, ice lenses, and schlieren, as well as paleotemperature reconstruction based on isotope data.

Study Area and Dated Material

The cross-section is located in the Lower Kolyma River valley in Northern Yakutia (69°N, 158°E), about 160 km from the mouth of the Kolyma River, in typical forest tundra. This is the best exposure of the vast (more than 1000 km^2) Omolon-Anyui edoma (Figure 1). Over the last 30 years more than 50 ^{14}C dates were obtained from this site (Figure 2). Kaplina (1986) performed first sampling of organic material for ^{14}C dating in 1972 and 1974. Two large series of ^{14}C dates were obtained in 1985 by Tomirdiaro (Tomirdiaro and Chyornen'kiy 1987) and Vasil'chuk and Sulerzhitsky (Vasil'chuk 1992; Vasil'chuk and Vasil'chuk 1997; Vasil'chuk and Kotlyakov 2000). The approximately vertical sampling profiles are shown in Figure 2a. During the 1990's Gubin (1999) derived a number of ^{14}C dates (Figure 2b). The time difference between sampling hampers the comparison of ^{14}C dates. First, because the ice-wedge sediments of the Duvanny Yar is very rapidly eroded by the Kolyma River. According to our evaluation, the shoreline degrades several meters per year; at Duvanny Yar it has been displaced by more than 100 m over the last 30 years. Second, since the layers with organic material are not strongly horizontal, it is very difficult to compare the data from the same layer as some layers are thinning out.

The first oxygen isotope record was obtained in 1985 (Vasil'chuk 1992, Table 1, Figure 3). In August 1999 the Duvanny Yar cross-section was well exposed along the Kolyma River. Samples

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could be taken in detail of the ice-wedge complex fragments of various origin and composition. A large number of ^{18}O and ^{2}H data were obtained (see Figure 2b).

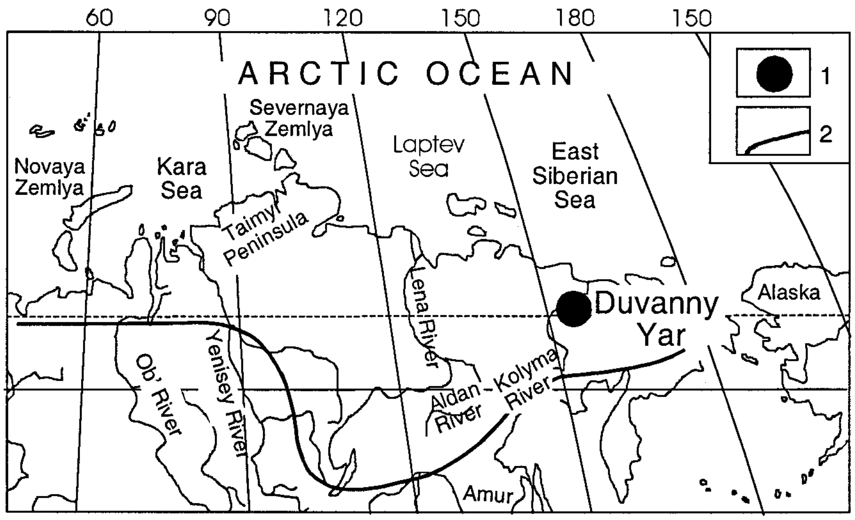

Figure 1 Map showing the location of the Late Quaternary Duvanny Yar natural exposure with syngenetic ice wedge in northern Yakutia: 1. syngenetic ice wedge sites; 2. southern boundary of modern and preserved Late Pleistocene syngenetic ice wedges.

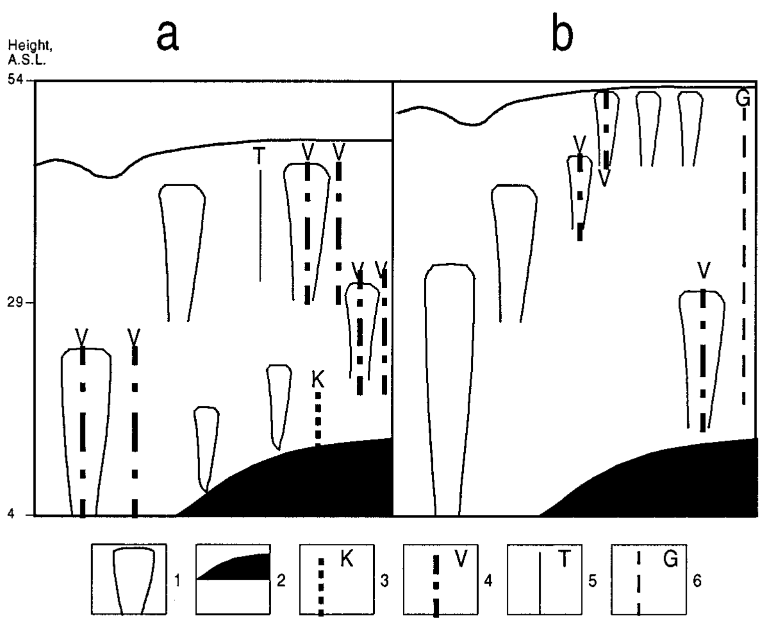

Figure 2 Sketch of the Duvanny Yar cross-section in 1970–1985 (a) and in 1995–1999 (b) and location of sampling points: 1. wide syngenetic ice wedges; 2 bluish-gray sandy loam; 3. ^{14}C samples collected in 1972 (Kaplina 1986); 4. ^{18}O, D, ^{14}C samples, collected in 1985 and 1999 (Vasil'chuk 1992; Vasil'chuk and Kotlyakov 2000); 5. ^{14}C samples collected in 1985 (Tomirdiaro and Chyornen'kiy 1987); 6. the same collected in 1993–1997 (Gubin 1999).

Mechanism of Ice-Wedge Formation

The formation of syngenetic permafrost sediments has a cyclic character that occurs independently of climatic change and results from changes of sedimentation regime. The macro cyclic formation of syngenetic ice wedges causes a cyclic structure of the section and a rhythmic distribution of the composition in host sediments and ice wedges. The main source of water for syngenetic ice wedges is snowmelt. Minor sources comprise of hoarfrost and melt of an active layer. Within high terraces and divides, syngenetic ice wedges are formed exclusively by freezing of atmospheric water within the frost cracks (those of the epigenetic type). On flood plains and coastal plains, small ice wedges also form by snow (rain) flowing into the frost cracks (if the crack is open to the surface) or sometimes by water from seasonally thawed layers (in the case of intrastratal frost cracks). When peat accumulates, ice wedges grow at a subaerial stage. At the subaqueous stage, the layers of sandy loam, loam and sand deposit, and the formation of syngenetic ice wedges slow down (Vasil'chuk and Vasil'chuk 1996, 1998). Several ice wedges are multistage.

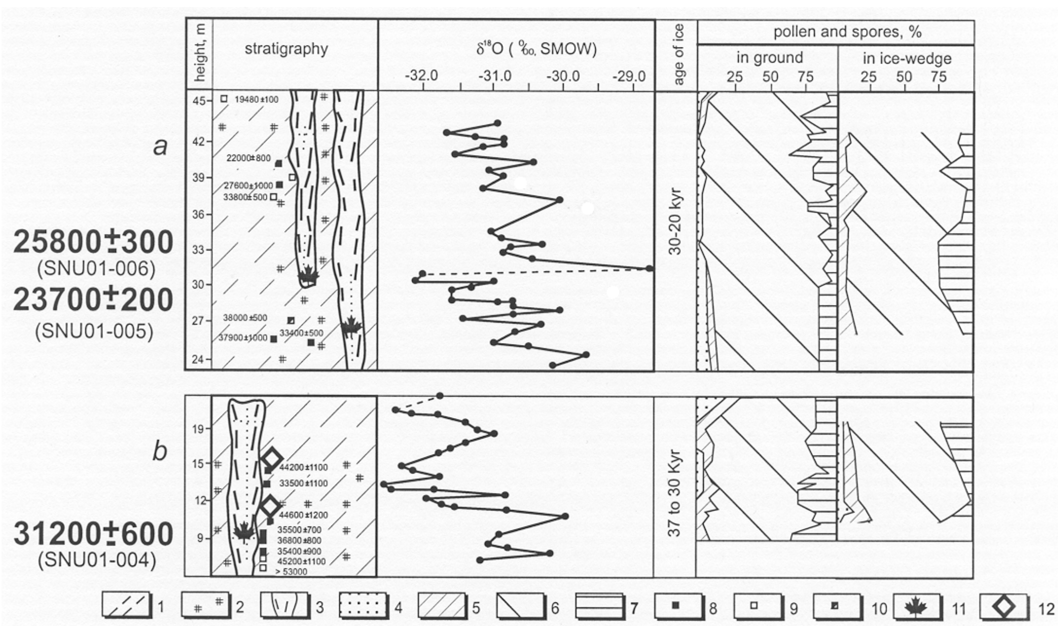

Figure 3 Late Pleistocene syngenetic ice wedges in (a) upper part at middle-stream fragment and (b) lower part at down-stream fragment of the natural exposure Duvanny Yar, oxygen isotope plots of large syngenetic ice wedge and ^{14}C dating of different organic matter enclosed in sediments: 1. Sandy loam; 2. Peat and plant remains; 3. Large syngenetic ice wedge. Content of pollen and spores in spectra; 4. Tree pollen; 5. Shrub pollen; 6. Grass and small bush pollen; 7. Spores. Conventional ^{14}C dates of: 8. Dispersed amorphous organic plant material (DAOPM); 9. Bones; 10. Wood; 11. AMS ^{14}C date of ice-wedge ice; 12. AMS ^{14}C dating of different DAOPM fractions.

The formation mechanism, which has been proposed, allows allocating the isotopic, palynologic and other data to a chronological scale with sufficient accuracy. The $\delta^{18}O$ and other diagrams are discontinued in time, and for long-term subaerial stages corresponding to the polygonal ice wedge formation. The breaks correspond to subaqueous stages (as a rule this stage is shorter than the subaerial one). The organic matter appointed to the subaerial phases is commonly better dated with ^{14}C.

Cross-Section Description

Exposures of highly icy ice-wedge complexes are destroyed from year to year. During every field season investigators can observe different parts of the same ice-wedge complex, so several different series of ^{14}C dates have been obtained during different field seasons (Table 1). However, the main structure of the cross-section has been preserved for many years. There are two evident parts of the section: the upper 15–17 m with a very poor content of organic material, but still sufficient for ^{14}C dating, and the lower 28–30 m, which is enriched in organic matter.

The latter part contains three layers of peaty sediment with a high admixture of allochthonous organic material. The sequence mainly consists of sandy loam sediments and large syngenetic ice wedges. The total ice content, including the structure-forming ice, is about 50%. The ice wedges are wider (up to 2–2.5 m) in the lower part and narrow (up to 1–1.5 m) in the upper part. The distance between ice wedges in the lower part is 12 m, in the upper part it is reduced to 4 m. In the upper part of the cross-section 1.5–2 m ice wedges together with tall (up to 7 m high) veins, narrow (1 m wide) and short (4–5 m high) ice wedges occurred under a cover of gray sandy loam at a large circus-like exposure (150–180 m long, 45–55 m high). Ice wedge ice is gray with big bubbles and veins of gray sandy loam. Large ice wedges often have shoulders at the top of the peaty layer. The appearance of shoulders varies from evident to slight crooks. In the upper part of the cross-section the shoulders are located at the same level as the top of the small ice wedges. This is attributed to synchronous accumulation of ice wedges and host sediments.

A cyclic distribution of the ice content and cryo-structures is observed. This is seen as the appearance of the ice lenses: the thickness of the ice and total ice content decrease from poor peaty sediments toward sediments enriched by peat. However, in the peat layers the ice content decreases rapidly. Such cryogenic structure is explained by the formation of sediments in subaqueous conditions and their freezing at the drainage stage during the formation of the peat layer.

A specific shape of the bottom of organic layers is observed, with downward pointing "dents" about 1.5 m long and 0.4 m wide at the top. The same "dents" are found at the Holocene *alas* (drainage lake) exposure near the Duvanny Yar cross-section. Here, the peat is underlain by sandy loam. At the bottom of this Holocene peat the "dents" are about 0.5 m long and about 0.2 m wide at the top. This is seen as evidence for the similarity of the Holocene *alas* series and every cycle of ice wedge complex.

The upper fragment of the cross-section also consists of three cycles. Every cycle is presented by pure gray sandy loam (3–4 m) covered by peaty sandy loam (0.7–1 m). There are accumulations of allochthonous shrub branches at the peaty layers, similar to those at present found in shallow oxbows in lakes. Throughout the cross-section clear signs of lacustrine and alluvial origin are observed. It is interesting that at the top of the cross-section fresh mammoth bone has been collected at the height of 39 m in situ and horse bone at the height of 46 m.

METHODS AND RESULTS

Permafrost occupies a great part of the Russian territory and vast areas of Canada and Alaska. In the geological past almost all Northern Europe and Northern America were covered by permafrost with temperature close to the present in the north of west Siberia and Northern Yakutia (Vasil'chuk and Vasil'chuk 1995, 1998). This phenomenon is, therefore, important for paleoreconstructions for areas that were covered by permafrost in the past.

In order to exclude the influence of microbes and algae, the samples were dried in the field or transported in frozen state and at last resort acid was added to inhibit algae activity. One part of the samples from cross section in Indigirka River valley was washed by river water and another part by melt water from simultaneous ice wedges. The results obtained (32,900 ± 800 BP, GIN-1678 on rootlets washed by river water, 29,300 ± 1300 BP, GIN-1679 on rootlets washed in water of simultaneous ice wedges) are very similar (Sulerzhitsky 1998). The samples of organic material from the bottom of the cross-sections of Plakhinski Yar and Ayon Island were also washed with water from ice wedges (Vasil'chuk 1992). For the Ayon cross-section the dates obtained were 28,600 ± 1000 (GIN-4968) and 28,100 ± 800 BP (GIN-4969), respectively. In the bottom of the Plakhinski Yar cross-section the rootlets also gave similar ^{14}C dates, 26,000 ± 1100 (GIN-3980), 27,000 ± 600 (GIN-3981) and 31,500 ± 1100 BP (GIN-3983).

All available components of organic material have been used for dating. For comparison, bone, peat, and dispersed amorphous organic plant material was collected. Allochthonous material such as bones, wood, dispersed plant material was found frequently. However, the autochthonous material was also sampled. In order to obtain ^{14}C dates of dispersed amorphous organic plant material the rootlets from bulk samples were separated by washing in ice-wedge water.

To check the preservation of the ^{14}C stratigraphy of thick cross-sections of permafrost sediments, we have collected series of ^{14}C dates for samples from different field seasons, since it is unlikely that microbe activity can change the dates uniformly. Table 1 and Figure 2 show four series of ^{14}C dates obtained by different scientists in different years.

Radiocarbon Dating

In cross-sections of syngenetic permafrost sediments age-inversions are common. Due to considerable admixture of allochthonous material in the bottom of the Duvanny Yar cross-section ages between 60,000 (or older) and 40,000 BP were reported. Therefore, only reliable material can be taken into consideration, such as layers of autochthonous peat, hay, and seed conglomerations from rodent burrows.

Because blue clay underlies the river level in marginal part and exposes only in the central part of the cross-section, the foot of the ice-wedge complex has a dome shape. The central part of the cross-section freezes earlier and expands. As it is located higher, organic material comes in to the marginal areas and lower parts accumulates in inverse order.

This can explain some uncertainties in ^{14}C dates between series of different years. The dates obtained from marginal parts of the ice wedge complex (see Figure 3b) were additionally enriched by old organic material, because during formation of this sediments erosion of old deposits took place.

Some investigators (e.g. Kaplina 1986) suppose that the lower 10 m of the cross-section is older than 40,000–50,000 BP. However, it was confirmed later, that a date of 36,900 BP at the height of 8.5 m is reliable enough, because a number of dates was obtained for the same depth interval: 29,900, 30,100, 31,100, and 35,500 BP (Vasil'chuk 1992; Gubin 1999). Using the youngest series of dates we assume that the age of the lower 25–30 m is 40,000–35,000 BP. A high concentration of old organic material is characteristic of this part; it leads to irregular results from ^{14}C dating.

Pollen spectra have been used for evaluation of the amount of allochthonous material. Relatively high percentages of *Betula sect Nanae* (up to 19%), the presence of *Pinus pumila, Larix sp., Betula sect Albae, Alnaster sp.* and *Ericaceae* characterize pollen spectra from the lower part. This may be

Table 1 The assay of ^{14}C dates from different authors for different kind of organic material of The Duvanny Yar Late Pleistocene ice wedge complexes in Northern Yakutia (Height-altitude above sea level; DAOPM-dispersed amorphous organic plant material. The presumable ^{14}C dates of re-deposited material are shown in italic).

Date (BP)	Laboratory N	Height (m asl)	Material
Kaplina 1986			
17,850 ± 110	MAG-592	42	DAOPM
31,100 ± 400	GIN-2280	20	DAOPM
>50,000	GIN-3866	15	Bone
33,800±1400	GIN-2279	12	DAOPM
38,000 ± 1400	GIN-2277	12	DAOPM
37,600 ± 1100	MSU-468	ca. 11	Peat
38,000 ± 2000	GIN-1688	9.5	DAOPM
36,900 ± 500	MSU-469	8.5	Peat
>53,370	LU-1678	8	Wood
>45,000	MSU-573	6	Wood
Tomirdiaro and Chyornen'kiy 1987			
24,070 ± 410	SOAN-2304	ca. 42	Peat
26,060 ± 650	LU-1675	ca. 42	Peat
34,025 ± 550	SOAN-2303	ca. 40	Peat
34,400 ± 1010	LU-1674	ca. 40	Peat
42,840 ± 2400	LU-1676	ca. 38	Peat
48,410 ± 3145	SOAN-2304	ca. 38	Peat
>50,000	SOAN-2305	ca. 14	Wood
>53,370	LU-1678	ca. 14	Wood
Vasil'chuk 1992			
19,480 ± 100	GIN-3868	46.0	Horse bone
22,000 ± 800	GIN-4017	40.8	DAOPM
27,600 ± 1000	GIN-4016	39.0	DAOPM
33,800 ± 500	GIN-3861	39.0	Bone
33,400 ± 500	GIN-4018	29.0	DAOPM
37,900 ± 1000	GIN-4015	24.0	DAOPM
34,700 ± 400	GIN-4434	24.0	Bone
37,900 ± 1000	GIN-4015	24.0	Rootlets
38,000 ± 500	GIN-3864	21.0	Rootlets
35,100 ± 100	GIN-3865	21.0	Soil
42,600 ± 1200	GIN-3862	19.0	Wood
28,600 ± 300	GIN-3867	15.0	Bone
44,200 ± 1100	GIN-4003	14.0	Rootlets
33,500 ± 1100	GIN-4006	13.0	Rootlets
44,600 ± 1200	GIN-4000	10.0	Rootlets
29,900 ± 400	GIN-4588	10.0	Black peat
35,500 ± 700	GIN-3999	9.5	DAOPM
30,100 ± 800	GIN-3998	9.0	DAOPM
45.200 ± 1100	GIN-3852	8.0	Wood
36.800 ± 800	GIN-3997	8.0	DAOPM
35,400 ± 900	GIN-3996	7.5	DAOPM
Gubin 1999			
13,080 ± 140	EP-941555	ca. 51	Soil
28,100 ± 700	GIN-7697	ca. 36	Soil
31,100 ± 900	GIN-8016	ca. 26	Soil
42,400 ± 1100	GIN-9596	ca. 15	Soil
43,800 ± 1700	GIN-9595	ca. 14	Soil
Sulerzhitsky and Romanenko 1997			
20,000 ± 1300	GIN-7696		Deer bone

connected both with the occurrence of re-deposited pollen and spores, and with warmer summer temperatures in comparison with the upper part. The regional pollen rain is presented by pollen spectra from ice wedge ice i.e. pollen, which come into frost cracks during spring. The key species are *Pinus pumila, Betula sect Nanae, Artemisia sp.*, immature herb pollen and *Selaginella sibirica* in the wide ice wedges of the lower part. The upper part is dated 30,000–13,000 BP, if we take into consideration only the youngest dates for every layer 13,080 BP at the height 51 m (soil), 19,480 BP at the height 45 m, horse bone, 28,100 at the 36 m height soil. It is obvious that older dates at the same levels point to the presence of allochthonous organic material. The pollen spectra from the upper part are characterized by a low percentages of shrub pollen and the abundance of immature herb pollen together with spores of *Selaginella sibirica.* These pollen and spores are often found in the ice wedge complex of Northern Yakutia and probably reflect facial conditions of edoma accumulation (and possibly inundation) when immature herb pollen are mixed in flood plain during rapid accumulation of the sediment. The same process provides re-deposition of allochthonous organic matter. In pollen spectra of the narrow ice wedges of upper part *Poaceae, Artemisia* sp., and Betula sect. *Nanae* dominated. According to pollen data the re-deposition of organic material was more probable during the formation of lower part the cross section.

Table 2 shows only the youngest ^{14}C dates obtained in each horizon. It is a matter of convention for evaluating the possibilities of ^{14}C dating by using the youngest dates only. Evidently, these results are not in contradiction with our age evaluation of the Duvanny Yar formation and show that the accumulation of the main part of the complex started at about 35,000–37,000 BP, and ended at about 13,000–10,000 BP. The approximate rate of accumulation of the complex is about 2 m per 1000 yr.

Table 2 The youngest number of ^{14}C dates

Date (BP)	Lab nr	Height (m asl)	Material
13,080 ±140	ÅĐ-941555	about 51	Soil
17,850 ± 110	MAG-592	about 42	DAOPM
19,480 ± 100	GIN-4016	40.8	Horse bone
28,600 ± 300	GIN-3867	15.0	Bone
29,900 ± 400	GIN-4588	10.0	Black peat
35,400 ± 900	GIN-3996	7.5	DAOPM

As is shown in Table 2, the upper part of the section accumulated faster than the lower. This is reflected by the external appearance of the ice wedges. Upper ice wedges are narrow; this is caused by rapid accumulation of their host sediments and ice wedges. Lower ice wedges are considerably wider, as a result of a low accumulation rate. Possibly, subaerial stages dominated during the deposition of the lower part, which is evident from the horizontal occurrence of peat layers at the lower part. For example, the date 36,900 BP from pure peat obtained at a height of 8.5 m. The ice of the upper ice wedges contains admixture of loam and sandy loam, the ice of the lower stage is pure.

The results of AMS ^{14}C dating in Seoul National University obtained in August 2001 confirmed our assumption to consider the youngest number of ^{14}C dates more reliable. The tested sample 316-YuV/9 has been taken from +14.0 m above sea level of the Duvanny Yar cross-section. The hot alkaline extract of bulk sample was dated in 1986 to 44,200 ± 1100 BP (GIN-4003). The sample (plant material preserved after acid and alkaline pretreatment in 1986 and dried) has been separated into three parts and dated using AMS techniques: 1) fragments of seeds: 45,700 ± 1200 BP (SNU01-077); 2) white thin twigs without crust (size about 1–0.5 mm): 40,500 ± 500 BP (SNU01-078), and 3) herb remains and detritus: 39,000 ± 1300 BP (SNU01-079). This points to an essential participation of allochthonous old organic matrix in this sediment. So do the youngest data obtained from herb remains and detritus. However, the third date is younger than the date of bulk samples by more than 5 ka and even this date did not match the age of sedimentation. Possibly, the sediments at the height of +14.0 m above the sea level are younger.

The date of bulk sample is close to the oldest date obtained from seed fragments. The sample 316-YuV/5 coming from the lower part of this cross-section (+9,8 m above the sea level) was dated in 1986 by hot alkaline extract to 44,600 ± 1200 BP (GIN-4000). Fragments of insects have been selected for microscope study from this sample in 2001 (preserved after acid and alkaline pretreatment in 1986 and dried also). The insect remains have been dated by AMS to 34,900 ± 800 BP (SNU01-076). This data fits well into the range of the youngest dates in Table 2. Thus, it is necessary to use the youngest number of dates as the most reliable in permafrost syngenetic sediments.

Direct ^{14}C Dating of Ice by AMS

In late May 2001, after this paper had been finished and accepted for publication, we obtained three new ^{14}C dates of organic material extracted directly from ice-wedge ice. The dating was made on organic material from these ice-wedge samples—they were collected in 1985 from three ice-wedges shown in Figure 3. The melted ice wedge water with small organic material was filtered and treated with acid-alkaline-acid method. Then, the plant micro-organic residue after this AAA treatment was combusted to the graphite and ^{14}C measurements were made by Tandetron 4130 (from HVEE) of Seoul National University. The obtained dates confirm the relatively young age of this ice-wedge complex (see Table 3).

Table 3 AMS ^{14}C dates of ice-wedge ice[a]

Field N	Height in m asl (depth)	AMS date (BP)	Laboratory nr
319-YuV/10	+26,9 (21,1)	23700 ± 200	SNU01-005
320-YuV/3	+31,7 (16,3)	25800 ± 300	SNU01-006
316-YuV/47	+9,7 (38,3)	31200 ± 600	SNU01-004

[a]Note: the sample with field N 319-YuV/10 is from ice wedge showed in the upper right part of Figure 3a; 320-YuV/3 in the upper left part of Figure 3a, in the lower part of Figure 3b and in Figure 4.

The results of direct dating clearly showed that ice-wedge complex has vertical stratification, i.e. starting at the bottom to the top of the cross-section the ice becomes younger. Importantly, this result is also a good correlation between the youngest ^{14}C dates from host sediments and the AMS dates from ice-wedges at the same depths.

DISCUSSION

The main issue of ^{14}C dating in our case is finding of the proper strategy for dating permafrost sediments and ground ice, and adequately dating the stable isotope—deuterium and oxygen isotope records from basic cross-sections of Northern Eurasia.

Contamination by old material is the main problem in ^{14}C dating of permafrost sediment because of the low decay rate and repeated re-deposition of old organic material. The younger sediments, thus, are contaminated by the old material together with old pollen and spores. In permafrost re-deposited pollen and spores are older than Pleistocene and are not uncommon even in autochthonous peat. If the percentages of re-deposited pollen and spores in a sample is more than 15–20%, the obtained ^{14}C date is probably too old. For example, 15% of old organic admixture can distort a ^{14}C date of a 10,000 BP sediment by 1300 years (Olsson 1974, 1991) and dating error of organic material older than 20,000 may be more than 10,000 yr.

It was shown by special study that the presence of allochthonous organic matter is a rule rather than exception, in the vertical direction as well as the horizontal. Sedimentation at different distances from the washed out peat or peaty sediments results in certain ^{14}C age variations through the area of present accumulation of lacustrine deposit. All these samples look similar and there it is impossible to make selection of the most reliable samples for dating. Evidently, in this case the most reliable date is the youngest. This was applied to the interpretation of ^{14}C dating. As shown by Payette et al. (1986), even autochthonous accumulation of peat at polygonal bog with ice wedges at Clearwater Lake area in subarctic Quebec can give various ages for the same subsurface layer of peat, with the difference of almost 2000 yr: from 2220 ± 80 to 335 ± 75 BP.

Stable Isotope Composition

Mainly, we have paid attention to the precision and replication of stable isotope data, the accuracy of the ^{14}C chronology of the stable isotope records, and the correct paleoclimatic interpretation of oxygen and hydrogen isotopic composition in relict ice wedges.

The $\delta^{18}O$ values in upper part of the studied cross-section range from –32.2 to –28.7‰ (Figure 2) of which about 80% of the samples are within 1.5‰ (–31.7 to –30.2‰). The spread of $\delta^{18}O$ values in the Duvanny Yar ice wedges over 20,000 yr was negligible; the geocryologic conditions of the ice-wedge complex obviously were quite stable. At the lower part of the cross-section the $\delta^{18}O$ values of the lens range from –28.7 to –22.2‰, whereas $\delta^{18}O$ values of the ice wedges are –32.7 to –30.1‰ (Figure 3).

We have used the lower part as a model to consider the way of sampling. Comparison of the results for vertical (Figure 3A) and horizontal (Figure 3B) sampling show that the $\delta^{18}O$ range is small. Consequently, the information is not lost using vertical sampling. In Figure 3B the values located to the right are in accordance with sampling. To locate them in chronological order it is necessary to date them.

The $\delta^{18}O$ plot of lens ice (see Figure 3) shows that the changes have a facial origin as $\delta^{18}O$ variations are observed within one cycle of the ice-wedge complex from –27.9‰ at the lower part of subaqueous sandy loam to –22.2‰ at the subaerial peat.

The isotope distribution of the cross-section is characterized by the similarity of the $\delta^{18}Î$ and $\delta^{2}H$ plots (Figure 5). The variations d_{exc} are not more than 3.4 to 8.1‰ (in single case the d_{exc} is slightly more than 10‰). So it is evident that the atmospheric water is the source for the ice wedges and the reason why, at least for this part of the cross-section, the ice wedge isotope composition is constant. If we take into account the data obtained earlier, it appears that during the Duvanny Yar formation climatic conditions were stable and all changes were caused by changes in the erosion level and connected facial changes—for example changes in inundation.

$\delta^{18}O$ of the recent ice wedges of the Kolyma River flood plain varies between –26.1 and –23.0‰; $\delta^{18}O$ of structure forming ice here ranges –23.0 and –19.1‰, i.e. Late Pleistocene ice wedges were 8‰ lighter, Late Pleistocene structure forming ice is lighter than recent ones by 4–5‰.

Detailed horizontal sampling has been performed over each 10 cm from the large ice wedge at +14.4 m above sea level (asl) in 1999 (Figure 6). The essential coincidence of $\delta^{18}O$ and δD plots point to the atmospheric origin of ice wedge water. However, external parts of the ice wedges differ by heavier isotope composition ($\delta^{18}O$ more by 1–1.2‰, and δD by 6‰). Therefore, sub-vertical marginal zones of ice wedge (about 10–20 cm) has anomalous isotopic composition and cannot be used for paleotemperature reconstruction. This ice was formed in the initial stage, when river or

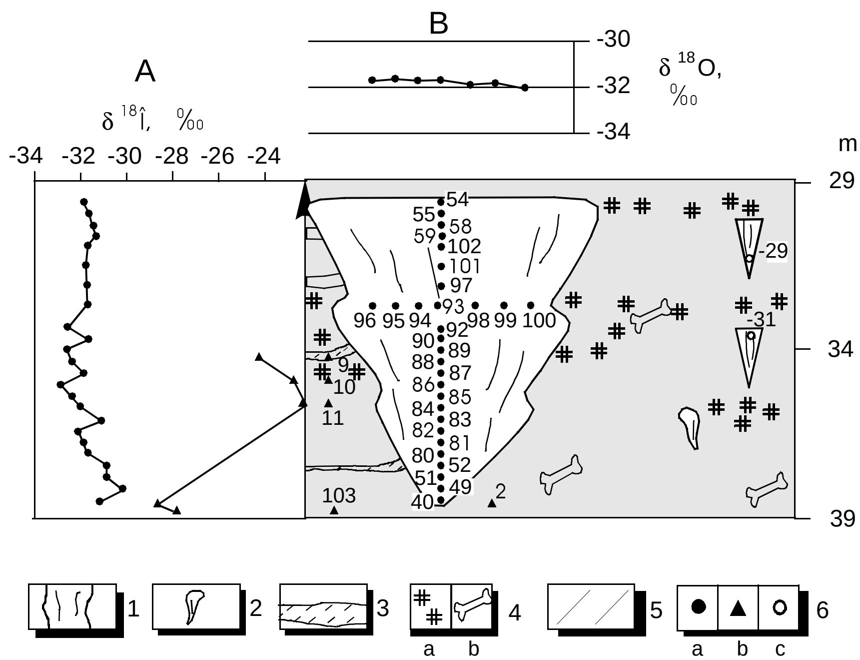

Figure 4 Comparison of oxygen isotope plots obtained by vertical (A) and horizontal (B) sampling of thick syngenetic ice wedge in the lower part of the Duvanny Yar cross-section (Lower Kolyma, north of Yakutia) and oxygen isotope data from structure forming ice (i.e. schlieren, segregated ice) in host sediments and from buried small ice-wedges: 1. Ice of large syngenetic ice wedge; 2. Ice of small buried syngenetic ice-wedges; 3. Structure forming ice (i.e. schlieren, segregated ice) in host sediments; 4. Peat (a) and bones (b) in host sediments; 5. Sandy loam; 6. Samples for oxygen isotope analysis from large syngenetic ice wedge (a), from structure forming ice (b) and from small buried syngenetic ice-wedges (c). Note: Evidently, the scales of variations of oxygen-isotope ratios are equal in both horizontal and vertical (at the same depths) direction. However, the age determination of horizontal samples is very problematic.

lake-water could enter the cracks. Due to diffusion, slow isotopic exchange with host sediments also occurs. In the central part of the ice wedge an ice vein with progressive changes of isotopic composition was found. It is particularly visible when δD changes between the axis and the margin of the vein from –250.5 to –248‰ (the same is true for $\delta^{18}O$ distribution). This gradual manner is typical of continuous ice accumulation in the central part of the ice wedge. There is a symmetry distribution of isotope composition on each side relative to the central vein with light isotope composition. This indicates simultaneous formation of the ice on each side. The ranges of vertical (Figure 5) and horizontal (Figure 6) isotopic plots are very close, showing that careful vertical sampling allows following the whole sequence. Taking into account that the ends of elemental veins tend to be located toward the top, it is possible to collect ice wedge ice vertically in chronological sequence.

Alluvial-lacustrine deposition caused the accumulation of autochthonous and allochthonous organic matter, especially inshore, near the erosion bank containing old organic material, or in inundated parts. Our main strategy for ice wedge complex dating is the rigid rejection of the ^{14}C samples containing old organic matter.

Syngenetic ice wedges are unique. The dating of stable isotope variation by ^{14}C gives the possibility for obtaining paleopermafrost and paleoclimatic reconstructions that have no parallel among conti-

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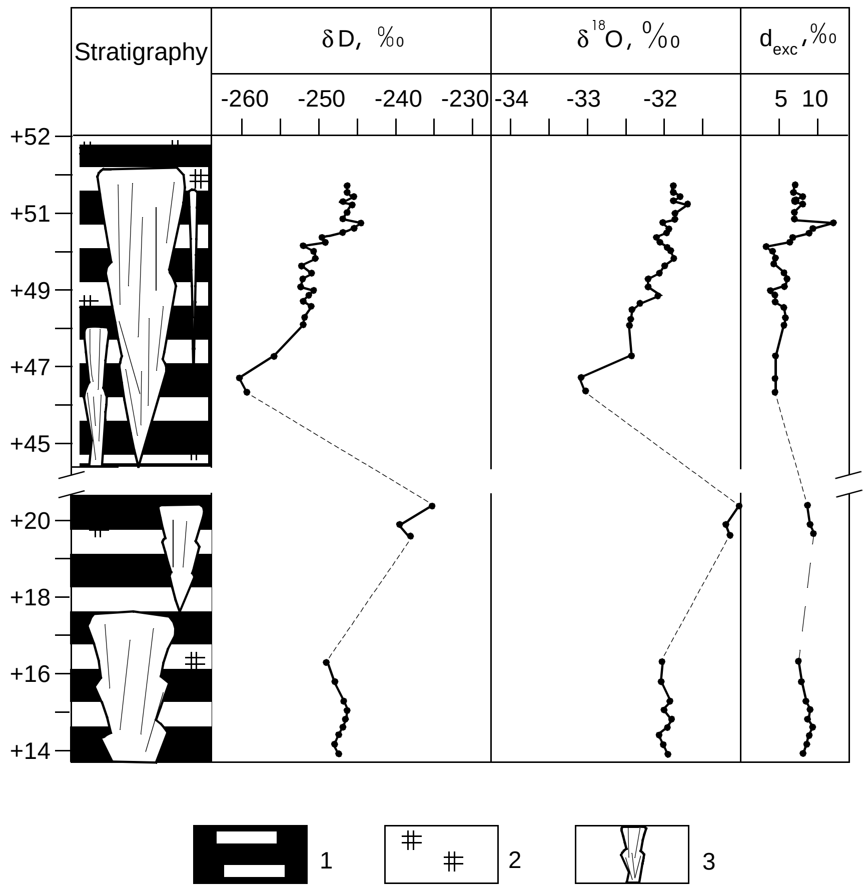

Figure 5 δ18Î, δD and d_{exc} plots in upper part of the Duvanny Yar cross-section: 1. Sandy loam; 2. Peat; 3. Ice of syngenetic ice wedge. Sampling in August 1999.

nental objects. Stable oxygen and hydrogen isotope analysis of the ice is one of the best tools available to obtain paleotemperature information with adequate ^{14}C dates within the last 40,000 yr. Modern laboratory techniques permit to examine properties of different components of sediments and to make careful evaluations.

Study of stable isotope variations in ground ice could result in a paleotemperature record for vast permafrost areas on continents. This information can essentially complete our knowledge about the development of the environment, along with ice sheet records of Greenland and the Antarctic.

There are some difficulties with dating syngenetic ice wedge: their formation in frost cracks is not horizontal. As we have shown (Vasil'chuk and Vasil'chuk 1996, 1997) the subaqueous-subaerial cyclic mechanism of ice wedge ice formation makes it possible to correlate separate fragments of ice wedges to a certain subaerial period of ice wedge accumulation, as this is the period of intensive accumulation of autochthonous organic matter.

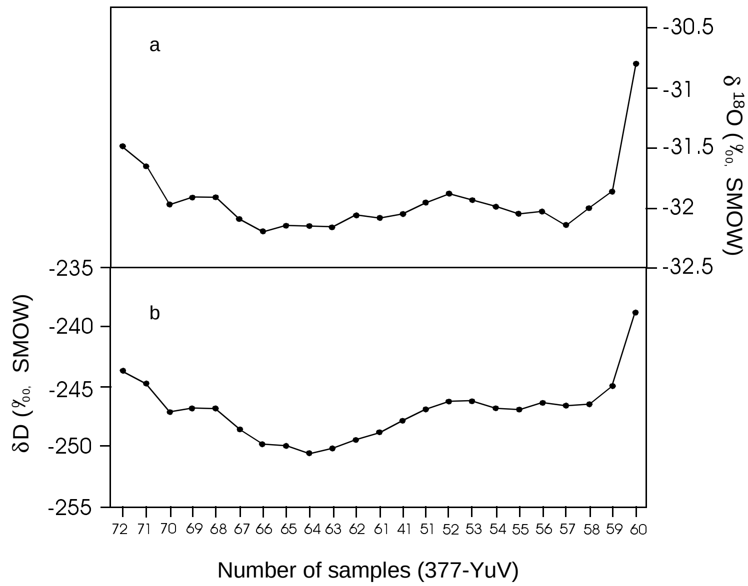

Figure 6 δ18Î (a) and δD (b) plots of horizontal sampling over 10 cm at the high =14.4 m above sea level (asl) from a large ice wedge (width about 2.5 m) of the lower part of the Duvanny Yar cross-section.

Earlier, we (Vasil'chuk and Vasil'chuk 1997, 1998) have remarked that the active formation of the syngenetic ice wedges in northern areas of the Russian permafrost zone occurred during 40,000–10,000 BP; named by Vasil'chuk (1992) Late Pleistocene cryochron. For this complicated period ^{14}C proves a reliable dating method. The peculiarities of ice-wedge dating are related to the character of their formation. Dating of the host sediments has been the main procedure. Special methodology allows determining not only the ice wedge age, but also the age of the separate fragments.

In the near future we expect to perform additional AMS dating (at the Seoul University AMS Facility) of ice wedge isotope plots shown in Figures 2–6. This will allow setting the plots on an accurate time scale.

We believe that stable isotope studies of syngenetic ice wedges can allow precise reconstruction of winter air paleotemperatures at least for the last 40,000–50,000 yr. The main factor providing the paleotemperatures reconstructions is the atmospheric origin of water that constitutes a source of the ice wedges. As a rule, meltwater penetrates into frost cracks in early spring; ice wedge ice is, therefore, an indicator of winter temperature.

CONCLUSION

A critical analysis of the ^{14}C-dates resulted in a valid chronology of the Duvanny Yar ice wedge complex formation: the dates suggest a time frame of about 35,000–40,000 to 13,000 BP.

The ice wedges of the Duvanny Yar formed under very stable conditions over at least 30,000 years, when winter temperature oscillations were within 4–5 °C. However, from the lithologic and geocryologic differentiation of the cross-section it is evident that the formation conditions have changed. First of all, there is a difference between the upper (12–15 m) and the lower (30–35 m) parts. Wide (2.5–3.5 m) ice wedges exist, with the distance of 10–12 m at the lower part, and narrow (1.5–2 m) ice wedges, 4–4.5 m distant at the upper part. Within these macrocycles, mesocycles represented by layers enriched with organic material are observed. They are about 1 m thick and formed in subaerial conditions. Sandy loam layers low in organic matter (3–5 m) are separated by organic layers accumulated under subaqueous conditions. During subaerial stages ice wedges accumulated rapidly, at the subaqueous stage ice wedge growth slowed down. However, the rate changes of the ice wedge growth have not been connected with climatic oscillations rather than with successive changes of subaerial and subaqueous regimes.

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