^{14}C AND ^{18}O IN SIBERIAN SYNGENETIC ICE-WEDGE COMPLEXES

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ABSTRACT. We discuss the possibility of dating ice wedges by the radiocarbon method. We show as an example the Seyaha, Kular and Zelyony Mys ice wedge complexes, and investigated various organic materials from permafrost sediments. We show that the reliability of dating ^{18}O variations from ice wedges can be evaluated by comparison of different organic materials from host sediments in the ice wedge cross sections.

INTRODUCTION

Permafrost covers 60% of the Russian territory and a large part of North America. During the glacial period, almost all of Europe was also covered by permafrost, with temperatures close to the present ones in the north of western Siberia and Yakutia (Vasil'chuk and Vasil'chuk 1995a). That permafrost melted not more than 10,000 yr ago. This enables radiocarbon dating of paleopermafrost sediments from Europe and North America.

Hydrogen and oxygen stable isotopes in syngenetic ice wedges of northern Eurasia and North America permafrost zones yield paleoclimatic parameters, such as paleotemperature. The oxygen isotope composition of a recently formed syngenetic ice wedge together with present winter temperatures of surface air (Vasil'chuk 1991) made it possible to use stable isotope variations in ancient syngenetic ice wedges as a quantitative paleotemperature indicator (to make sure that the same dependence took place in the past). There are two important parameters for this paleoclimatic geocryologic analysis. The first one is paleotemperature interpretation of obtained data, the second is the age determination.

Paleogeocryologic investigations have been made at a number of natural exposures of Late Quaternary syngenetic permafrost sediments including large syngenetic ice wedges in the north of Western Siberia, in Yakutia, Chukotka, Magadan and Chita Regions. Every sample was tested by various hydrochemical, geochemical and biochemical methods (more than 10 kinds of analyses); for this we collected *ca.* 100–300 samples in every cross-section with special attention to stable isotope measurements and ^{14}C dating.

We do not discuss here the features of paleotemperature interpretation of oxygen isotope data; for this we refer to earlier publications (Vasil'chuk and Trofimov 1988; Vasil'chuk 1991, 1992, 1993; Vasil'chuk and Vasil'chuk 1995a,b, 1997a,b). The aim of this paper is to discuss the difficulties that arise when dating oxygen isotope variations both in syngenetic ice wedges and in segregated ice of the host permafrost sediments.

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Syngenetic Ice Wedges and Radiocarbon Dating

Ice wedges are formed as a result of repeated frost cracking of the surface of frozen ground, followed by filling of frost fissures by water from melting snow. This ice wedge formation can happen in two ways: epigenetic and syngenetic. Epigenetic ice wedges are formed exclusively within the permafrost body; they are usually 3–4 m high and up to 3 m wide, and there is no accumulation of sediment deposits. Syngenetic ice wedges are also formed exclusively in the permafrost body, and are very large: 20–30 m high or more and 3 m wide (Vasil'chuk 1992). There is a continuing accumulation of sediment deposits.

For these syngenetic ice wedges we distinguish two stages: mainly growth of ice (the subaerial stage), and mainly accumulation of sediments (the subaqueous stage). During syngenetic ice wedge growth, the sedimentation can be interrupted for some time (subaerial stage) and then resume again (subaqueous stage). Ice wedges grow (preferably in width) during the subaerial stage. Under water, a new ice wedge rarely penetrates into an older ice wedge (Vasil'chuk and Vasil'chuk 1995a, 1997b).

For ^{14}C analysis of ice wedges, there is no way to determine directly whether or not the organic material is autochthonous, and there is also no guideline for estimating which part of organic material was washed out after thawing or was decomposed by microbes. To evaluate changes caused by thawing, one must know the type of organic accumulation and preservation during permafrost conditions.

To determine the possible influence of microbes on the ^{14}C age, the samples were treated by different methods:

- One part was dried in the field.
- One part was washed in ice-wedge meltwater.
- One part was thawed only, and not treated by any means.

In almost all cases, the ^{14}C dates for these different parts were close together (for example 27, 28 and 30 ka BP; Vasil'chuk 1992). We assume that the most reliable dates were those from samples washed in ice-wedge meltwater and subsequently dried.

DISCUSSION OF RADIOCARBON DATES

Three Syngenetic Ice Wedge Complexes

To date the syngenetic permafrost sediments with ice wedges, it is important to obtain ^{14}C dates for various organic materials. Usually, these are autochthonous peat, wood, roots, branches, trunks, bones of skeleton, teeth, tusks and residual organic plant material. We assume that the best strategy is to obtain a series of dates from one ice wedge cross-section. However, it does not always happen that two or more kinds of organic material are found. Here we discuss three large ice wedges from the Russian permafrost zone: Seyaha, Zelyony Mys and Kular (Fig. 1).

Seyaha Polygonal Ice-Wedge Complex

We studied the Seyaha lagoon-marine ice-wedge complex in 1978 (pioneering description), 1979 and 1996. It is located in the north of Western Siberia, at the eastern coast of Yamal Peninsula, 70°N, 72°E (Fig. 1). A two-level system of syngenetic polygonal ice wedges is exposed naturally 22–24 m in height along the Ob Bay coast. Ice wedges from the 11–12 m lower level are typically 3 m wide and have a conical shape. Sediments from the upper level contain narrow 1–1.5 m wide ribbon-shaped ice wedges.

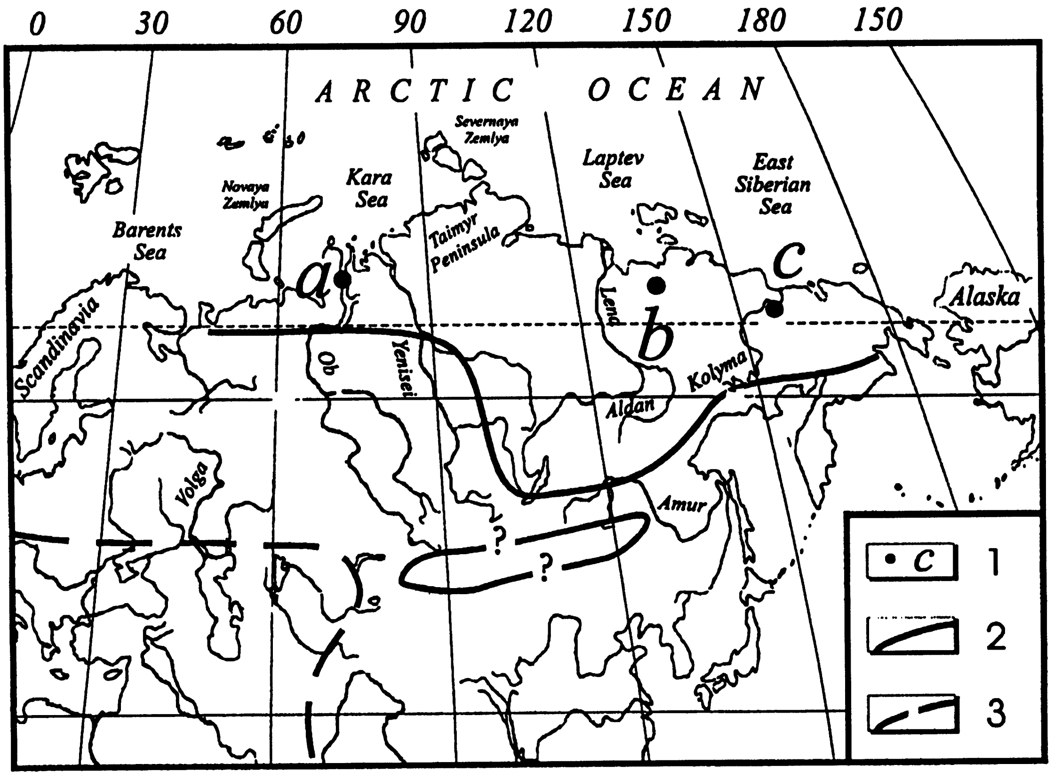

Fig. 1. Russian permafrost zone with three ice-wedge sites mentioned in the text. Ice-wedge complexes near the Seyaha settlement (a), near the Kular settlement (b) and near the settlement Zelyony Mys (c). 1. localities of cross-sections; 2. southern limit of present ice-wedge distribution; 3. southern limit of Late Pleistocene ice-wedge distribution.

The stratigraphy, $\delta^{18}O$ results for the ice, and ^{14}C dates for organic material from the ice are shown in Figure 2. During the first investigation, a sequence of six ^{14}C dates from *ca.* 15 m were obtained (triangles on the right side of Fig. 2) (Vasil'chuk and Trofimov 1988). All dates were obtained from organic material forming a 1-m-thick layer with thin layers of sandy loam. We consider the main part of this material to be autochthonous. In 1996, we took 150 samples for $\delta^{18}O$, some of which were measured in this study. New dates of the cross-section have also been obtained. They supplement and broaden the dating possibilities. The Seyaha cross-section has been investigated by others as well. Very interesting ^{14}C dates were obtained, which are shown in the middle part of Figure 2. We can see that the visible part of polygonal ice wedge complex began to form *ca.* 36 ka BP (Hel-3950), and finished at *ca.* 11.6 ka BP (Hel-3942). The ^{14}C date of *ca.* 17 ka BP (Hel-4023) is the most interesting, because it is indicative of continuous subaqueous sedimentation in the Ob Bay (or lagoon).

There is a notable coincidence among the dates at a height of +11 m, *ca.* 22.5–22.7 ka BP (GIN-2473, 2475, 8931). A mammoth bone from the +20-m level was dated at 14,400 ± 80 BP (GIN-7292), which corresponds well with the other ^{14}C dates. The sedimentation rate and vertical ice-wedge growth varied from *ca.* 1 m 1000 a^{-1} in the upper part of the section to *ca.* 0.8 m 1000 a^{-1} in the lower part. The difference can be explained by changes in the sedimentation pattern from subaqueous-subaerial in the sea-coast plain 35–22 ka BP (judging from finds of *Ledum* remains and diatoms in felt-like layers), to a shallow subaqueous regime 22–11 ka BP (suggested by finds of subsaline water foraminifera).

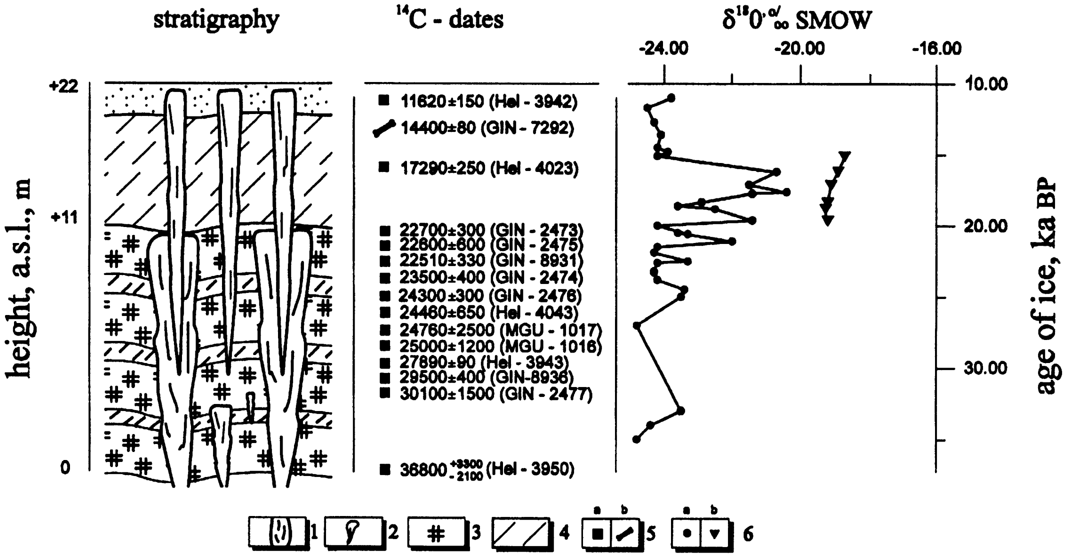

Fig. 2. ^{14}C dates and continuous δ^{18}O profiles along syncryogenic thicknesses with ice-wedge complexes near the Seyaha settlement: 1. syngenetic Late Pleistocene large ice wedges; 2. syngenetic Late Pleistocene small (buried) ice wedges; 3. peat remains and dispersed organic remains; 4. sandy loam; 5. ^{14}C dates: a) of dispersed plant material, b) of bones; 6. oxygen-isotope data: a) of ice wedge, b) of segregated ice.

Kular Polygonal Ice-Wedge Complex

The Kular slope-lacustrine polygonal ice-wedge complex is located in the submountain belt of the Kular mountain chain (70°N, 134°E; Fig. 1). The cross-section here is 24 m thick, and is shown in Figure 3 with δ^{18}O and ^{14}C measurements.

The base of the permafrost cross-section is composed of bed-rock, covered by a 1-m layer of eluvium with rock debris. There is a 2–3-m fine river sand layer with pebbles. The 20–25-m layer of sandy loam contains a lens of autochthonous peat (*ca.* 1.5 m) and bones of horse, mammoth, and bison (*Bison bison* and *B. bonasus*). There are concentrations of small branches, bushes, roots, grass and moss stalks, which are evidence for accumulation in bog conditions. The section is penetrated by large and wide (*ca.* 3 m) syngenetic ice wedges up to the eluvium layer. Separated ice lenses are also found. The non-inversed ^{14}C date series of peat has been obtained from the top to the bottom at a depth 11–18 m and ranges from 33.3 ka to >40 ka BP (measurements from GIN). Somewhat higher, at a depth of 9–12 m, "in situ" bones are dated at 37.7, 38.7 and 40.5 ka BP, *i.e.,* the bones are apparently redeposited. The concentration of small branches at a depth of 11 m is dated at 42.4 ka BP, so that these branches also must be redeposited. Two fragments of wood at the bottom of the section are dated to >43. and 41.1 ka BP. It is possible that the latter was not redeposited. It can be concluded with some certainty that the sediments at 11 m depth formed 33 ka BP, and at 18 m depth accumulated 40–41 ka BP. The rate of accumulation and ice-wedge growth was *ca.* 1 m 1000 a^{-1} according to the ^{14}C dates of the lower part of the section, and probably remained the same rate later. Taking into account the whole thickness of ice wedges, it may be suggested that ice wedge formation took place between 40 and 20 ka BP. Organic redepositing and occurrence of bones and wood show that deposition and transportation took place under subaqueous conditions; the accumulation of small branches, in pools or natural dams. The inundation periods, marked by pure sandy loam beds and subaerial condition, are marked by autochthonous peat layers in the section. Surprisingly, no clastic material has been found.

Zelyony Mys Polygonal Ice-Wedge Complex

The Zelyony Mys lacustrine-bog ice-wedge complex is located in the northeast of Yakutia in the Kolyma valley (69°N, 161°E; Fig. 1). It was first described in 1985 (Vasil'chuk *et al.* 1985), and the cross-section was investigated later in 1986, 1987 and 1988. The natural 35 m exposure was formed as a result of a lake burst. There are systems of large and wide (*ca.* 3 m) syngenetic ice wedges. The main features of the section are three organic layers at a depth of 10–25 m and poor organic sediments in the upper 9–10 m part (Fig. 4). At the upper part of the section, large ice wedges occur (up to 3 m) together with small narrow burial ice wedges located at various depths. One noticeable peculiarity of the organic layers is their shape. It is a downward pointed "dent", *ca.* 1.5 m long and *ca.* 0.4 m wide at the top. We have observed the same shape at alas (depressed) sections in lower parts of Holocene peats and their underlying lacustrine deposits. This is evidence of a common origin of Late Pleistocene cyclic peat series and Holocene alas (lacustrine-peat) deposits.

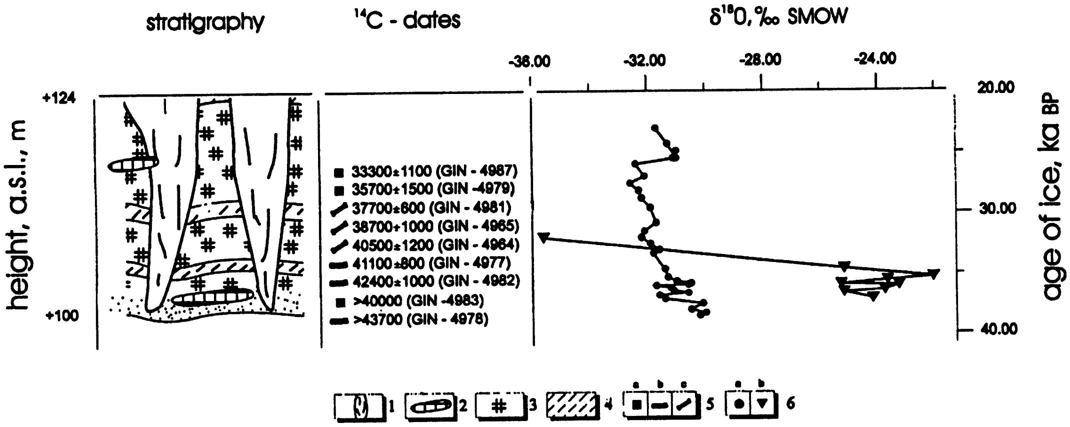

Fig. 3. ^{14}C dates and continuous δ^{18}O profiles along syncryogen thicknesses with ice-wedge complexes in an intermountain depression near the Kular settlement: 1. syngenetic Late Pleistocene large ice wedges; 2. lens-shaped ice; 3. peat; 4. loamy sand; 5. ^{14}C dates of: a) peat, b) small branches and tree remains, c) bones; 6. oxygen-isotope data: a) ice wedges, b) segregated ice.

A series of consistent ^{14}C dates was obtained in the cross-section for dispersed organic plant material (residual detritus). The upper peat layer dated 27.9 and 28.6 ka BP, the middle one 33.8 ka BP, and the lower one 37.6 ka BP (dates by GIN). Data for seeds in two fossil suslik holes are very important in terms of dating strategy because they give information about undeniably non-redeposited organic material. Good preservation of seeds, down, hair, leaves and stem remains show that at the early stage the burial conditions were dry and cool; later the sediments froze syngenetically and never thawed. Some seeds preserved their germination ability. Using *in-vitro* cultures makes it possible to induce a germination of pink family (*Caryophyllaceae*) seed rootlets and to extract fragments of undeveloped germ from sedge seeds (Gubin *et al.* 1997). The occurrence of suslik holes indicates a long subaerial stage of polygonal ice-wedge complex development, when the ice wedges were growing in width. Rodent holes are common at the sections of syngenetic permafrost sediments with ice wedges. Some rodent holes have been found in subaerial peaty sandy loam located in the lower part of the Duvanny Yar cross-section that is covered by subaqueous sand. Insect fauna, with dominating beetle, *Morychus aeneus* Fabr., which dwells in the sand banks of lakes and rivers of the northern taiga forest, has been found here. There are many tundra hygrophile species found such as *Pterostichus* (*Cryobius*) sp. (Kaplina 1986). A hole with seeds and rodent droppings has been found at the Vorontsovsky Yar cross-section in the Indigirka valley. It is dated to >41 ka BP (GIN-1674). A date 37,000 ± 1100 BP (GIN-1675) (Kaplina 1986) has been obtained for bush roots at 3 m higher. A similar find of seeds in a rodent hole dated to 29,800 ± 1800 BP (GIN-1683), found at a height of 43 m between ice wedges at the cross-section in the Allaicha River valley. At the same section peat layers alternating with sandy loam are dated 34,900 ± 1000 BP (GIN-1685) at a height of 24 m, and 41,400 ± 800 BP (GIN-1686) at 18 m above sea level (asl) (Kaplina 1986). These dates indicate alternating cycles of subaerial and subaqueous syngenetic permafrost sediments with ice-wedges.

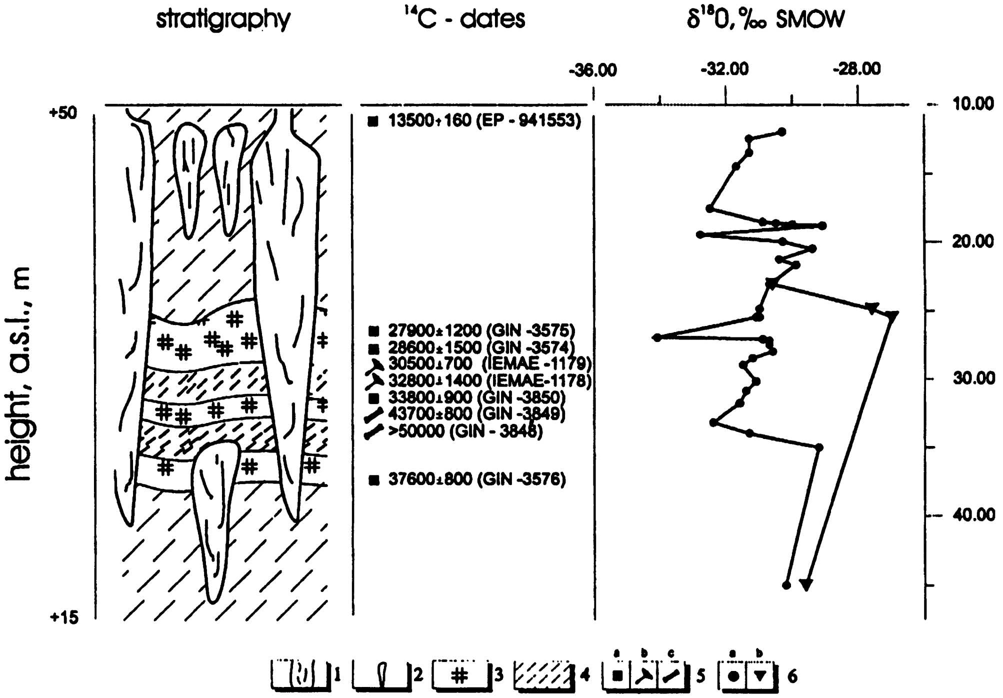

Fig. 4. ^{14}C dates and continuous δ^{18}O profiles along syncryogen thicknesses with ice-wedge complexes near the settlement Zelyony Mys: 1. syngenetic Late Pleistocene large ice wedges; 2. syngenetic Late Pleistocene small (buried) ice wedges; 3. horizons enriched with autochthonous and allochthonous organic; 4. loamy sand with small content of allochthonous organic; 5. ^{14}C dates of: a) rootlets and dispersed plant materials, b) seeds in suslik holes, c) bones; 6. oxygen-isotope data: a) ice wedge, b) segregated ice. Note: the AMS date (EP) was obtained by Prof. E. M. Pfeffer of Hamburg University.

^{14}C dates of seed concentrations in holes dated 30.5 and 32.8 ka BP (Gubin *et al.* 1997) fit into our earlier obtained series of dates for the Zelyony Mys cross-section. These samples were not collected at exactly the same site but at some distance (not far) away. It is interesting that branches and twigs sampled near holes are older by 0–12 ka than seeds from a rodent hole. For mammoth cannon and skull bones, the dates 43.7 and >50 ka BP are deviant. Since these bones occur separately without skeletons, they are probably redeposited.

Buried narrow ice wedges, which had no time to join into large ones, are evidence for a high sedimentation rate. We noticed three periods of subaerial conditions between 37 and 27 ka BP. According to ^{14}C dates they lasted 2–3 ka, therefore the subaqueous stages lasted *ca.* 1–1.5 ka.

Of importance is the accelerator mass spectrometry (AMS) date from the soil layer in the upper part of the section: 13.5 ka BP (Gubin *et al.* 1997). The date both refines the time of ice-wedge formation completion, and allows evaluation of an earlier estimation by interpolation, which gave an age of 16 ka BP. We think that the uncertainty of *ca.* 3 ka is reasonable. As a whole the period of ice-wedge formation is evaluated as being from 45 to 13 ka BP.

DISCUSSION

The materials obtained for the above mentioned cross-sections allow us to establish the reliability of ^{14}C dates for different materials, compare and range a number of obtained dates of peat, dispersed organic plant material/residual detritus, wood and bones.

Dates of Peat

Autochthonous peat is one of the best materials for ^{14}C dating of syngenetic permafrost sediments with large ice wedges. Series of reliable and non-inversed dates have been obtained for Holocene syngenetic ice wedges. Late Pleistocene autochthonous peats within ice wedges have not yet been found. Thick autochthonous peat layers are rare in Late Pleistocene sections. Layers >1.5 m thick were found in the lower part of the Duvanny Yar cross-section (Kaplina 1986; Vasil'chuk *et al.* 1988), dated 36,900 ± 500 BP (MGU-469) and 35,800 ± 1200 BP (GIN-2278). Wood remains in this horizon are also autochthonous. The ^{14}C date 37,600 ± 1100 BP (MGU-468) is contemporaneous with the peat. Two persistent peat beds at the Molotkovsky Kamen' exposure are dated 24,550 ± 260 BP (MAG-160), 26,950 ± 330 BP (MAG-153) and 28,100 ± 1000 BP (GIN-2396) for the upper bed, and 42,800 ± 400 BP (GIN-143) for the lower one. These beds are considered indicative of climatic warming (Kaplina 1986); however, the occurrence of large syngenetic ice wedges is not evidence of that conclusion. Such thick peat layers with abundance of tree pollen probably form an argument for warming of the short arctic summer, but the geocryologic and climatic situation were stable. Due to thermal properties of peat (isolating and cooling), syngenetic ice-wedges were growing at the same or greater rate and they were more abundant at that time (Vasil'chuk 1992).

Dates of Dispersed Organic Plant Material–Residual Detritus

Due to good preservation, dispersed organic plant material occurs and redeposits repeatedly in permafrost sediments very often. Permafrost sediments can be impregnated by allochthonous organic material in such a way that it is possible to obtain non-inversed series of ^{14}C dates. If sediments have been formed under fluvial conditions the dispersed organic plant material usually can be only one object for ^{14}C dating in permafrost cross-sections. However, it is very difficult to obtain a correct interpretation. The age of dispersed organic plant material can vary, both vertically and horizontally. The age difference between samples of organic material can be >10 ka. For example, a sample of modern detritus near Cape Sabler was dated to 13,600 ± 400 BP (GIN-1529). In this cross-section, a series of dates ranging from 2.5–24 ka BP was obtained. Organic material from the straight coast of Cape Fus was dated to 2860 ± 150 BP (Sulerzhitsky 1982) and an organic matter sample from the beach between Cape Fus and Cape Sabler was to dated 7400 ± 60 BP (GIN-1287). On the beach of the Khatanga River (southeast of the Taimyr Peninsula), two samples were dated at 4600 ± 150 BP (GIN-1249) and 690 ± 100 BP (GIN-1248), demonstrating a significant admixture 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 2100 ± 80 BP (GIN-1508), the other is modern 170 ± 50 BP (GIN-1509). In this case the first sample differs by admixture of felt-like material (Sulerzhitsky 1982).

The sedimentation at different distances from washed out peat or peaty sediments results in ^{14}C age variations through the area of modern accumulation of lake deposits (Vasil'chuk and Vasil'chuk 1997b). All these dated samples show similar attributes. It is impossible to select the most reliable date from modern sediments. Evidently, the most useful sample is the youngest one, which must be used for ^{14}C dating interpretation.

Dating Wood

^{14}C dates of wood are the most problematic in syngenetic permafrost sediments with ice wedges. Most Late Pleistocene ice wedges originated in tundra conditions. Wood remains are generally transported from the southern regions by rivers, in which case the wood is contemporaneous to the host sediments, or redeposited from more ancient sediments, so that it is usually older. The isolated wood finds are useful for ^{14}C dating in tundra and paleotundra conditions. This is different for ice wedges formed in forest-tundra or forest conditions during the Late Pleistocene and Holocene. These are the areas of central Yakutia, Trans Baikal and Magadan Regions. The chances are better that here the wood finds will be autochthonous. However, in the case of fluvial sedimentation, wood could be redeposited. For example, in the upper part of the cross-section of Mamontova Gora in the Aldan River valley, lacustrine loess-like sediments with ice wedges are exposed. According to the dates obtained from autochthonous peat and ^{18}O data they date to *ca.* 9–4.5 ka BP. However, there were many dates obtained in the interval 40–35 ka BP from trunks and branches found in the sediments (Vasil'chuk 1988).

Dating Bones

Bone dates require a special approach for their interpretation (Vasil'chuk *et al.* 1997). On one hand, bone is the best material for ^{14}C dating because it is characterized by very good replication results. Although some have questioned whether reliable ^{14}C dates for bones can be obtained, the latest publications devoted to controlled dating of the same bone material in different laboratories shows validity of the approach. (*Cf.* Table 1.) On the other hand, bones used as a dating material of syngenetic permafrost sediments can also be redeposited. Animal carcasses are usually taken away immediately after their death by beasts or relatives (modern elephants remove the carcass of a deceased elephant). Even if an animal was drowned and froze after death very quickly, later the carcass could be stripped due to washout of host sediments. Then these bones could be removed by beasts to some distance away, often to dry, elevated places. The skeletons were also washed out by the erosion activity of rivers, lakes, or sea, removing the bones to the lower hypsometric levels. A complete carcass can be redeposited in frozen state, preserving its original state, due to landsliding, as happened with remains of the well-known mammoth-baby "Dima" in the Magadan Region.

We assume that removing and redeposition of bones is a more natural process than carcass burial "in situ" (Vasil'chuk *et al.* 1997). The occurrence of separate bones in sediments is indicative of redeposition. This is clearly demonstrated at the above-mentioned cross-sections Kular and Zelyony Mys. The difference between different bone dates from the same layer shows the allochthonous character of their occurrence. The bones found are older than other organic material. For example we can compare the dates of pure autochthonous peat and dates of bones at the Kular cross-section. Therefore, we conclude that the bones are redeposited. However, the dates can be used to establish dating limits.

Radiocarbon Dating of Ice-Wedge ^{18}O Curves

Interpretation of ice-wedge δ^{18}O data in terms of paleotemperature depends on the formation mechanism of syngenetic ice wedges. Mainly, subaerial ice accumulation in ice wedges means that δ^{18}O curves are interrupted as ice accumulation is stopped during subaqueous stages. However, this is an important advantage; due to the atmospheric origin of ice-wedge ice, δ^{18}O corresponds directly to the mean winter air temperature. It is important to obtain ^{14}C dates for the period of the most active ice-wedge growth, together with active accumulation of autochthonous organic material such as peat, trees, organic concentration in rodent holes, animal skeletons or sometimes whole carcasses (Vasil'chuk *et al.* 1997). This way, it is possible to date large parts of the δ^{18}O variations. This is

TABLE 1. Radiocarbon Dates of Different Preservations of Material of Mammoth Remains in Permafrost*

^{14}C age (yr BP),† lab no.	Material dated	Location of finds
Different preservations of material dated the same laboratory		
a. 31,800 ± 500 (GIN-3240)	Bone	Severnaya River, Taimyr Peninsula
b. 30,500 ± 400 (GIN-3240)	Decayed bone	Severnaya River, Taimyr Peninsula
a. 38,500 ± 500 (GIN-3136)	Bone	Boderbo-Tarida River, Taimyr
b. 37,500 ± 400 (GIN-3136)	Decayed bone	Boderbo-Tarida River, Taimyr
a. 46,100 ± 1200 (GIN-3073)	Bone	Lake Taymyr
b. 43,000 ± 1000 (GIN-3073)	Decayed bone	Lake Taymyr
a. 21,200 ± 400 (GIN-2224)	Skull	Pakhtcha River
b. 21,300 ± 200 (GIN-2224)	Decayed skull	Pakhtcha River
c. 21,300 ± 600 (GIN-2224)	Molar	Pakhtcha River
Different parts of material dated in different laboratories		
a. 9600 ± 300 (VSEGINGEO)	Soft tissue	Yuribey River, Gydan Peninsula
b. 9730 ± 100 (MGU-763)	Stomach content	Yuribey River, Gydan Peninsula
c. 10,000 ± 70 (LU-1153)	Stomach content	Yuribey River, Gydan Peninsula
a. 12,530 ± 60 (SOAN-2203)	Bone	Achchagyy-Allaikha River, Yakutia
b. 12,570 ± 80 (MAG-826)	Bone	Achchagyy-Allaikha River, Yakutia
b. 40,350 ± 880 (LU-595)	Stomach contents	Shandrin River, Yakutia
c. 41,750 ± 1290 (LU-505)	Soft tissue	Shandrin River, Yakutia
a. 6260 ± 50 (LU-2799)	Molar	Wrangel Island
b. 6360 ± 60 (AA-11529)	Molar	Wrangel Island
a. 6760 ± 50 (LU-2736)	Tusk	Wrangel Island
b. 6750 ± 30 (GIN-6990)	Tusk	Wrangel Island
a. 7250 ± 60 (LU-2809)	Molar	Wrangel Island
b. 7295 ± 95 (AA-11530)	Molar	Wrangel Island

*After L. Sulerzhitsky, personal communication (1997) and Vartanyan *et al.* (1995)

†Letters a, b and c indicate that different parts of the same individual were dated.

shown for the continuous regional $\delta^{18}O$ curves for such permafrost regions as Yamal, Taimyr or Chukotka Peninsulas.

A considerable mixture of allochthonous material in marine, alluvial and lacustrine sediments caused a discrepant series of dates. This led to repeated research for the same sections. For example, this happened in a study of the Fox Permafrost Tunnel section (Hamilton *et al.* 1988; Long and Pewe 1996) in North America and the Duvanny Yar section (Vasil'chuk *et al.* 1988) in northern Asia. In both sections, slightly corresponding numbers of dates have been obtained where the total number of dates in every section is >60. However, reliable dates have not been obtained. The only result of this work is a discussion about age estimation of the sections. For example, the beginning of the Duvanny Yar thickness is dated from 400 to 40 ka BP.

CONCLUSIONS AND PROSPECTS

We discussed here the development of authentic age determinations of syngenetic permafrost sediments and stable isotope variations of ground ice, and to verify the ^{14}C data in terms of allochthonous and autochthonous organic material. This can be used both in present permafrost regions in

Russia and in the paleopermafrost ones in European and North American Late Pleistocene permafrost (Vasil'chuk 1992; French 1996).

When ^{14}C dating ice wedges, one needs to take into account the following factors:

1. Contamination of syngenetic sediments by old organic material is the rule, not the exception;
2. Taking into consideration that old organic material is common in permafrost sediments, it may be deduced that only autochthonous organic material gives realistic results. Allochthonous material dominates in these sediments and only well-dated objects can be considered valid for ^{14}C dating, such as: layers of autochthonous peat, hay, shoots and seeds from rodent burrows, and also allowing possible redeposition of well-preserved animal bones, detritus and wood;
3. ^{14}C dates obtained at different times for chronological stratification should not be used, because organic material can be distributed irregularly both in horizontal and vertical directions;
4. Organic remains that retained their morphology through time are most appropriate for ^{14}C dating. Examples are skin and tissues of animals, joined bones, leaves or joined needles, fragments of antlers or sporangia, tree stumps with roots and cortex;
5. For paleotemperature reconstruction, the $\delta^{18}O$ variations of ice-wedge ice can be used;
6. The $\delta^{18}O$ variations can be dated by a series of dates from the host sediments together with immediate dating of organic material from ice wedges. Examples include seeds, bulk peat, pollen and spores, or air from bubbles.

AMS ^{14}C measurements are best suited for dating ice-wedge ice directly. There are various objects suitable for AMS dating in ice-wedge ice, such as 1) micro- and meso-inclusions of plant or animal origin; organic material penetrated into the body of ice wedges *via* cracks contemporaneous with ice of ice wedges (several samples from the Seyaha ice-wedge complex are presently handled by the Groningen Radiocarbon Laboratory for AMS ^{14}C-dating); and 2) ^{14}C from CO_2 and other gases trapped in ice-wedge ice.

A new sublimation technique for direct study of ice ^{14}C age developed by A. Wilson (Moorman *et al.* 1996) allows for carbon dating of atmospheric gases in ice weighing as little as 0.5–3.0 kg, depending on its CO_2 content. The authors measured the AMS age of trapped gases (CO_2) in massive ground ice from the western Canadian Arctic: 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). A. Wilson has presented (1998) several new results of AMS dating of different types of natural ice studied using the sublimation technique: fountain glacier sample 10,600 BP, stagnation glacier sample 1700 BP and 6000 BP, Arctic massive ground ices from Peninsula Point 20,500 BP and 20,000 BP, and from Sermilik 32,000 BP. Application of this technique for Siberian ground ice makes it possible to obtain more precise dates for the organic host sediments.

In addition, ^{14}C dating of pollen and spores extracted from ice-wedge ice yield new possibilities. There are some difficulties extracting enough material for AMS ^{14}C analyses, but we expect to solve this problem in the near future.

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