Y.K. Vasil'chuk and A.C. Vasil'chuk

Late Pleistocene Oxygen Isotope Curves and Radiocarbon Dating for Syngenetic Ice-Wedges

Abstract

Late Pleistocene syngenetic ice wedges and their oxygen isotope curves can be dated indirectly by radiocarbon dating of the host sediments. It is necessary to take into account the periodically interrupted formation of syngenetic ice wedges. The fluvial origin of the sediments determines the presence of allochthonous and autochthonous organic material. This is the main cause of age inversions or disturbances in radiocarbon age series for syngenetic permafrost cross-sections.

Introduction

There are two problems in dating syngenetic permafrost ground with large ice wedges. The first one is the dating of casts in the palaeopermafrost zone. Cast ages are determined by radiocarbon dates of organic material both from the cast body and from the host sediments (Kolstrup, 1987; Vandenberghe and Kasse, 1993; Vandenberghe and Pissart, 1993). However, accurate chronological allocation is not always possible when primary (before thawing) and secondary (after thawing) factors cannot be distinguished. There is no way to determine whether or not the organic material is autochthonous, and also there is no guidance to estimate which part of organic material was washed out after thawing, or was decomposed by microbes. To evaluate the changes in the thawing state requires knowing how organic material in permafrost conditions is accumulated and preserved. It is impossible to obtain evidence for this from data found outside the permafrost zone.

The second problem is the synchronization of data obtained from ice wedges and host sediments, since dating of oxygen isotope curves form the basis for numerical palaeotemperature reconstruction of the Late Quaternary permafrost. Isotopic investigations were focused on sampling techniques, choice of objects and guidelines for palaeoreconstructions (Mackay, 1983; Michel, 1989). The synchronization of the oxygen isotope curves, however, needs more attention. This motivated us to perform radiocarbon dating of Late Pleistocene syngenetic permafrost thicknesses with large ice wedges throughout Northern Russia, combined with oxygen isotope analysis and age correlations.

A comparison of oxygen isotope composition of ancient ice with its present analogues at the same locality is our starting point. We compare the oxygen isotope composition of modern syngenetic ice wedges (i.e. ice wedges from flood plains and peats not older than 60-100 years) with their Holocene and Late Pleistocene analogues. This permits us to make an independent comparison of the results, and correct palaeotemperature reconstructions as new information becomes available and the data become better understood theoretically.

The study sites

The oxygen isotope records discussed here are from samples collected on the vast


a
a'
b
c
d
e
f
g
h
i
j
k
l
m

Figure 1. Map showing localities of ^{14}C dated syngenetic ice - wedges formed during the Late Pleistocene and site of oxygen isotope plots: (a) the natural exposure near the Seyaha settlement (Yamal Peninsula); (a') natural exposure near Gyda settlement (Gydan Peninsula); (b) the natural exposure at Bykovsky Peninsula (mouth of the Lena River); (c) the natural exposure near the Zelyony Mys settlement; (d) the natural exposure at the Ayon Island; (e) the Ledovy Obryv natural exposure in Mayn River valley; (f) Greenland Ice-core Project, Summit ice core; (g) deep-sea core SU 90-08 in the North Atlantic; (h) the natural exposure at Mongatalyangyakha River (Yavay Peninsula); (i) the natural exposure at Cape Sabler; (j) the natural exposure in a depression near the Kular settlement; (k) the Duvanny Yar natural exposure (north-east of Yakutia); (l) the Molotkovski Kamen' natural exposure (Maly Anyui River valley); (m) the Ust'-Algan Obryv natural exposure in the Mayn River valley (Southern Chukotka).

Arctic Region of Russia (Fig. 1) from Yamal and Gydan Peninsulas in the West to Chukotka and Magadan Region in the East, and from the islands Belyi and Ayon in the Arctic Ocean in the North to the Trans-Baikal Region in the south (Vasil'chuk, 1991, 1992). Earlier (Vasil'chuk, 1982, 1991, 1992, 1993), we noted that the syngenetic ice wedges in the northern areas of the Russian permafrost zone were formed in the period 40-10 ka BP (named by Vasil'chuk, 1991 as the Late Pleistocene cryochron). For this period radiocarbon is the most suitable dating technique.

The main purpose of our study is the possible finding of age inversions or disturbances in the radiocarbon date series for syngenetic permafrost cross-sections. If this is not clarified there remain two opposite possibilities: either distrust the radiocarbon dating, or take into account all obtained dates. We discuss here three aspects of this problem.

When small samples are dated by AMS we must be certain that this is not allochthonous material. So one has to decide what kind of ice wedge is preferred for sampling, large or small. Also the amount of organic matter of host sediments transmitted to separate parts of ice-wedge ice and their oxygen-isotope plots has to be determined for possible age corrections.

Synchronization of oxygen isotope plots and their palaeotemperature interpretation is determined by formation mechanism of syngenetic ice wedges. The mechanisms for understanding syngenetic ice wedge growth is understood. For example J.R.Mackay (1990) formulated this mechanism as follows: ice wedges grow as the upper permafrost surface rises in response to the addition of material on the ground surface. The added material may be alluvium, as in flood plains; peat, as in a tundra polygon; gelid deposits, as at the bottom of a slope; etc. If thermal contraction cracking and ice-veinlet growth keep pace with the addition of new material, the ice veinlets will grow to progressively greater heights to form a syngenetic ice wedge. The ice wedge height corresponds to the material in which it grows: hence the name "syngenetic" (Mackay, 1990). They grow higher, often vertically nested in a chevron pattern. The shape is a function of both horizontal and vertical growth rates (Dostovalov and Popov, 1963; Popov, 1967; Mackay et al., 1979).

However, in practice this situation occurs rarely. More common is periodically-interrupted formation of large ice wedges. A continuous sedimentation process during 20-

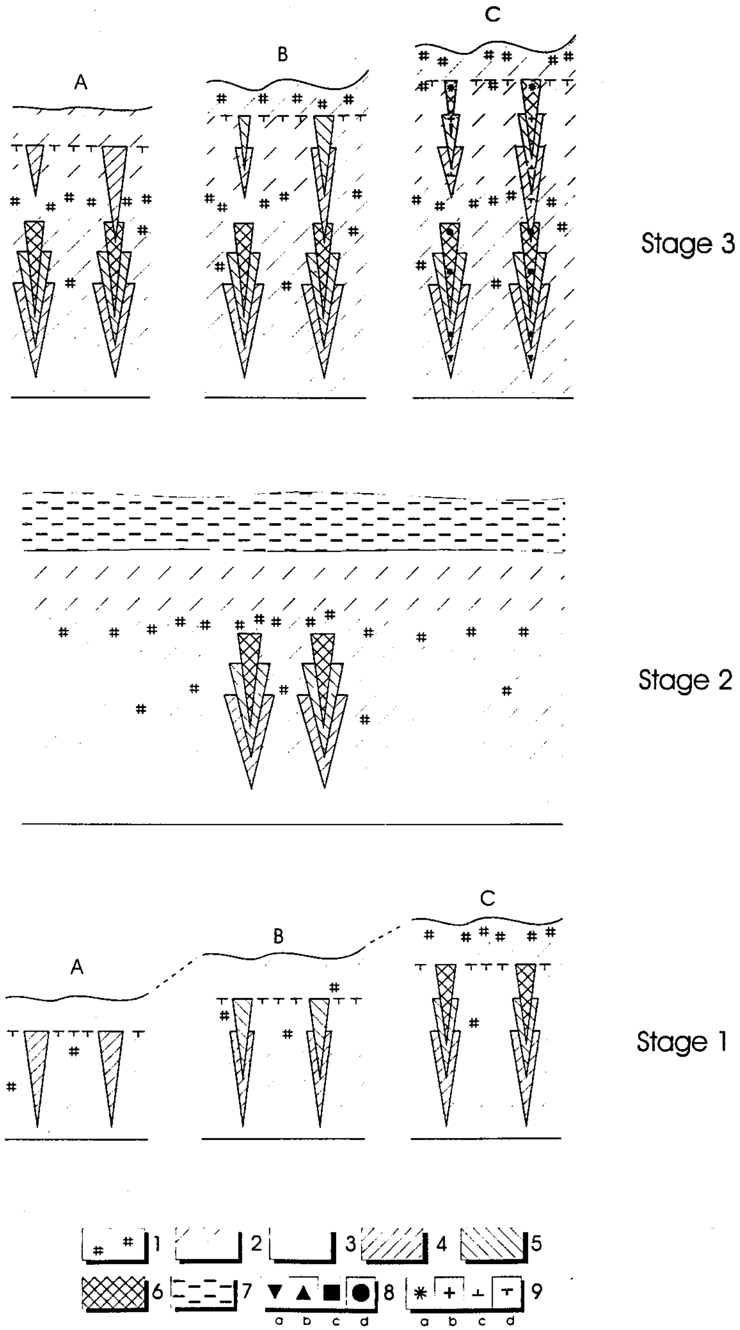


Figure 2. Schematic drawing of multistage ice wedge formation. Intensive growth occurred in subaerial conditions (stages I and III); ice wedge development stopped in subaqueous regime (stage II). 1. peat; 2. sandy loam; 3. loam; 4-6. oldest, intermediate and youngest ice wedge growth stages; 7. water; 8. ice sample formed in stage I; 9. ice sample formed in stage III.

30,000 ka is not realistic, the accumulation is interrupted often. Large subaqueous depositional pulses (3-7 m sandy loam and loam) alternate with ice wedge growth. Active growth of syngenetic ice wedge complexes happens realized in the subaerial stage. This stage is fixed by the concentration of peat forming sediments in interbanded subaqueous - subaerial sediments of differing origin (alluvial and lacustrine). After the subaerial stage a period of active sedimentation begins and thick layers of ground are accumulated. The growth of ice wedges stops or decreases during the subaqueous stage. The sedimentation of a new deposit enabled ice wedges to grow vertically. When the subaerial phase returns, the active growth of ice wedges recommences. This is shown in fig. 2. At times the stratigraphically higher ice wedges as a whole are located in the overlying bed above the ice wedges of the previously formed cycle, and do not penetrate into stratigraphically lower ones. As a result several ice wedges show a multistage (no single) formation. If the thickness of subaqueous strata is thin enough (e.g. < 3-4m), the toes of younger and stratigraphically higher ice wedges penetrate into buried ice wedges of the previous phase. If the thickness of the subaqueous sediment exceeds 4-5 m, the stratigraphically higher ice wedges do not penetrate the lower wedges. When the toes of the new ice vein is incorporated into the underlying ice wedge, a single (transit) ice wedge is formed. This process leads to the generation of multicycle (multistage) ice wedges or cryocyclites. The formation of the syngenetic permafrost sediments has a cyclic character; the periodic structure is independent of climate (Vasil'chuk, 1991; Yu.Vasil'chuk and A.Vasil'chuk, 1995a).

The sampling techniques for oxygen-isotope and radiocarbon analysesare based on this growth model. All samples were collected using the same procedure in the field (fig. 2). ^{14}C dating was performed at the Radiocarbon Laboratory of Geology Institute of the Russian Academy of Sciences and the Radiocarbon Laboratory of University of Helsinki. Organic matter was sampled for oxygen-isotope analysis, large (transit) syngenetic ice-wedges, small syngenetic buried ice-wedges, and segregated ground ice (lenses) were sampled. The samples were collected for every interval of about 0.5-1.0 m into a two-layer plastic utricle for thawing. Every ice sample was placed into a 100 ml glass ampoule and was transported to one of three laboratories: the Water Problem Institute of Russian Academy of Sciences, the Geology Institute of Estonian Academy of Sciences and the University of Helsinki. Control samples weretaken done for intercomparison of the laboratories.

Results

There are different opinions about the age of syngenetic ice-wedges. The prevailing opinion used to be Middle-Pleistocene age (Popov, 1967). Later, thanks to radiocarbon dating one started to believe that almost all syngenetic ice-wedges are essentially younger. There was evidence for this in almost all dated cross-sections of syngenetic permafrost with ice wedges in Northern America and Northern Russia.

The first radiocarbon dated Late Pleistocene permafrost sequences were studied in Alaska: the exposure of Barrow Peninsula dated 14.000 to 18.000 BP (Brown, 1965). Sellmann and Brown (1973) showed later data on the Beach Ridge shaft of 36,000 ± 2000 BP, W-2679 and 37,000 6,$\pm^{2900}_{2000}$ BP, I-2359 which changed the stratigraphy and syngenetic thickness age for the Barrow. The beginning of the Barrow formation now dated 37-35 ka BP, and ice-wedge formation began after accumulation stopped, i.e. about 25 ka BP. The exposure at McLeod Point dated as more than 40 to 11,5 ka BP (Black, 1983); the Fox permafrost

Table 1. Radiocarbon dates of the Late Pleistocene thick syngenetic ice-wedges of the Russian permafrost zone, obtained from autochthonous organic accumulation

Localities, ^{14}C age, yr BP (Lab. no.) and depth or height (altitude above sea level) of samples (location on figure 1) and (reference). Kind of samples: p - peat; w - wood; b - bone; r - ramules; d - dispersed amorphous organic plant material (detrital organic remains), s - soil.

Seyaha settl., Western Siberia (Fig. 1-a) (Vasil'chuk, 1992	Mongatalyakha River, Western Siberia (Fig. 1-h) (Vasil'chuk, 1992)	Cape Sabler, Lake Taimyr, Taimyr Peninsula (fig. 1-i) (Sulerzhitsky, 1982)	Kular settlement, Northern Yakutia (fig. 1-j) Vasil'chuk, 1992)
9300 ± 100 (GIN-2472)p +22 m	3900 ± 310 (GIN-2468)p +9 m	2580 ± ± 160 (GIN-1288)p +33.7 m	37700 ± 600 (GIN-4981)b +109 m
22700 ± 300 (GIN-2477) d +13 m	21900 ± 900 (GIN-2469) d +6 m	12100 ± 100 (GIN-1528) d +33.0 m	38700 ± 1000 (GIN-4965) b +109 m
22600 ± 600 (GIN-2475) d +12 m	25100 ± 220 (GIN-2471) d +5 m	11600 ± 200 (GIN-1527) d +31.5 m	33300 ± 1100 (GIN-4987) p +107 m
23500 ± 400 (GIN-2474) d +10 m	28600 ± 800 (GIN-2638b) d +4.5 m	12000 ± 150 (GIN-1289) d +29.2 m	42400 ± 1000 (GIN-4982) r +107 m
24300 ± 300 (GIN-2476) d +6 m	30200 ± 800 (GIN-2470) d +4 m	17750 ± 300 (GIN-1290) r +27 m	35700 ± 1500 +106 m
24760 ± 300 (MGU-1017)* d +6 m		18400 ± 1000 (GIN-1526) d +22 m	40500 ± 1200 (GIN-4964) b +106 m
30100 ± 1500 (GIN-2477) d +1 m		21400 ± 1100 (GIN-1525) d +15 m	41100 ± 800 (GIN-4977) w +101 m
		2490 ± 700 (GIN-1291) p +15 m	> 43700 (GIN-4978) w +100 m
		24200 ± 800 (GIN-1524) d +14 m	> 40000 (GIN-4983) p +100 m

Duvanny Yar, Northern Yakutia (fig. 1-k) (Vasil'chuk, 1992)	Zelyony Mys settl. Northern Yakutia (Fig. 1-c) (Vasil'chuk, 1992)	Molotkovski Kamen, Northern Yakutia (fig. 1-l) (Kaplina, 1986)	Ledovy Obryv Southern Chukotka (Fig. 1-e) (Kotov, 1988)
13080 ± 140 (EP-941555) s +46 m	13500 ± 160 (EP-941553)* s +45 m	3350 ± 70 (MGU-426) p +28 m	19500 ± 500 (MAG-815) d +60 m
19480 ± 100 (GIN-3868) b +46 m	28600 ± 1500 (GIN-3575) d +29 m	24550 ± 260 (MAG-150) p +23.5 m	22300 ± 200 (MAG-814) d +56 m
22000 ± 800 (GIN-4017) d +40 m	27900 ± 1200 (GIN-3575) d +27 m	24800 ± 400 (GIN-2397) p +23 m	23500 ± 500 (MAG-813) d +51 m
27600 ± 1000 (GIN-4016) d +38 m	33800 ± 900 (GIN-3850) d +26 m	26500 ± 500 (MAG-153) p +22.5 m	27000 ± 500 (MAG-811) d +48 m
33800 ± 500 (GIN-3861) b +38 m	37600 ± 800 +20 m (GIN-3576) d	28100 ± 1000 (GIN-2396) p +22 m	27000 ± 500 (MAG-810) d +44 m
33400 ± 500 (GIN-4018) d +30 m		34400 ± 1000 (MAG-155) p +16 m	31400 ± 500 (MAG-805) d +40 m
37900 ± 1000 (GIN-4015) d +25 m		42800 ± 400 (GIN-143) +16 m	35000 ± 1000 (MAG-804) d +38 m
35100 ± 100 GIN-3865) s +22 m	27200 ± 200 (MAG-298)** p +12 m	44000 ± 1500 (MAG-152) p +9 m	34500 ± 500 (MAG-803) d +36 m
38000 ± 500 (GIN-3864) r +21 m	28240 ± 330 (MAG-294)** d +11 m		38000 ± 1000 (MAG-802) d +33 m
42600 ± 1200 (GIN-3862) r +20 m	35200 ± 800 (MAG-295)** d +8 m		42000 ± 1300 (MAG-801) d +30 m

*in addition data by I. Danilov, **data by A. Lozhkin (personal communication)

Table 1 (continued)

tunnel thickness of Goldstream valley near the southern margin of the Yukon-Tanana Upland dated 43,3 to 11,9 ka BP, (Pewe and Sellmann, 1973; Hamilton et al., 1988); the top of the Fox Gravel dated by AMS as 43,410 ± 240 BP, (A-7520, Long and Pewe, 1996); the exposure at Titaluk River (dated 35,3 to 29,5 ka BP (Carter, 1988).

The Late Pleistocene syngenetic permafrost thickness with polygonal ice wedges (named edoma in Yakutia) were studied in detail in Northern Yakutia and in the Russian Arctic Islands. The exposure at Khroma River dated 37,5 to 11,5 ka BP; the exposure at Allaikha River dated 50,7-10,6 ka BP; the exposure Stanchikovski Yar at Malyi Anyui River dated 47,1 to 34,4 ka BP; the exposure at Bol'shaya Kuropatoch'ya River dated 37 to 10,4 ka BP; the exposure at Shandrin River dated from more than 41 to 10,6 ka BP; the coastal (Dmitri Laptev Strait coast) exposure Oiyagosky Yar dated from more than 41 to 22,9 ka BP; the Mus-Khaya exposure at Yana River dated 38,8 to 11,5 ka BP; the coastal exposure of Bol'shoi Lyakhovsky Island dated from more than 39,6 to 30,9 ka BP; the coastal exposure Balyktakh of Kotel'ny Island dated 28,4 to 12,3 ka BP; the exposure of Alyoshkinskaya terrace, in Lower Kolyma River valley dated 17,2 to 14,8 ka BP (Kaplina, 1986; Tomirdiaro and Chyornen'kii, 1987, Makeev et al., 1989; Nagaoka et al., 1995). In northwestern Siberia detailed Late Pleistocene sequences with large ice-wedges were studied too: the exposure at Ekaryauyakha River dated 31 ka BP (Avdalovich, Bidzhiev, 1984); the Lysukan exposure at Yuribey River dated 18,3 to 16,5 ka BP (Bolikhovsky et al., 1987).

We have studied the radiocarbon age of more than 30 Late Pleistocene polygonal syngenetic sequences in Northern Russia. Our most reliable cross-sections are shown in Table 1. The data presented clearly show that the beginning of active growth of the majority of syngenetic ice wedges is dated as Late Pleistocene, i.e about 50-45 ka BP. Their active growth in vast areas of Northern America, Asia and Europe did not last less than 30-40 ka. Therefore this period is named Late Pleistocene cryochron (Vasil'chuk, 1991). There was no time period when the growth of syngenetic ice-wedges was slowed down due to climatic change within the Late Pleistocene cryochron. The decrease of their active growth dates back to about 11-10 ka BP.

Radiocarbon dating does not solve all chronological and stratigraphical problems in the permafrost. First of all there exists the question of allochthonous organic material. There are many examples showing inversions. We will discuss a few here.

Researchers of the Institute of Low Temperature Science from Hokkaido tried to date Yakutia permafrost syngenetic sequences by means of radiocarbon repeatedly, and obtained in some cases very different results. Before their investigation, this cross-section was dated three times with varying results: 40.8; 40.4; 40.2 and 43.3 ka BP by Yu.Vasil'chuk (1988) shown in Table 2 (with laboratory index GIN); 32.2; 19.8; 22.0; 20.8 and 15.1 ka BP by Ye. Slagoda (shown in Table 2 with index PI). Both sets were obtained from the lower part. Nagaoka et al. (1995) obtained dates 32.8; 25.7 and 11.1 ka BP - in upper part of cross-section (from +14 to +25m).

A similar observation we made at syngenetic Late Pleistocene deposits (with a multistage system narrow ice-wedge) of an alluvial cone of small River Algan at the Main River in Southern Chuckotka. There are two layers of almost pure peat located at the heights 1m and 3m dated 32.7 ka BP and 42.4 ka BP correspondingly.

Table 2. Radiocarbon dates of the Late Pleistocene thick syngenetic ice wedges of the Russian permaforst zone, obtained from allochtonous organic accumulation.

<table>
<tr><td colspan="4">Localities, ^{14}C age, yr BP (Lab. no.) and depth or height (altitude above sea level) os samples (location on figure 1). Kind of samples: p - peat; w - wood; b - bone; r -ramules; d - dispersed amorphous organic plant material, s - soil (Vasil'chuk, 1992)</td></tr>
<tr><td colspan="2">Gyda settl., Western Siberia (figure 1-a')</td><td colspan="2">Bykovsky Penins., Norther Yakutia (figure 1-b)</td></tr>
<tr><td>3470 ± 40 (GIN-3586) p</td><td>+8 m</td><td>2905 ± 00 (PI-750) p</td><td></td></tr>
<tr><td>3700 ± 40 (GIN-3602) p</td><td>+8 m</td><td>15100 ± 750 (PI-751) d</td><td>+13 m*</td></tr>
<tr><td>10260 ± 280 (GIN-3584) d</td><td>+7 m</td><td>43300 ± 900 (GIN-4334) d</td><td>+7 m*</td></tr>
<tr><td>14400 ± 160 (GIN-3592) d</td><td>+5 m</td><td>20836 ± 500 (PI-749) d</td><td>+7 m*</td></tr>
<tr><td>14810 ± 280 (GIN-3603) d</td><td>+5 m</td><td>40200 ± 800 (GIN-4334) d</td><td>+6 m</td></tr>
<tr><td>15890 ± 150 (GIN-3585) d</td><td>+5 m</td><td>40400 ± 1200 (GIN-4593) d</td><td>+5 m</td></tr>
<tr><td>14670 ± 220 (GIN-3587) d</td><td>+4 m</td><td>22000 ± 1600 (PI-752) d</td><td>+5 m*</td></tr>
<tr><td>10570 ± 350 (GIN-3593) d</td><td>+4 m</td><td>19800 ± 500 (PI-753) d</td><td>+3 m*</td></tr>
<tr><td>13850 ± 150 (GIN-3591) d</td><td>+3 m</td><td>32200 ± 930 (PI-748) d</td><td>+2 m*</td></tr>
<tr><td>14590 ± 150 (GIN-3609) d</td><td>+3 m</td><td>40800 ± 1200 (GIN-4591) d</td><td>+1 m</td></tr>
<tr><td>11000 ± 150 (GIN-3608) d</td><td>+3 m</td><td colspan="2" rowspan="3">Ust'-Algan sequence, Mayn River Valley, Southern Chukotka (figure 1-m)</td></tr>
<tr><td>13780 ± 200 (GIN-3596) d</td><td>+2.5 m</td></tr>
<tr><td>13840 ± 180 (GIN-3612) d</td><td>+2 m</td></tr>
<tr><td>10970 ± 200 (GIN-3594) d</td><td>+2 m</td><td>42400 ± 2100 (GIN-5366) p</td><td>+33 m</td></tr>
<tr><td>12300 ± 400 (GIN-3597) d</td><td>+2 m</td><td>32700 ± 1800 (GIN-5367) p</td><td>+31 m</td></tr>
<tr><td>13600 ± 150 (GIN-3595) d</td><td>+2 m</td><td>43000 ± 3000 (MAG-923) p</td><td>+29 m**</td></tr>
<tr><td>12090 ± 220 (GIN-3611) d</td><td>+2 m</td><td>> 57000 (MAG-967) p</td><td>+32 m**</td></tr>
</table>

* in addition data by Ye. Stagoda (personal communication

** Kotov (1988)

We have conducted a detailed investigation of the 7m first terrace of the Gyda River in the north of Western Siberia. The samples for radiocarbon analyses have been selected over a length of 50 m from several horizons at the same height. At first dating results seemed random (there are more than 15 samples for radiocarbon analysis, see Table 2). However, closer inspection shows a regular occurrence of younger dates about 12 ka BP at a height of +2 m; dates about 13-14 ka BP at a height of +3m, and dates about 15,5 ka BP at a height +5 m.

At a small lake in Mammoth Peninsula (North of Western Siberia) we investigated an almost pure peat with a minor admixture of lacustrine sandy loam with large ice wedges. At the bottom we have dated the Late Pleistocene peat as 31800 ± 700 BP, GIN-3579 (Yu.Vasil'chuk and A.Vasil'chuk, 1995b). At this thickness age inversions are considerable. At the same depth dates of 11 ka BP and 6 ka BP have been obtained. This polygonal permafrost thickness has been reliably dated due to intensive peat growth, and the find of a rodent burrow with undoubted autochthonous seeds and plant remains. Moss and grass active growth led to domination of autochthonous organic in some horizons of the lacustrine peat thickness.

Anomalous radiocarbon ages from a Holocene detrital organic lens in Alaska were found by Nelson et al. (1988). The authors stressed that in an area such as the Arctic Coastal Plain, old, well-preserved organic material is abundant. For AMS dating it is important to know that all size fractions of organic sediments from such areas are likely to be contaminated by re-deposited organic carbon. The 5 different radiocarbon dates from 13250 ± 100 BP (USGS-2046A) to 30260 ± 530 BP (USGS-2046D) were obtained for different size fractions from one large sample. They demonstrate that contamination by old organic material is abundant in all fractions, independent from the size. Re-buried mammoth's remains and whole mammoth's carcasses have also shown the possibility of repeated re-deposition of allochthonous organic material in permafrost (Vasil'chuk et al., 1996).

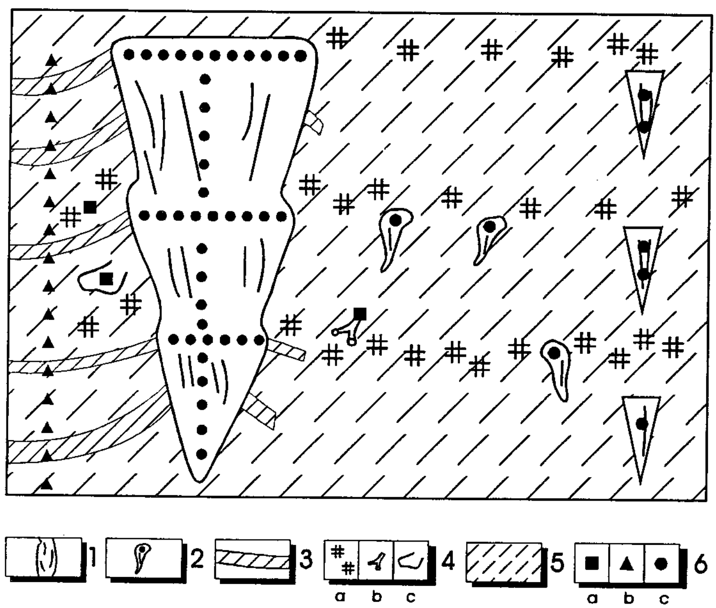


Figure 3. Schematic radiocarbon and oxygen-isotope sampling of syngenetic ice-wedges: (1) transit syngenetic ice - wedges; (2) small syngenetic buried ice-wedge; (3) separated ground ice; (4) peat (a) wood (b) and bones (c) used for radiocarbon dating; (5) (loamy) sand; (6) location of sampling: (a) for ^{18}O determinations from ice wedges, (b) for ^{18}O determinations from separated ice in host sediments, and (c) for radiocarbon dating.

For the Late Pleistocene sequences, some ^{18}O curves are shown in Fig. 3. All our oxygen isotope curves are reliably dated by radiocarbon. This makes it possible to make palaeopermafrost and palaeoclimatic reconstructions, which is rather unique for continental objects. Oxygen isotope plots of syngenetic ice-wedges from Western Siberia (Fig. 3a), Northern Yakutia (Fig. 3b,c) and Chukotka (Fig. 3d,e) are shown. For reference, oxygen isotope data of the GRIP Summit ice core is also shown (Fig. 3f), because this is the best Greenland bore hole due to its location in the central part of the island above snow line. AMS dated planktonic foraminifera from the Northern Atlantic (Fig. 3g) are also shown for comparison, since the Northern Atlantic is the main water source for both Greenland and Siberia. A common feature is noted in all plots, which is the distinction of Late Pleistocene cryochron characteristics from modern ones by means of the ^{18}O value. This remarkable fact supports our conclusion about the common water source for ice wedges and glacier for the present and also for the Late Pleistocene: evaporated surface water from the Northern Atlantic. Pacific Ocean water and water from the Canadian Arctic reaches Greenland in limited amounts.

Discussion and conclusions

A first reaction on date inversions and lack of correspondence is to distrust one or another series of radiocarbon dates. However, the situation needs a different approach. The thickness of the Bykovsky edoma is a deposit of the Siberian Lena river delta, impregnated with allochthonous organic material. Some part of the allochthonous organic material is dislocated from neighbouring mountains. The sediments of the Bykovsky edoma are truly delta, as is shown by alternation of fluvial facies (sand and gravel) with flood-plain facies (sandy loam and peaty horizon). The absence of date inversions in such a section is not likely. This ^{14}C inversion reflects a regular sequence of erosion by river water of Late Pleistocene peat, which occurred upstream not far away. The radiocarbon inversions in the Ust'- Algan syngenetic deposits is a result of disturbance during deposition in an alluvial cone of the small River Algan at its mouth into the Main River in Southern Chuckotka. The ^{14}C inversion at the first terrace of the Gyda River reflects a regular sequence of erosion by river water of Late Pleistocene peat, which occurred upstream not far away. At first the river eroded the younger part, accumulated about 12-13 ka BP, deposited this material downstream at a basis to form the terrace at that time. Later older parts of peat washed out and were removed by the river and covered previous beds, rich by younger organic material. It is reasonable to suggest that if organic material is removed from a small distance, so that age inversions can be considerable even in case of scattered detritus matter. If transportation in a small or large river even over a short distance takes place, rewashed material is dispersed. Therefore in case of transportation over large distances age inversions are not large. Lake deposits similar to alluvial can form with radiocarbon inversions as shown in the dating of a Holocene deposit in the Mammoth Peninsula. Here the deposits accumulated in a small lake depression. Considerable age inversions are explained by the immediate vicinity of Late Pleistocene peat (with assumed age about 30 to 20 ka BP) which was eroded by water of the lake (Yu.Vasil'chuk and A.Vasil'chuk, 1995b).

The problem of allochthonous organic material in polygonal ice-wedge thickness obviously is a complicate one. The origin of mineral components of polygonal ice wedge thickness may be alluvial, lacustrine, marine, slope or eolian.

A high degree of inundation during subaqueous accumulation of the mineral components is not doubted. Autochthonous organic material very rarely comprise polygonal ice-wedge thickness. Only peat of high moors does not contain allochthonous admixtures. As shown by palaeobotanic analysis of Late Pleistocene and Holocene peat, sections with ice wedge inclusions of oligotrophic peat of a high moor are unique. As a rule there was peat of eutrophic bogs and very rarely mesotrophic ones. If we date peat in polygonal ice-wedge thickness we can not escape allochthonous admixtures.

Allochthonous organic material is not only a problem in the vertical dimension, but also horizontal. This was demonstrated by Sulerzhitsky (1982), who studied radiocarbon ages of allochthonous organic material on the beach of Taimyr Lake (central part of Taimyr Peninsula), and showed that age differences between samples of fresh wave-built organic material can be more than 10 ka. A sample near the Cape Sabler cross-section dated 13600 ± 400 BP (GIN - 1529) (in this cross-section non-inversed dates of 2.5 - 24 ka BP were obtained - see Table 1). Organic material from the straight coast of Cape Fus - 2860 ± 150 BP and from the beach between Cape Fus and Cape Sabler a sample 7400 ± 60 BP (GIN - 1287) was dated. On the sloping beach of Khatanga River (south-east of Taimyr Peninsula) Sulerzhitsky dated two samples of fresh wave-built organic material 4600 ± 150 BP (GIN - 1249) and 690 ± 100 BP (GIN - 1248). A significant admixture was demonstrated in the first sample.

The same was observed at the beach of the Engel'gard Lake bay (north of Taimyr Peninsula, Lower Taimyra River valley); one date is old: 2100 ± 80 BP (GIN - 1508), the other is modern: 170 ± 50 BP (GIN - 1509). In this case the first sample is different by the admixture of felt-like material. Even autochthonous accumulation of peat (at a polygonal bog with ice wedges at Clearwater Lake area, subarctic Quebec) can give various ages for the same subsurface layer of peat, differing by almost 2 ka: from 2220 ± 80 to 335 ± 75 BP (Payette et al. 1986). The process of allochthonous organic enrichment appeared also in other conditions of syngenetic sedimentation, such as lacustrine. Here we emphasize the regularity of the age inversions, especially for permafrost syngenetic thickness with ice wedges. The majority of them were formed under influence of subaqueous - subaerial conditions.

AMS dating of a polygonal ice-wedge complex is complicated by the presence of allochthonous organic material. If small samples are dated it is very difficult to be certain that this is autochthonous material. Nelson et al. (1988) noted as very important for AMS dating of small samples that all size fractions of organic sediments from the Arctic Coastal Plain are likely to be contaminated by redeposited organic carbon, even after cleaning of coal and amber. Only autochthonous objects such as plants in growth position, fossil rodent burrows etc. are suitable for AMS dating.

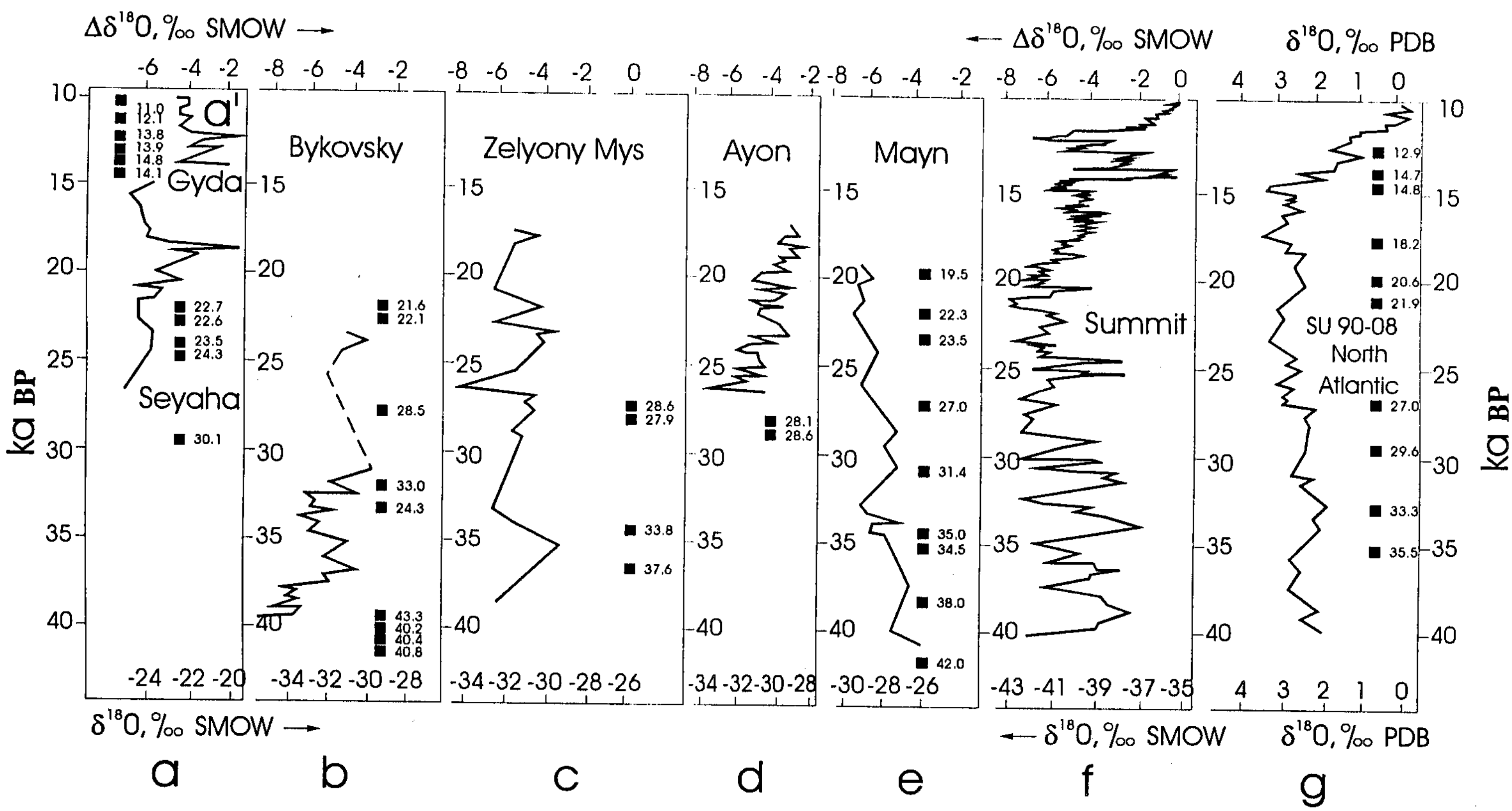
All our radiocarbon dated oxygen isotope curves were performed on ice from syngenetic wedges. We performed numerous isotope data comparisons for buried small (1-3 m high and several cm wide) and large (15-20 m high and 3 m wide) ice wedges (Vasil'chuk, 1991, 1992). The large wedges have a relatively uniform isotopic composition, they are more representative for a long time period than small wedges. In a number of cases the isotope data obtained for small and large ice wedges were close together, and the palaeotemperature reconstructions from both gave similar results.

Small syngenetic ice wedges allow us to assign stratigraphically oxygen and deuterium isotope data to any layer of permafrost thickness. However, it is important to note that small ice wedges form in conditions of increased inundation and mark a deceleration or interruption of ice-wedge formation. This usually results in an increased addition of allochthonous material into the sediment above the small ice-wedge. This leads in general to increased age of the layer accumulated above the small ice wedge. Consequently, the advantage of a more accurate setting of small ice wedges is undone by a less accurate dating of the sediment. Mineralised peat water penetrates into small ice wedges, growing in inundation conditions. This water has an isotopic composition different from atmospheric water because of evaporation from the surface of the polygonal peat (this isotope shift can be falsely interpreted as warming).

Oxygen isotope variations were studied mainly in vertical profiles of the large ice wedge, when it is possible to complement the data with those from small buried ice wedges found in the cross-sections. Dating of syngenetic ice wedges dating is possible by dating inclusions in ice-wedge ice, or taking into account syngenetic ice-wedge formation peculiarities, in particular those that are synchronous to their host sediments. It is possible to date ice-wedge ice indirectly using radiocarbon dates of the host sediments. With ^{14}C, host sediments ice wedges not older 37-40 ka BP can be dated because older dates are not valid in the permafrost zone (Vasil'chuk, 1992).

However, we can not date just any ice-wedge fragment. The difficulties with dating of small ice wedges have been discussed above. The accurate determination of the radiocarbon age of syngenetic permafrost deposit was the main prerequisite for the method. If ice wedges are present relatively uniform at cross-section, it is conceivable that the age of the host sediment (the time between beginning and completion of deposition) is equal to the age of the intersecting ice wedges. The age of separate ice wedge fragments can be estimated by interpolation. For example, if the basement of a 20-m high section is dated at 40 ka BP and its top at 20 ka BP, and the deposit contains large ice wedges which visual appearance does not change, the rate of sedimentation is considered as 1m per 1 ka. Therefore, the age of an ice-wedge fragment at a depth 5-10m will be 25-30 ka BP. If the ice wedge visual appearance changes or the dates are problematic, the age of a separate fragment can be determined only by taking the features of every individual fragment into account. For example, if the basement of a 20-m height section is dated at 30 ka BP, the top at 15 ka BP, the middle level at 20 and the deposit contains large ice wedges in the lower part of the cross-section and narrow ice-wedges in the upper part of cross-section, the rate of sedimentation changes from 1m per ka during 30-20 ka BP to 2 m per ka during 20-15 ka BP. This way, the ice wedges and their oxygen isotope plots are dated.
Here we discuss some examples concerning the ^{18}O data on syngenetic ice wedges (see also Vasil'chuk and Trofimov, 1984a,b, 1988; Vasil'chuk et al., 1985, 1988; Vasil'chuk, 1991, 1992, 1993; Vasil'chuk, Yu. and Vasil'chuk, A., 1995a,b).

Oxygen isotope diagrams of syngenetic ice wedges are complicated in many cases because of the lack of organic material in the upper parts of the permafrost sections with ice wedges. The upper parts of oxygen isotope plots have been dated by extrapolation of sedimentation rates obtained from ^{14}C dated fragments. An oxygen isotope plot from the ice-wedge complex near Zelyony Mys has been dated this way (Vasil'chuk et al., 1985). We have dated the top of section at about 16 ka whereas the highest date was located 9m below. This extrapolation dating has been confirmed by S.Gubin (personal communication, 1996), who obtained a date of about 13 ka BP (see Table 1) for the upper part of the section. Close dates were obtained for the top of the Duvanny Yar section. These data demonstrate that it is possible to date ice-wedge fragments by age extrapolation in cases where dates are



Δδ18O, ‰ SMOW →
← Δδ18O, ‰ SMOW
δ18O, ‰ PDB
ka BP
a'
Gyda
Seyaha
Bykovsky
Zelyony Mys
Ayon
Mayn
Summit
SU 90-08
North
Atlantic
δ18O, ‰ SMOW →
← δ18O, ‰ SMOW
δ18O, ‰ PDB
a
b
c
d
e
f
g

Figure 4. Comparison of radiocarbon dated oxygen isotope plots of Late Pleistocene syngenetic ice wedges in natural exposure of Northern Eurasia: Western Siberia: cross-sections near Gyda (a - upper) and Seyaha (a - lower) settlements; (b-c) Northern Yakutia: cross-sections in Bykovsky Peninsula (b) and near Zelyony Mys settlement (c); (d-e) cross-sections in Chukotka: Ayon Island (d) and Mayn River valley (e); (f) GRIP Summit ice core (Dansgaard et al., 1993); (g) deep-sea SU 90-08 (Labeyrie et al., 1995).

concentrated in a certain part, and are absent in the other.

We have used different methods of ice wedge sampling in order to date oxygen isotope curves. Both vertical and horizontal sampling have been applied for studies in the first stage (see Figure 2). We have found that the range is identical in both vertical and horizontal direction. Taking into consideration the ice wedge growth features, horizontal sampling seems preferable (Michel, 1990). However, in horizontal sampling there is no way to determine which samples are older, right or left, the sample located close to an axis of the ice wedge or the sample located close to a periphery part, etc. In the case of vertical sampling this can be done in a straightforward way. In general, the lower sample is older than the upper one or at least is not younger than the upper.

It is not necessarily true that because the location of texture-forming ice shows its chronological position, palaeotemperature reconstructions are accurate (Vasil'chuk, 1991, 1992). It was shown that cryogenic fractionation is considerable during (non-atmospheric) ice formation, and to use such data for palaeotemperature reconstructions is not correct. There is one paper (Nikolaev and Mikhalev, 1995), which ignores this fact; the authors state that oxygen isotope composition of texture-forming ice is a new palaeothermometer for the Siberian permafrost zone. They used mostly materials from the Kolyma lowland and selectively used our data for other permafrost regions, neglecting contradictions. Examples are anomalous ^{18}O values in $^{18}\delta$ in texture-forming ice of the Kular ice wedge complex (one sample has -35,6‰) and in 8 samples the ^{18}O values changed from -22,1‰ to -25,3‰ (Vasil'chuk, 1990) and anomalous values in the Duvanny Yar section: the ^{18}O values in two samples are -22,2‰ and -23,1‰ and about -30‰ (Vasil'chuk et al., 1988). Data obtained from a detailed sampled cross-section at Seyaha demonstrate relatively high values of ^{18}O in Holocene texture-forming ice -12,5 to -14,6‰, whereas Holocene ice-wedge ice ^{18}O values are -16,4 to -20,1‰ (oxygen isotope determinations were made at the Isotope Laboratory of Helsinki University). Values of ^{18}O in Late Pleistocene texture-forming ice are -18,6 to -19,3‰. Values for Late Pleistocene ice-wedge ^{18}O are -20,4 to -24,5‰. This demonstrates a considerable influence of summer temperatures on the isotope composition of texture-forming ice and a noticeable shift to warmer summer temperatures in Late Pleistocene-Holocene transmission, compared to the winter temperatures trend.

Evidently palaeotemperature information from epigenetic sites is not possible, because it is very difficult to date the time of freezing and to determine all possible ways of water transport is also not realistic. Although we agree that age allocation of oxygen isotope plots of texture-forming ice is rather reliable, we do not recommend to use them as a palaeothermometer. We usually use them together with oxygen isotope data of ice wedges (Vasil'chuk et al., 1985, 1988; Vasil'chuk, 1991, 1992, 1993) for additional information such as palaeofacial reconstruction, because fractionation effects are varying in oxygen isotope ratios of texture-forming ice of different facies.

It is obviously better to date ice wedges more directly. The main problem for ice dating is the impossibility of immediate dating of water older than thousands years, because the radioactive isotopes tritium and ^{210}Pb which are common in glacier and ice-wedge ice water can not be used due to their short half-life. The use of other radioactive isotopes such as ^{10}Be, ^{26}Al and ^{36}Cl and tens of tons of ice is required making measurements impossible.

Dating polar glacier ice using radiocarbon from inclusions of carbonic-acid gas (Oeschger et al., 1967) required thawing of a few tons of ice in vacuum conditions. These methods allows to study the upper hundreds of meters, but the majority of Late Pleistocene ice cores is located deeper than one thousand meters (Oeschger et al. 1967 obtained 7 dates from 4490 ± 30 to 6030 ± 700 BP).

A promising technique to date oxygen isotope data of ice-wedge ice is the application of AMS. Ice wedge ice encloses much more inclusions suitable for AMS dating, compared with ice of polar glaciers. These are the following: 1) pollen and spores extracted from the the ice; 2) other micro inclusions of plant or animal origin; organic material can penetrate into the body of ice wedges at cracks contemporaneous to ice of ice wedges; 3) radiocarbon from methane and inclusions of other gases in ice-wedge ice. The methane concentration in ice-wedge ice is high enough AMS-^{14}C analysis. However, the dating is limited to the Holocene, as shown in investigations of the Sapporo Institute of Low Temperature using Northern Yakutia (Moriizumi et al., 1995). B.Moorman et al. (1996) obtained on CO_2 gas trapped in massive ground ice from the Western Canadian Arctic, which yielded Late Pleistocene ages: North Point - 10,500 ± 120 BP (AA-13658), Peninsula Point - 13,860 ± 100 BP (AA-13013), and Herschel Island 17,570 ± 300 BP (AA-14234). The dates obtained from Peninsula Point agree well with three previously obtained AMS dates: 14,270 ± 250 BP, NUTA-594; 17,000 ± 250 BP, NUTA-594 and 17,070 ± 180 BP, NUTA-589 which were measured for elemental carbon of sediments in massive ice below the top of the ice body: 11,2 m, 21,2 m and 21,5 m, respectively (Kato et al., 1988).

Dating of pollen and spores is considered as the best technique, because they are separated immediately from ice-wedge ice, as they are truly simultaneous to syngenetic ice wedges (Yu.Vasil'chuk and A.Vasil'chuk, 1996).

Acknowledgments

Many persons provided help and assistance and most of them also provided comments and points for discussion: Professor Joakim Donner, Professor Vyacheslav Konishchev, Dr. Laurent D.Labeyrie, Dr. Jean-Claude Duplessy, Dr.Hogne Jungner, Dr. Nils-Axel Morner, Dr.Ingrid U. Olsson, Professor Troy L.Pewe, Professor Mati Punning, Professor Matti Seppala, Eloni Sonninen, Leopold Sulerzhitsky, Professor Victor Trofimov, Dr. Rein Vaikmae and Dr. Alexander Yesikov. We extend special thanks to Dr.Julius B. Murton for kindly reviewed and commented of our papers.

This work has been supported as a part of a grants (96-05-65528 and 96-04-50038) from the Russian Foundation for Basic Research, for which we express grateful appreciation.

Yurij K.Vasil'chuk
Department of Cryolithology and Glaciology,
Moscow State University,
Vorob'yovy Gory, 119899, Moscow
and
Theoretical Problems Department
Russian Academy of Sciences
Denezhnyi pereulok, 12, 121002 Moscow, Russia
and
Alla C.Vasil'chuk
Institute of Cell Biophysics
The Russian Academy of Sciences
142292, Pushchino, Moscow Region, Russia

References

AVDALOVICH, S.A. and BIDZHIEV, R.A. (1984). *Kargin marine terraces in north of Western Siberia and problem of sartan ice sheet* (In Russian). Proceedings of Academy of Sciences of Éian). *Proceedings of Academy of Sciences of The USSR. Geographical series.* 1, 89-100.

BLACK, R.F. (1983). *Three superposed systems of ice wedges at McLeod Point, Northern Alaska, may span most of the Wisconsinan stage and Holocene.* In *Permafrost.* Fourth International Conference, Proceedings. Fairbanks. Alaska. pp.68-73. National Academy Press. Washington.

BOLIKHOVSKY, V.F. (1987) *The edoma deposits of Western Siberia* (In Russian). In *New data in Quaternary Geochronology.* pp. 128-136. Nauka publ. House, Moscow.

BROWN, J. (1965). *Radiocarbon dating, Barrow, Alaska. Arctic.* 18 (1), 37-48.

CARTER, L.D. (1988). *Loess and deep thermokarst basins in Arctic Alaska.* In *Permafrost.* Fifth International Conference, Proceedings. Volume One, Trondheim. Norway. pp. 706-711. Tapir Publishers, Trondheim.

DANSGAARD, W., JOHNSEN, S.J., CLAUSEN, H.B., DAHL-JENSEN, D., GUNDESTRUP, N., HAMMER, C.U., HVIDBERG, C.S., STEFFENSEN. J.P., SVEINBJORNSDOTTIR, A.E., JOUZEL, J. & BOND, G. *Evidence for general instability of past climate from a 250-kyr ice-core record. Nature.* 1993. 364. (6434), 218-220.

DOSTOVALOV, B.N. and POPOV, A.I. (1963). *Polygonal systems of ice-wedges and conditions of their development.* In *Permafrost.* First International Conference, Proceedings. Lafayette. USA. pp. 102-105. National Academy of Sciences - National Research Council, Washington, D.C.

HAMILTON, T.D., CRAIG, J.L. and SELLMAN, P.V. (1988). *The Fox permafrost tunnel: A Late Quaternary geologic record in central Alaska. Geological Society of America Bulletin.* 100 (6), 948-969.

KATO, K., SATO, S. and FUJINO, K. (1988). *Radiocarbon dating by accelerator mass spectrometry on sediment in a core from a massive ice body in Mackenzie Delta, N.W.T., Canada: Preliminary report.* In Fujino, K.(ed.), *Characteristics of the Massive Ground Ice Body in the Western Canadian Arctic Related to Paleoclimatology.* pp.58-69. Institute of Low Temperature Science, Hokkaido University, Sapporo, Japan.

KAPLINA, T.N. (1986). *Regularities of development of cryolithogenesis in Late Cenocoicum in accumulation flood plain on North-Eastern Asia.* Summary of Dr.Sci. Dissertation (in geology and mineralogy). Permafrost Institute of Siberian Branch Academy of Science of USSR. Moscow. (In Russian). 48 pp. (475 pp. is volume of Dissertation).

KOLSTRUP, E. (1987). *Frost-wedge casts in western Jutland and their possible implications for European periglacial research. Zeitschrift fur Geomorphologie* N.F., 31, 449-461.

KOTOV A.N. (1988). *Polifacial complex of Late Pleistocene epigenetic and syngenetic deposits in Mayn River valley (Chukotka).* (In Russian).In P.I.Mel'nikov (ed.). *Problems of Geocryology.* pp. 108-115. Nauka publ. House, Moscow.

LABEYRIE, L.L., VIDAL, L., CORTIJO, E., PATERNE, M., ARNOLD, M., DUPLESSY, J.C., VAUTRAVERS, M., LABRACHERIE, M., DUPRAT, J, TURON, J.L., GROUSSET, F. and VAN WEERING, T. (1995). *Surface and deep hydrology of the Northern Atlantic Ocean during the past 150 000 years. Phil. Trans.* Royal Society London. B. 348, 255-264.

LONG, A. and PEWE, T.L. (1996). *Radiocarbon dating by high-sensitivity liquid scintillation counting of wood from the Fox Permafrost Tunnel near Fairbanks, Alaska. Permafrost and Periglacial Processes.* 7 (3). P.281-285.

MACKAY, J. R. (1983). *Oxygen isotope variations in permafrost, Tuktoyaktuk peninsula area, Northwest Territories. Geological Survey of Canada. Current Research.* Part B. Paper 83-1B: 67-74.

MACKAY, J.R. (1990). *Some observations on the growth and deformation of epigenetic, syngenetic and anti-syngenetic ice wedges. Permafrost and Periglacial Processes.* Vol.1 (1). P.15-29.

MACKAY, J.R., KONISHCHEV, V.N. and POPOV, A.I. (1979). *Geologic controls of the origin, characteristics, and distribution of ground ice.* In *Permafrost.* Third International Conference, Proceedings. Volume Two. Edmonton, Canada. pp.1-18. National Research Council of Canada. Ottawa.

MAKEEV, V.M., ARSLANOV, H.A., BARANOVSKAYA, O.F., PONOMAREVA, D.P. and TERTYCHNAYA, T.V. (1989). *Late Pleistocene and Holocene stratigraphy, geochronology and paleogeography of Kotelny Island.* (In Russian). In *Bulletin of Commission for Study of the Quaternary.* N 58. pp.58-69. Nauka publ. House, Moscow.

MICHEL, F.A. (1989). *Isotope techniques in permafrost investigations.* In *Geocryological studies in Arctic Regions.* Proceedings of the International Symposium. Volume Four. Yamburg. USSR. pp. 130-145. Northern Development Institute Reprint, Tyuman'.

MICHEL, F.A. (1990). *Isotopic composition of ice-wedge ice in northwestern Canada.* In *Permafrost* - Canada. Proceedings of the Fifth Canadian Permafrost Conference, 54, pp. 5-9. Collection Nordicana, Centre d'etudes Nordiques, Universite Laval. National Research Council of Canada, Quebec.

MOORMAN, B.J., MICHEL, F.A. and WILSON, A. (1996). *^{14}C dating of trapped gases in massive ground ice, Western Canadian Arctic. Permafrost and Periglacial Processes.* 7 (3), 257-266.

MORIIZUMI, J., IIDA, T. and FUKUDA, M. (1995). *Radiocarbon dating of mathane obtained from air in the ice complex (edoma), in Arctic coast area of east Siberia.* In Takahashi, K., Osawa, A. and Kanazawa, Y. (eds.). Third Symposium on the Joint Siberian Permafrost Studies between Japan and Russia in 1994, held at Tsukuba, Japan. *Proceedings.* pp.14-21. Hokkaido University.

NAGAOKA, D., SAIJO, K. and FUKUDA, M. (1995). *Sedimental environment of the edoma in high Arctic eastern Siberia.* In Takahashi, K., Osawa, A. and Kanazawa, Y. (eds.). Third

Symposium on the Joint Siberian Permafrost Studies between Japan and Russia in 1994, held at Tsukuba, Japan. *Proceedings*. pp.8-13. Hokkaido University.

NELSON, R.E., CARTER, L.D. and ROBINSON, S.W. (1988). *Anomalous radiocarbon ages from a Holocene detrital organic lens in Alaska and their implications for radiocarbon dating and paleoenvironmental reconstructions in the Arctic. Quaternary Research.* 29 (1), 66-71.

NIKOLAEV,V.I. and MIKHALEV, D.V. (1995). *An oxygen-isotope paleothermometer from ice in Siberian permafrost. Quaternary Research.* 43(1), 14-21.

OESCHGER, H., ALDER, B. LANGWAY, C.C. (1967). *An in situ gas-extraction system to radiocarbon date glacier ice. Journal of Glaciology.* 6. 939-942.

PAYETTE, S., GAUTHIER, L. and GRENIER, I. (1986). *Dating ice-wedge growth in subarctic peatlands following deforestation. Nature.* 322 (6081), 724-727.

PEWE, T.L. and SELLMANN, P.V. (1973). *Geochemistry of permafrost and quaternary stratigraphy.* In *Permafrost.* Second International Conference, Proceedings. Yakutsk, USSR. pp. 166-170. National Academy of Sciences, Washington, D.C.

POPOV, A.I. (1967). *Permafrost phenomena in the earth's crust: cryolithology* (In Russian). Moscow University publ. House, Moscow. 304 p.

SELLMANN, P.V. and BROWN, J. (1973). *Stratigraphy and diagenesis of perennially frozen sediments in the Barrow, Alaska, Region.* In *Permafrost.* Second International Conference, Proceedings. Yakutsk, USSR. pp. 171-181. National Academy of Sciences, Washington, D.C.

SULERZHITSKY, L.D. (1982). *Reliability of the radiocarbon age and exactness of the dates.* (In Russian). *In The Antropogene of the Taimyr Peninsula.* pp. 10-17. Nauka publ. House, Moscow.

TOMIRDIARO, S.V. and CHYORNEN'KII, B.I. (1987). *Cryogenic-aeolian deposits of the Eastern Arctic and Subarctic.* (In Russian). Nauka publ. House, Moscow. 198 pp.

VANDENBERGHE, J and KASSE, C. (1993). *Periodic ice-wedge formation and weichselian cold-climate floodplain sedimentation in the Netherlands.* In *Permafrost.* Sixth International Conference, Proceedings. Volume One. Beijing, China. pp. 643-947. South China University of Technology Press. Wushan, Guangzhou.

VANDENBERGHE, J. and PISSART, A. (1993). *Permafrost changes in Europe during the Last Glacial. Permafrost and PeriglacialProcesses.* 4 (2), 121 - 135.

VASIL'CHUK, YU.K. (1982). *Regularities of Development of Engineering Geology Conditions in the North of Western Siberia in the Holocene.* English summary (27 pp.) of PhD Dissertation in Geology and Mineralogy). Moscow State University. Nauka publ. House, Moscow. (305pp. is volume of Dissertation, in Russian).

VASIL'CHUK, YU.K. (1988). *Paleological permafrost interpretation of oxygen isotope composition of Late Pleistocene and Holocene wedge ice of Yakutia. Transactions (Doclady) of the USSR Academy of Sciences.* Earth Science Sections. Published by Scripta Technica, Inc. A Wiley Company. New York. 298 (1), 56 - 59.

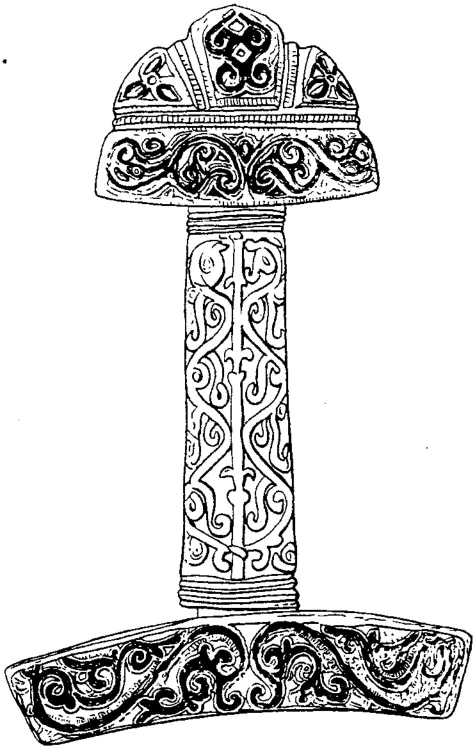
VASIL'CHUK, YU.K. (1990). *Isotope geochemical characteristics of the Late Pleistocene ice-wedge complex of Kular depressions.* (In Russian). *Transactions (Doclady) of the USSR Academy of Sciences.* 310 (1), 154-157.

VASIL'CHUK, YU.K. (1991). *Late Quaternary syngenetic permafrost sediments of Northern Eurasia: Structure, oxygen - isotope composition and forming conditions.* English summary (48 pp.) of DSci Dissertation in Geology and Mineralogy). Permafrost Institute of Siberian Branch Academy of Science of USSR. Nauka publ. House, Moscow. (622pp.

is Volume One and 244 pp. - Volume Two of Dissertation, in Russian).
VASIL'CHUK, YU.K. (1992). *Oxygen isotope composition of ground ice application to paleogeocryological reconstructions).* (In Russian, with English the contents, all figure captions and appropriately summary). Theoretical Problems Department, Russian Academy of Sciences and Moscow University publ., Moscow. Volume One - 420 pp., Volume Two - 264 pp.
VASIL'CHUK, YU.K. (1993). *Northern Asia cryolithozone evolution in Late Quaternary.* In *Permafrost.* Sixth International Conference, Proceedings. Volume One. Beijing, China. pp. 945-950. South China University of Technology Press. Wushan, Guangzhou.
VASIL'CHUK YU.K., PUNNING J.-M. and VASIL'CHUK A.C. *Radiocarbon age of Mammoths in Northern Eurasia. Radiocarbon.* 1996. Vol. 38 (3).
VASIL'CHUK, YU.K. and TROFIMOV, V.T. (1984a). *Debated problems of paleogeocryology of the Pleistocene and Holocene of Western Siberia in light of new data. Moscow University Geology Bulletin.* Allerton Press Inc. New York. 39 (3). 67-80.
VASIL'CHUK, YU.K. and TROFIMOV, V.T. (1984b). *Oxygen-isotope diagram of ice-wedges in Western Siberia, its radiocarbon age determination and paleogeocryological interpretation.* (In Russian). *Transactions (Doclady) of the USSR Academy of Sciences.* 275 (2), 425-428.
VASIL'CHUK, YU.K. and TROFIMOV, V.T. (1988). *Oxygen isotope variations in ice-wedge and massive ice.* In *Permafrost.* Fifth International Conference, Proceedings. Volume One. Trondheim. Norway. pp. 489-492. Tapir Publishers, Trondheim.
VASIL'CHUK, YU.K., VAIKMAE, R.A., PUNNING, J.-M. and LEIBMAN, M.O. (1988). *Oxygen-isotope distribution, palynology and hydrochemistry wedge ice in organic-mineral complex of Duvanny Yar type section. Transactions, USSR Academy of Sciences.* Earth Science Sections. Scripta Technica, Inc., A Wiley Company. New York. Vol. 292 (5), 69-72.
VASIL'CHUK, YU.K. and VASIL'CHUK, A.C. (1995a). *Climate variations last Late Pleistocene cryochron 40-10 Kyr B.P. in Northern Eurasia.* In International Conference on Past, Present and Future Climate. Proceedings of the SILMU conference held in Helsinki. pp. 67-70. *Publications of the Academy of Finland,* Helsinki.
VASIL'CHUK, YU.K. and VASIL'CHUK, A.C. (1995b). *Ice-wedge formation in Northern Asia during the Holocene. Permafrost and Periglacial Processes.* 6 (3), 273 - 279.
VASIL'CHUK, YU.K. and VASIL'CHUK, A.C. (1996). *Palynology for solution of problems of ice origin and its formation conditions* (In Russian). In First Conference of Russian Geocryologyst held in Lomonosov's Moscow University 3-5 June 1996. *Materials.* Volume Three. pp.414-429. Moscow University publ. House.
VASIL'CHUK, YU.K. and VASIL'CHUK, A.C. (1997). *A new (18O continental palaeotemperature record (40-0 ka) from Northern Russian syngenetic ice-wedges. Quaternary Science Reviews* (in press).
VASIL'CHUK, YU.K., YESIKOV, A.D., OPRUNENKO, YU.F., PETROVA, YE.A., VASIL'CHUK, A.C. and SULERZHITSKIY, L.D. (1985). *New data on the concentrations of stable oxygen isotopes in syngenetic Late Pleistocene wedge ice of the lower Kolyma River. Transactions (Doclady) of the USSR Academy of Sciences.* Earth Science Sections. Published by Scripta Technica, Inc. A Wiley Company. New York. 281 (2), 91 - 94.

INTERNATIONAL WORKSHOP ON

ISOTOPE-GEOCHEMICAL RESEARCH IN THE BALTIC REGION



Lohusalu, Estonia
March 14-16, 1996

J. van der Plicht (Groningen), editor
J.-M. Punning (Tallinn), chairman

Published by: Centre for Isotope Research
Faculty of Mathematics and Natural Sciences
University Groningen
Nijenborgh 4
9747 AG Groningen
The Netherlands

tel.: (+31)(0) 50 363 4760
fax: (+31)(0) 50 363 4738
email: plicht@phys.rug.nl
home page: http://www.cio.phys.rug.nl/

ISBN no. 90-367-1059-6

Cover: sword with decoration from Karabchiev (Ukraine)