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# Strategy of valid $^{14}$C dates choice in syngenetic permafrost

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Strategy of valid $^{14}$C dates choice in syngenetic permafrost

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## Abstract

The main problem of radiocarbon dating within permafrost is the uncertain reliability of the $^{14}C$ dates. Syngenetic sediments contain allochthonous organic deposit that originated at a distance from its present position. Due to the very good preservation of organic materials in permafrost conditions and numerous re-burials of the fossils from ancient deposits into younger ones the dates could be both younger and older than the true age of dated material. The strategy for the most authentic radiocarbon date selection for dating of syncryogenic sediments is considered taking into account the fluvial origin of the syngenetic sediments. The re-deposition of organic material is discussed in terms of cyclic syncryogenic sedimentation and also the possible re-deposition of organic material in subaerial-subaqueous conditions. The advantages and the complications of dating organic micro-inclusions from ice wedges by the accelerator mass spectrometry (AMS) method are discussed applying to true age of dated material search. Radiocarbon dates of different organic materials from the same samples are compared. The younger age of the yedoma from cross-sections of Duvanny Yar in Kolyma River and Mamontova Khayata in the mouth of Lena River is substantiated due to the principle of the choice of the youngest $^{14}C$ date from the set.

## 1 Introduction

Numerous $^{14}C$ dates of bulk samples have been obtained from syncryogenic (syngenetic – i.e. permafrost, that formed more or less simultaneously with the deposition of the soil material in which it occurs – Glossary of Permafrost and Related Ground-Ice Terms, 1988) sediments of Russian permafrost, first of all in yedoma (yedoma is an organic-rich (about 1–2 % carbon by mass) Late Pleistocene-age loess permafrost with a structure ice content of 50–90 % by volume and with an ice wedge content of 10–60 % by volume). The results of $^{14}C$ dating very often can not be used due to irregular vertical distribution of $^{14}C$ dates in cross-section of permafrost sediment. Syngenetic sediments contain allochthonous organic deposit that originated at a distance from its present position. To clarify this problem it is necessary to have a strategy to select the valid dates for age determination of permafrost sediments.

At first it was assumed that $^{14}C$ dates from permafrost usually rejuvenated. It followed from this that older $^{14}C$ dates are more reliable. It was supposed that the contamination with modern $^{14}C$ is the main factor for obtaining invalid $^{14}C$ dates. However, while this is correct for an open system, the array of syncryogenic permafrost sediments is not a true open system. Rejuvenation can take place if there are conditions for microbial processing of modern fluids such as carbon, methane or carbon dioxide. It is possible to evaluate the probable rejuvenation of the $^{14}C$ date based on heightened tritium concentrations. Usually the tritium concentration in syncryogenic sediments is very low. Accumulation and simultaneous freezing of the sediments isolates the permafrost deposits surely. We suppose that contamination with old organic material in permafrost is of importance in aging of the $^{14}C$ dates. But this problem is poorly studied in literature.

Findings of large terrestrial macrofossils such as tree trunks and roots are rare within the areas of syncryogenic accumulation, where herbs and bushes are typical. Very often vegetation cover is not continuous in the areas of syncryogenic accumulation. These factors favoured the re-deposition of ancient organic material in permafrost. Therefore, it is possible to find both animal bone which is older than the sedimentation, weathered wood, and also older and younger plant detritus in the same layer of the peat. Abnormally old $^{14}C$ dates together with younger ones are often obtained from lacustrine and marine sediments. This is especially true for areas of active accumulation of redeposited material (Stanley, 2001; Butler et al., 2004; Broecker et al., 2006; Oswald et al., 2005; Refsnider et al., 2014). It was shown by $^{14}C$ dating of the driftwood in the modern beaches of Wollaston Peninsula, Victoria Island of the Canadian Arctic Archipelago that only one out of 30 beached logs was modern. As it turned out, most of the $^{14}C$ dates of the logs are about 3.2–4.7 kyr BP, while one log is older than 80 kyr BP (Dyke and Savelle, 2000). All the dated logs belong to the genus *Picea* which does not grow in this area. We can expect an error of more than three thousand years





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if we try to determine the formation time of the beach sediment of Victoria Island in correspondence with the $^{14}$C dates of the wood.

Stanley (2001) found enrichment with ancient organic material in depressions of river valleys and deltas. The problem of "old wood" and "old shells" is well-known in archaeology. The differences between the dates of very similar material range from 100 yr to more than 10 000 yr. For example, two *Olivella* shells in the beads in the Chimney Cave in San Miguel Island, California have a very different age. The $^{14}$C date of one shell is 10 160±25 and the $^{14}$C date of the other very similar shell is 30 900±100. Other archaeological findings from this cave are about 10 000 yr (Rick et al., 2005).

Foraminifera shells can also be dated with inversions because both younger and older material are involved in foraminifera shells. Broecker (Broecker et al., 2006) proposed to compare the $^{14}$C dates of thin-walled and normal shells and to test the presence of secondary calcite in the sediment for $^{14}$C dating sediments that had accumulated very fast.

In permafrost, such anomalous dates or inversions of dates between different fractions of the same sample are not an exception but rather the rule. At first, anomalous $^{14}$C dates were obtained from the syngenetic polygonal ice wedge complex at Cape Barrow (Brown, 1965). The syngenetic sediment of yedoma was dated as no older than 8300 yr. Two $^{14}$C dates of sedge remains and lemming pellets were obtained from the ice wedge. The date from the lateral part of the ice wedge is 14 500 yr BP, and the $^{14}$C date in the centre of the ice wedge is 8200 yr BP. It is clear that the older date was obtained from a mixture of uneven-aged organic material.

Abbot and Stafford (1996) measured the $^{14}$C activity of carbon sources entering the system by fluvial processes, including DOC (*dissolved organic carbon*) and POC (*particulate organic carbon*) in the lakes in southern Baffin Island. It was proved that $^{14}$C-depleted POC and DOC are the main cause of age discrepancy in oligotrophic Arctic lakes. The age differences between several chemical fractions in the same horizon increase with absolute $^{14}$C age and stratigraphic depth. These differences become greater than the standard measurement error after 2000 $^{14}$C yr.





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$^{14}$C inversions have been obtained in the Fox Permafrost Tunnel also. Some inversions are associated with bones which were transferred by water flow and are older than the surrounding sediments. The heterogeneity of plant detritus of alluvial origin is emphasized by the difference between the dates obtained from the same horizon, which is about 12 kyr, from 27 790 to 43 300 yr BP (Hamilton et al., 1988).

The problem of permafrost sediments with allochthonous organic material was studied by Nelson et al. (1988) at an exposure of Holocene sediments in the Ikpikpuk River valley in Alaska.

To define the sources of contamination, a large sample of the allochthonous peat from the lens was separated into different size fractions and each fraction was dated separately. The results ranged from 13 250 to 30 260 yr BP, as follows: the > 2 mm fraction of peat dated to 13 250 ± 100 (USGS-2046A); the 1–2 mm fraction was 17 730 ± 110 (USGS-2046B); the 0.5–1.0 mm fraction was 24 740 ± 320 (USGS-2046C); the 0.25–0.5 mm fraction was 30 260 ± 530 yr (USGS-2046D); and the < 0.25 mm fraction was 20 360 ± 190 (USGS-2046E). The date of the peat from the same layer is 13 730 ± 110 (USGS-883). It may be concluded that the smaller the fossil size, the older the date. Pollen analysis results have shown that in lenses of peat, the content of redeposited pre-Quaternary pollen and spores is about 50 % of the total. It was concluded that reliable $^{14}$C ages can be obtained if radiocarbon analyses are performed on several identified macrofossil remains from the deposit, and that ancient pollen amber and coal may be a source of contamination for fine fractions.

$^{14}$C dating of a 5 m cross-section of horizontally layered well-sorted sand and sandy loam in Cumberland Peninsula (Baffin Island, Canada) has shown an admixture of ancient organic material, as the $^{14}$C inversion is more than 7000 yr. As a result of the methodical study by Stuckenrath et al. (1979), it was possible to achieve a number of dates without inversions only on a rather large fraction of organic material which is insoluble in alkali (> 125 µm in size), whereas dating the soluble part of the alkali fraction has shown both a younger and an older age.





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As the main problem of radiocarbon dating within permafrost is the uncertain reliability of the $^{14}C$ dates, it is very difficult to interpret the totality of these data. The dates could be both younger and older than the true age of dated material. It is important to take into account the fluvial origin of most syngenetic sediments and the very good preservation of organic material in permafrost conditions. Various old organic materials incoming into sediment during the breakage of ancient deposits are washed out by rivers, lakes or the sea.

Cyclic character of syngenetic permafrost sediment accumulation, alternation of subaerial and subaqueous regim, multi re-deposition of organic material are factors caused.

Approaches for the choice strategy are, such as: (a) meso- and macro-cyclic model of thick syngenetic ice wedge formation (Vasil'chuk, 2006, 2013) tacking in to account, (b) modern re-deposition of organic material at subaqueous syngenetic conditions used as pattern for past syngenetic accumulation of yedoma deposits, (c) possible re-deposition of organic material at syngenetic subaerial or subaerial–subaqueous accumulation, (d) evaluation of AMS $^{14}C$ dating of organic micro-inclusions in the ice wedges, (e) comparison of the $^{14}C$ dates from various materials from the same samples.

The degree of preservation and the autochthonous nature of dated material can be used as a criterion for evaluation of the $^{14}C$ dates. The comparison of the dates from the same layer and various sets of $^{14}C$ dates may also be used for evaluation of the $^{14}C$ dates from the permafrost.

## 2 Foundations for permafrost $^{14}C$ dating strategy

### 2.1 Meso- and macro-cyclic model of thick syngenetic ice wedge formation

In the permafrost zone thick syngenetic ice wedges are the dominant form of the ice (Fig. 1). 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. It is widely thought that syngenetic ice wedges formed in slow, continuous sedimentation accompanied by repeated frost cracking only. However, we have found that such a situation occurs quite rarely and that a type of sedimentation during 20–40 kyr took place episodically, with big pulses of subaqueous deposition alternating with subaerial conditions of ice wedge growth.

The formation of syngenetic permafrost sediments has a cyclic character that occurs independently of climatic change and results from changes in the sedimentation regime. The macro-, meso- and micro-scale cyclic formation of syngenetic ice wedges causes a cyclic structure of the section and a cyclic distribution of the composition in host sediments and ice wedges (Vasil'chuk, 2006, 2013). Microcycles are associated with the seasonal periodicity of changes in the depth of an active layer and the accumulation of thin sediment layers. The duration of microcycles is estimated from several years to hundreds of years. The vertical scale of microcycles is several centimeters or tens of centimeters. Mesocycles are conditioned by the pulsing change of the water level of a reservoir, on the coast or shallows of which ice wedges are being formed. The duration of mesocycles is usually estimated from tens of hundreds to several thousand years. The vertical scale of mesocycles is several meters. For $^{14}C$ dating of ice wedge complexes it is important to take into account the mesocycles due to the essential difference of the organic material re-deposition at the subaerial and subaqueous stages. Macrocycles (Fig. 1) are caused by dramatic reorganization of the sedimentation mode. The duration of macrocycles is usually estimated in many tens – and sometimes hundreds of thousands of years. The vertical scale of macrocycles is more than tens of meters. Macrocycling, as a rule, is out of the frame of the radiocarbon method.

For syngenetic ice wedges two stages can be distinguished: mainly growth of ice (the subaerial stage), and mainly accumulation of sediments (the subaqueous stage). The growth of syngenetic ice wedges proceeds subaerially during the accumulation of peat or peaty sediments (Vasil'chuk, 2013). Periodically, when gravel, sand, sandy loam, loam, silt, and clay are deposited under subaqueous conditions, ice wedge growth decreases or stops. This model of syngenetic ice wedge growth is supported by the distribution of ice wedges in both higher and lower areas of sediment aggradation. For example, the polygonal network on the high flood plains of northern rivers tends to be widespread, whereas on low flood plains this is rare. This suggests that ice wedge growth occurs preferentially in the subaerial conditions. When the subaerial regime returns, ice wedge growth is recommenced. If the subaqueous stratum is thin enough (providing an approximate value e.g. less than 3–4 m), the toes of younger and stratigraphically higher ice wedges penetrate into buried ice wedges of the previous phase. When the tail of the new ice vein is incorporated into the underlying ice wedge a single ice wedge forms. By contrast, if the subaqueous sediment is thicker than 4–5 m, the stratigraphically higher ice wedges do not penetrate into the lower ice wedges. This process leads to the generation of multicycle (multistage) ice wedges. It does not comprise groups of epigenetic wedges of different stratigraphic levels.

The formation of the syngenetic permafrost sediments has a cyclic character that occurs independently of climate change or stability but is the result of the changes in the sedimentation regime. Sometimes buried ice wedges can be plastically uplifted (extruded) because of the impact of lateral compression. Both uplifting processes and thin overlapped layers lead to the formation of a single ice wedge from multistage ice wedges.

The cyclic model of ice wedge formation is useful for allocating the isotopic, palynologic and other data with sufficient accuracy on a chronological scale and also for evaluation of organic material for the dating. At the subaerial stage, incoming organic material is often – but not universally – autochthonous; at the subaqueous stage it is mainly allochthonous. The oxygen isotope and other plots of ice wedges are discontinued in time according to the stage changes.





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### 2.2 Modern re-deposition of organic material at subaqueous syngenetic conditions

One of the main prerequisites for more careful consideration of redeposited organic material is the essential participation of ancient organic material in modern alluvial, marine and lacustrine sediments. This was very clearly demonstrated by $^{14}$C dating of organic remains collected directly under the Seyaha yedoma exposure (Vasil'chuk et al., 2000a, b). Organic material of the exposure is dated from 30 to 11 kyr BP (Vasil'chuk, 2006). It was washed out by thermal abrasion on the modern beach, and separated and deposited in the scalloped form of almost pure (free from mineral particles) organic detritus (Fig. 2). The sediment is similar to peat layers which are found in yedoma cross-sections and are often treated by researchers as the autochthonous type, although such peat layers may be allochthonous. Of course, the $^{14}$C date will not be synchronous with sedimentation, and will be dated to the time when the detritus plants were composed. It is obvious that the $^{14}$C age of organic material accumulated on the beach will be more than 10–20 kyr older than the true time of sediment accumulation.

The proportion of redeposited material can be very large at the accumulative coastal areas far from abraded shores. This was confirmed by study of coarse and fine sand collected from the intertidal zone along the beach of the Kara Sea at the mouth of the Salemlekabtambda River, Mamont Peninsula. Pollen analysis showed a significant difference between pollen spectra of fine and coarse sand (Vasil'chuk, 2005). The percentages of the tree pollen in coarse sand were significantly higher (by 25–50 %) than in fine sand (Fig. 3). Meanwhile, the study area is situated in the Arctic tundra; the nearest tree is located more than 600 km to the south. It is clear that most of the tree pollen is washed out from older sediments as a result of thermal abrasion and is older than the sediment.

One of the aspects of re-deposition in permafrost has been considered by $^{14}$C dating of organic plant material at the beach of Taimyr Lake (Sulerzhitsky, 1982). The fresh-looking peat sampled at the beach near Sabler Cape is dated 13600 ± 400 (GIN-1529),





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while at a distance of several hundred meters at a rather flat low surface of Fus Cape the peat sample is dated 2860 ± 150, and a peat sample from the beach between these points is 7400 ± 60 (GIN-1287). It has been shown that the age difference between samples from simultaneous layers in the permafrost area could be more than 10 000 yr (Fig. 4). The $^{14}C$ date of this layer of beach sediments after a short time does not objectively correspond to the time of accumulation. But the youngest date is closest to the actual time of sedimentation from the series of dates from this horizon.

### 2.3 Possible re-deposition of organic material at syngenetic subaerial or subaerial–subaqueous accumulation

The accumulation time of syngenetic sediments in the subaerial environment can be dated with the organic material from the ice wedges and remains from rodent burrows. Unfortunately, we have no $^{14}C$ dates of material from modern burrows or modern ice wedges. But it is possible to compare the Late Pleistocene $^{14}C$ dates.

#### 2.3.1 The dating of organic material from burrows, soil and autochthonous peat

One of the best materials for $^{14}C$ dating of subaerial syngenetic sediments such as yedoma is organic remains in rodent burrows and in ice wedges. Organic remains such as plant seeds, remains of plants, charcoal, coprolites, phytoliths, and sometimes bones in burrows are excellently preserved (Dinesman, 1979; Khasanov, 1999; Gubin et al., 2003). As the inhabitants of the burrows bring contemporaneous organic material, residues in rodent burrows may be used for $^{14}C$ dating of the formation time of subaerial syncryogenic strata. In the wet tundra burrows are located on well-drained mounds which are not flooded during the spring snowmelt. Therefore, the incoming of allochthonous organic material into a burrow is unlikely. In the burrows, seeds can preserve their viability for dozens of thousand years. Viable seeds have been found in a *Urocitellus* suborder burrow in yedoma sediments with thick ice wedges in the Lower Kolyma at the Zelyony Mys cross-section. The age of the burrow is about 30–32 kyr BP.





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The burrow chamber shows no signs of flooding. The bulbs of *Polygonum viviparum*, and the seeds of *Caryophyllaceae*, *Brassicaceae*, *Carex* sp., *Potentilla* sp., *Ranunculus* sp. (two species), *Draba cinerea* Adam., *Poa* sp., *Bromus* sp. were very well preserved and retained all their morphological features and colour. The seeds of carnations and sedges were germinated successfully "in vitro" (Yashina et al., 1997, 2012). Earlier in Alaska, the seeds of *Lupinus arcticus* Wats. from lemming burrows were also successfully germinated. They were dated about 10 kyr BP. The organic material in the burrows is always autochthonous and $^{14}C$ dates of this material are reliable.

Organic remains from the lemming burrow at a depth of 3.5 m allowed dating of the yedoma of the second marine terrace in the Mamont Peninsula. The $^{14}C$ date of the small twigs in the burrow is 8630 ± 60 (GIN-3626). The peat layer above the burrow is dated about 10–11 kyr BP. It should be noted that there are no re-deposited pollen and spores in the burrow, but in the surrounding sediments the percentages of penecontemporaneous pre-Quaternary pollen and spores is 20–25 %.

Pollen spectra in the burrow correspond to the environment of typical tundra. Tree pollen is rare (*Pinus sylvestris* – 1 %). The pollen of shrub alder (7 %) and birch (30 %) are dominant. Herb pollen presented with tundra species as follows: cereals (9 %), sage (8 %), sedge (2 %), cloudberry (1 %), and buttercup (1 %). Spores of *Sphagnum* 23 %, *Bryales* (14 %) and *Lycopodiella innundata* are also found. The pollen spectra correspond to the tundra environment and there is no penecontemporaneous pollen or spores. Pollen concentrate from burrows could be a perspective for $^{14}C$ dating of syngenetic sediments. In order to use the material from the burrow for dating, we need to make sure that the burrow was not flooded. We have found penecontemporaneous pollen (2.6 %) in the burrow $^{14}C$ dated 31 800 ± 1400 (Beta-157195) in the Duvanny Yar cross-section. This is a very high concentration of ancient pollen for the Kolyma valley region (Vasil'chuk, 2005). The presence of penecontemporaneous pollen may be evidence of the flooding of the burrow.

There are many examples of age reversal from cross-sections that are known to be autochthonous without any signs of re-deposition. As shown by Payette (Payette et al., 1986), even autochthonous accumulation of peat at a polygonal bog with ice wedges in the Clearwater Lake area in subarctic Quebec can give various ages for the same subsurface layer of peat, with a difference of almost 2000 yr: from 2220 ± 80 to 335 ± 75 yr BP. But $^{14}C$ dating of the peat demonstrated normal distribution of the $^{14}C$ dates: at a depth of 0.9 m – 3.2 kyr BP, 0.5 m – 1.4 kyr BP, 0.2 m – 0.6 kyr BP, and 0.1 m – 0.3 kyr BP. Most likely, the plants that formed the peat used different sources of groundwater supply, with herb roots penetrating more deeply than mosses.

Ancient methane bubbled from the bottom of thermokarst lakes, as shown by Zimov et al. (1997) and Walter et al. (2006) in the permafrost area. So methanotrophic bacteria which provide *Sphagnum* mosses with carbon (Kip et al., 2010) could use ancient methane together with modern. Ancient soil carbon in permafrost soils may be metabolized upon thawing also. The radiocarbon ages of heterotrophically respired carbon ranged from less than 50 to 235 yr BP in July mineral soil samples and from 1525 to 8300 yr BP in August samples (Nowinski et al., 2010).

### 2.4 Evaluation of AMS $^{14}C$ dating of organic micro-inclusions in the ice wedges

Direct dating of ice wedges is possible using the technique of accelerator mass spectrometry (Vasil'chuk, 2006, 2013). As an ice wedge is a closed system, microbial activity is excluded. The dating of ice wedges allows us to obtain the age of the ice wedge directly. However, results of the AMS $^{14}C$ dating of organic inclusions in ice wedges have demonstrated that the problem of an inhomogeneous concentrate also occurs.

The comparison of the $^{14}C$ dates of different fractions from the samples of organic material in the syngenetic ice wedges of a 24 m terrace near the village of Seyaha demonstrates that the dates of the organic micro-inclusions (more than 200 µm) are the youngest (Table 1). The concentrations of tritium in the ice were measured in order to evaluate the possibility of modern water participation in the ice wedge. It was shown that modern water did not penetrate into the ice. Micro-inclusions at a depth of 1.8 m are dated as 14 550 yr, and at a depth of 12 m as 14 720 yr BP. The dates of alkaline extracts from the same samples are respectively 19 920 and 23 620 yr. Thus, the differences of 5 and 9 kyr between the dates of the micro-inclusions and alkali extracts may be explained only by a very intensive process of ice wedge accumulation over about 14–15 kyr BP.

The dates of pollen concentrates from the same samples also demonstrate inversion. The $^{14}C$ date of the upper sample was older than the alkali extract from the same sample and older than the $^{14}C$ date of the lower sample. Admixture of "dead" carbon is confirmed by the finding of pre-Quaternary pollen and spores. In this sample, the content of pre-Quaternary pollen and spores is 19.3 %. If we suppose that the real age of the sample with 19.3 % of pre-Quaternary pollen and spores is 14 550 yr BP, in order to obtain the date 25 200 yr BP, it is evident that most of the Quaternary pollen is re-deposited from older sediments. This confirmed the participation of the penecontemporaneous organic material in the sedimentation process in a period of intense accumulation of ice wedges.

In Lower Kolyma River we have dated the ice wedges in the Bison cross-section and also obtained a mismatch of $^{14}C$ dates from different fractions of ice wedge samples (Table 3). All the alkali extracts are older than the micro-inclusions (by more than 400 µm) from the same sample. The dates of the micro-inclusions are from 32 600 to 26 460 yr BP. A $^{14}C$ date inversion is marked at 7.6 m from the micro-inclusions dates. The date of 32 600 $^{14}C$ yr BP at this depth is older than the date at 11 m (30 500 $^{14}C$ yr BP). The date inversion is also obtained from $^{14}C$ dating of pollen concentrate at the top sample. The youngest date of pollen concentrate between all fractions is obtained at 4 m. Based on the choice of the youngest date for syncryogenic permafrost, we suppose that this fragment of yedoma began to accumulate no earlier than 30 500 $^{14}C$ yr and finished no earlier than 26 200 $^{14}C$ yr. By analysing the peculiarities of the spectra of pollen which had been formed in the tundra or forest together with the data set of a different fraction, we concluded that pollen concentrate in tundra should contain penecontemporaneous elements due to the low pollen productivity of the tundra vegetation. The $^{14}C$ dates of pollen concentrate from ice wedges which accumulated in forest regions are the youngest compared with the dates of the micro-inclusions (POC) and alkaline extract (DOC) because the concentration of contemporaneous pollen is tens of times greater than in the tundra.

However, in some cases the alkali extracts (DOC) may be younger than the organic micro-inclusions (POC), as has been shown by Lachniet (Lachniet et al., 2012) in the CRREL Permafrost Tunnel in Fox, Alaska. $^{14}$C ages both the carbon dioxide ($CO_2$) in air bubbles and the dissolved organic carbon within the ice (alkali extract) to 11 170 yr younger than the particulate organic carbon (organic micro-inclusions) contained within the same wedge. This indicates that the POC is detrital in origin. A Late Pleistocene ice wedge, formerly assigned to Marine Isotope Stage 3, with 24 $^{14}$C on wood, particulate organic carbon, air-bubble $CO_2$, and DOC dated between 28 and 22 cal kyr BP during the cold conditions of MIS 2 and solar insolation minimum, are possibly associated with Heinrich event 2. A buried ice wedge system and the sediments enclosing a permafrost ice wedge were studied in the tunnel near Barrow (Meyer et al., 2010). The Late Pleistocene age of the site is indicated by AMS dates in the surrounding sediments of 21.7 kyr BP at the lateral contact of the ice wedge system, as well as 39.5 kyr BP below the ice wedge system.

## 2.5 Comparison of the $^{14}$C dates from various materials from the same samples

The principle of the preference for the youngest date from a series at the same depth (Vasil'chuk and Vasil'chuk, 1997, 1998) was confirmed by AMS $^{14}$C dating of the various macro-organic fractions obtained from the same sample, selected in 1985 and their dating with the standard procedure to about 42.2 kyr.

Morphologically homogeneous macrofossils were selected from a mixture of heterogeneous organic material using a microscope, including black organic residues, remnants of grass and white twigs without bark. Three different AMS $^{14}$C dates older (45.7 kyr BP) and younger (39.0 kyr BP) than the bulk sample were obtained (Fig. 5 and Table 2). As shown by further measurements, the youngest date does not correspond to the true age, because the AMS date of an insect cornea from a sample occurring at

4 m below is 34.9 kyr BP. We suppose that, of these six dates, the closest to the true time of accumulation is the youngest date of 34.9 kyr BP.

The same situation is marked for the Seyaha cross-section. The bulk sample was dated 36.8 kyr BP, and the $^{14}C$ date of a dwarf birch (*Betula nana*) twig extracted from the sample is 31.2 kyr BP. Of course, the date of the twig is closer to the real-time accumulation of these yedoma (Vasil'chuk, 2006).

A comparison of the results for plant detritus and alkali extracts from the same sample was made in the GIN radiocarbon laboratory (Sulerzhitsky, 1982). A sample of plant detritus was taken from a depth of 9 m in an outcrop 22 m in height above the river. Nemu-Dika-Tarida River was dated 29 000 ± 300 (GIN-3479), and the date of the second alkali extract from the same sample is 32 500 ± 400 (GIN-3479gII); hence the alkali extract contains more ancient organic material. The first alkaline extract of scattered detritus from the south-east coast Bayanay Lake (Taimyr) from a depth of 3 m was dated 29 700 ± 300 yr (GIN-3475gI), and the second alkaline extract was 23 300 ± 400 (GIN-3475gII). It is likely that more ancient material was concentrated in the first cold alkaline extract, so the second extract is believable.

Investigations in the Yukon have proved that bulk $^{14}C$ ages on sediments contain a substantial "old" carbon component (Demuro et al., 2008), while $^{14}C$ ages of insects and woody material have different ages in the same deposit (Kennedy et al., 2010).

## 3 Comparison of $^{14}C$ dates in yedoma sediments

Analysis of available series of $^{14}C$ dates of syncryogenic sediments – yedoma of the Russian Arctic, as obtained by the authors (Vasil'chuk, 1992, 2006, 2007, 2009, 2013; Vasil'chuk and Vasil'chuk, 1997, 1998; Vasil'chuk et al., 2000a, b, 2004) and published elsewhere (Sulerzhitsky, 1982; Pewe et al., 1977; Fukuda et al., 1997; Schirrmeister et al., 2002a, b, 2003, 2008, 2010; Wetterich et al., 2009, 2014 and others) has revealed the important role of ancient redeposited material in syncryogenic sediments throughout the Russian Arctic, as well as offering the principle of choosing the youngest date as the most reliable.

Radiocarbon dating of organic micro-particles, pollen and spores (Table 1), using the technique of accelerator mass spectrometry (AMS) has allowed us to propose methods for the indication of secondary pollution with ancient organic material (Vasil'chuk, 2006, 2007) and therefore to assess the reliability of the radiocarbon dates.

To evaluate the results of $^{14}$C dating of syncryogenic strata with thick syngenetic ice wedges, a model of meso-and macro-cyclic thick syngenetic ice wedges was developed (Vasil'chuk, 1992, 2006, 2013). As an example, dating was carried out for the most representative sections of the Kolyma Lowland – Duvanny Yar and a cross-section in the delta of the Lena River – Mamontova Khayata. In each of these sections the number of $^{14}$C datings obtained was close to 100.

*Duvanny Yar*. 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 yedoma. More than 100 $^{14}$C dates were obtained from this site (Kaplina, 1986; Tomirdiaro and Chyornen'kiy, 1987; Vasil'chuk, 1992, 2006, 2013). However, these series of dates could not be compared directly. This is firstly because the ice wedge sediments of the Duvanny Yar are being very rapidly eroded by the Kolyma River. According to our evaluation, the shoreline degrades by several meters per year; at Duvanny Yar it has been displaced more than 100 m over the last 30 years. Secondly, since the layers with organic material are not strongly horizontal, it is very difficult to compare data from the same layer as some layers are thinning out.

All kinds of organic material were used for the dating of strata at Duvanny Yar (Yu. Vasil'chuk, 2006), such as bones, peat, wood, and scattered amorphous plant remains (particulate organic carbon POC). Of course, allochthonous material, wood, scattered amorphous plant remains and bones, being more mobile, occurs much more often.

It is unlikely that microbial activity may be cause the dates to rejuvenate evenly, keeping the chronological order in a series of $^{14}$C dates of different years. We have arranged



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the entire set of dates (Yu. Vasil'chuk et al., 2001; Yu. Vasil'chuk, 2006) according to their altitude, not to the relative levels of the river or the different revealed height of the exposures. Only the youngest $^{14}$C dates were selected for each horizon (Tables 2 and 3).

We acknowledge that there is some arbitrariness in the use of the youngest radiocarbon dates to estimate the age of the permafrost sediment. But the lack of inversion in the distribution of the youngest dates and their uniform location in the cross-section indicate that the formation of the main part of the yedoma began about 35–37 kyr BP and ended about 13–10 kyr BP.

This interpretation of $^{14}$C data is touched upon that fragment of Duvanny Yar yedoma which was available for sampling in 70–90th of XX century. Considering non-horizontal bedding of the yedoma sediments and clay dome in the central part in the context of further erosion more ancient yedoma fragments may become revealed. Duvanny Yar is an example of how the findings can be used.

*Mamontova Khayata.* $^{14}$C dating of yedoma sediments in the Bykovsky Peninsula, Lena River delta, is very indicative. The first series of dates were obtained by Fartyshev (Tomirdiaro and Chyornen'kii, 1987). These dates have a very good correlation. The bone date is 22 kyr BP, grass roots around the bone are 21.6 kyr BP. Dates of 28.5 and 33 kyr BP were obtained beneath the bone. A series of inversion $^{14}$C dates: 21 630±240 (LU-1328), 22 070 ± 410 (LU-1263), 28 500 ± 1690 (LU-1329) and 33 040 ± 810 (LU-1330) were obtained in the upper part of the exposure.

Later, Slagoda (2004) yielded a younger series of $^{14}$C dates as follows: 32 200 ± 930 (IM-748), at a depth of 20 m, 19 800 ± 500 (IM-753) at a depth of 20 m, 22 000 ± 1600 (IM-752) at a depth of 17 m, 20 836 ± 500 (IM-749) at a depth of 15 m, and 15 100 ± 750 (IM-748) at a depth of 9 m.

New 70 standard and 20 AMS $^{14}$C dates were obtained in the work of a Russian–German team at the exposure (Schirrmeister et al., 2008). These dates, together with yearly ones obtained, were used for aging the ice wedge complex and the overlying horizon. It was supposed that these sediments accumulated during the last 80 kyr.

Schirrmeister (Schirrmeister et al., 2008) came to this conclusion based on the oldest $^{14}C$ date of the wood as 58 400 +4960/−3040 (KIA-6730) at 2.7 m a.s.l.

We believe that the antiquity of the *Mamontova Khayata* yedoma is exaggerated, taking into account that the yedoma bottom is located 1.5 m below sea level and that the mean accumulation rate of the yedoma is 1.1 m per 1 kyr, while the $^{14}C$ date of the plant remains from the 0.2 m a.s.l. is 54 930 +4280/−2780 (KIA-12 509). The bone in situ at 14 m a.s.l. is dated about 32 kyr; that is, the bone is younger than the plant remains around the bone.

Having analyzed the whole set of the $^{14}C$ dates and selected the youngest date from every horizon as valid (Table 4), we concluded that the accumulation of the Mamontova Khayata yedoma began no earlier than 48–55 kyr BP and finished about 10.8 kyr.

Attempts to identify the yedoma age at Duvanny Yar and Mamontova Khayata have usually resulted in a recognition of the impossibility of exact dating amidst the apparent chaos of dates. However, the principle of the choice of the youngest $^{14}C$ date from the data set in the particular horizon allows us to obtain an adequate un-inversion age series of these complicated heterochronous complexes.

## 4 Conclusions

The strategy of valid $^{14}C$ dates choice in syngenetic permafrost includes several points such as:

- Re-deposition of organic matter in the permafrost is common. Syngenetic sediments contain allochthonous organic deposit that originated at a distance from its present position. There needs to be a careful cull of the manifestly more ancient $^{14}C$ dates, and especially the dates beyond the range of radiocarbon dating, which usually correspond to re-deposited organic material within polygonal ice wedge complexes.

- The youngest $^{14}C$ date from the data set in the particular horizon is closest to the actual time of accumulation and freezing of the yedoma sediment.
- Radiocarbon dating of organic micro-particles, pollen and spores, using AMS has allowed to indicate of secondary pollution with ancient organic material and therefore to assess the reliability of the radiocarbon dates.
- Based on the principle of the choice of the youngest $^{14}C$ date from every strata, it was shown that the formation of the main body of the ice wedge yedoma complex at Duvanny Yar began about 35–37 kyr BP and ended about 13–10 kyr BP, and the ice wedge yedoma complex at Mamontova Khayata began about 55 kyr BP (or later) and ended about 10.8 kyr BP.

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**Table 1.** Comparison of AMS radiocarbon dates obtained by dating different fractions of organic matter from the same ice samples from the ice wedge.

| Field number | Height, m a.s.l./ Depth, m | $^{14}C$ data of organic micro inclusions | $^{14}C$ data of alkaline extract | $^{14}C$ data of pollen |
|---|---|---|---|---|
| Seyaha outcrop, Ob bay coast, Yamal Peninsula, tundra | | | | |
| 363-YuV/27 | +20.2/1.8 | **14 550 ± 100** (GrA-10538) | 19 920 ± 130 (GrA-9847) | 25 200 ± 150 (SNU01-214) |
| 363-YuV/87 | +10.0/12.0 | **14 720 ± 100** (GrA-10539) | 23 620 ± 160 (GrA-9848) | 22 400 ± 100 (SNU01-215) |
| Bison oucrop, Lower Kolyma River, northern taiga | | | | |
| 378-YuV/195 | +18.0/2.6 | **26 460 ± 350** (GrA-16803) | 27 790 ± 400 (GrA-16793) | 31 400 ± 500 (SNU02-128) |
| 378-YuV/90 | +16.6/4.0 | 29 500 ± 500 (GrA-16802) | 32 000 ± 650 (GrA-16785) | **26 200 ± 300** (SNU02-147) |
| 378-YuV/100 | +13.0/7.6 | 32 600 ± 700 (GrA-16808) | 36 000 ± 1000 (GrA-16792) | **28 200 ± 600** (SNU02-150) |
| 378-YuV/102 | +13.0/7.6 | **30 750 ± 550** (GrA-16804) | 33 500 ± 75 (GrA-16788) | 35 600 ± 800 (SNU02-124) |
| 378-YuV/146 | +9.6/11.0 | **30 500 ± 550** (GrA-16805) | > 38 400 (GrA-12891) | 43 600 ± 1100 (SNU02-125) |

* The most reliable dates are marked in bold.





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**Table 2.** Conventional $^{14}C$ age from a bulk sample of Duvanny Yar yedoma (68°44′ N, 159°12′ E) and AMS $^{14}C$ ages for its different organic fractions.

| Field Number | Height (m a.s.l.)/ Depth, m | Conv. $^{14}C$ age of bulk sample | Organic fractions | AMS $^{14}C$ ages (yr BP) & Laboratory Number | $\delta^{13}C$ value (‰) |
|---|---|---|---|---|---|
| 316-YuV/9 | 14.0/34.0 | 44 200 ± 1100 (GIN-4003) – hot alkaline extract | Seed fragments | 45 700 ± 1200 (SNU01-077) | −32.4 |
| | | | Herb remains and detritus | 39 000 ± 1300 (SNU01-079) | – |
| | | | Thin white twigs without crust | 40 500 ± 500 (SNU01-078) | −25.6 |





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**Table 3.** The youngest $^{14}C$ ages obtained in each horizon of Duvanny Yar, Lower Kolyma River.

| Radiocarbon age ($^{14}C$ BP) | Laboratory Number | Height (m a.s.l.) | Organic Material |
|---|---|---|---|
| 13 080 ± 140 | EP-941555 | ca. 51 | Soil |
| 17 850 ± 110 | MAG-592 | ca. 42 | Dispersed plant material |
| 28 600 ± 300 | GIN-3867 | 18.0 | Mammoth bone |
| 29 900 ± 400 | GIN-4588 | 10.0 | Black peat |
| 35 400 ± 900 | GIN-3996 | 7.5 | Dispersed plant material |





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**Table 4.** The youngest $^{14}C$ ages obtained in each horizon of Mamontova Khayata (71°61′ N, 129°28′ E) (from Schirrmeister et al., 2002, selected by Y. Vasil'chuk)

| Radiocarbon age ($^{14}C$ BP) | Laboratory Number | Height (m a.s.l.) | Organic Material |
|---|---|---|---|
| 10 840 ± 50 | KIA-11441 | about 36 | Peat |
| 17 160 ± 90 | KIA-9195 | 30.0 | Dispersed plant material |
| 28 470 ± 160 | KIA-6716 | 22.2 | Wood |
| 35 860 +610/−570 | KIA-6707 | 16.0 | Herb |
| 42 630 +980/−870 | KIA-6701 | 8.8 | Herb |
| 54 930 +4280/−2780 | KIA-12509 | 0.2 | Dispersed plant material |





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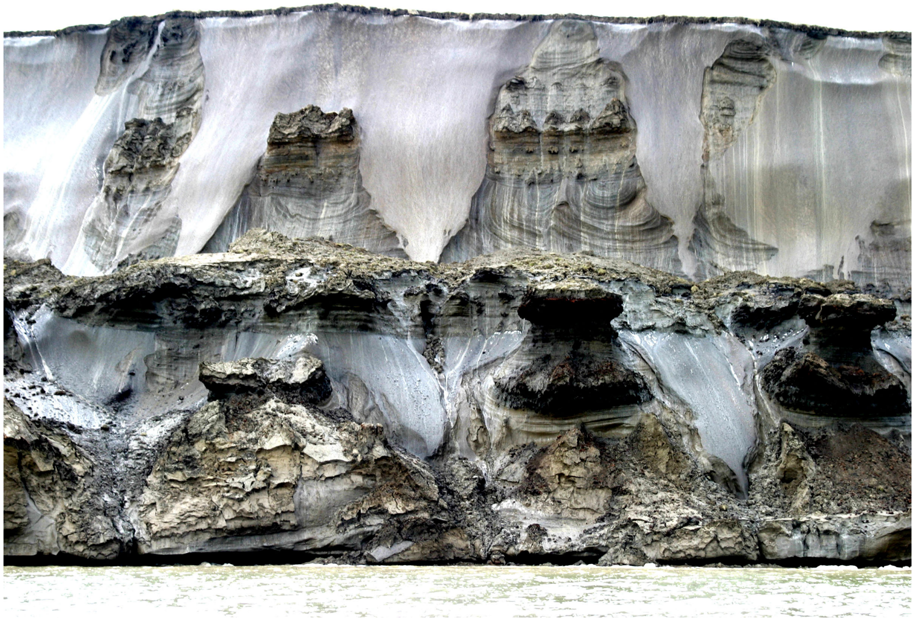

**Figure 1.** Yedoma of Bolshoy Lyakhovsky Island (73°20′ N, 141°45′ E). Photo: V. Tumskoy.





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**Figure 2.** Organic detritus washed out by thermal abrasion on the modern beach of Seyaha yedoma (70°25′ N, 72°38′ E), and separated and deposited in almost pure scalloped form. Photo: Y. Vasil'chuk.





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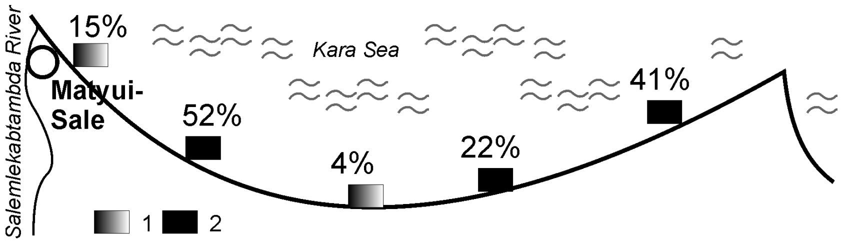


**Figure 3.** Percentage variations of tree pollen depending on the grain size of sediments at the modern beach in the Salemlekabtambda River mouth, on the coast of Mamont Peninsula (71°59′ N, 76°22′ E), North Gydan Peninsula (Vasil'chuk, 2005): 1 – percentage of tree pollen in the fine sand; 2 – percentage of tree pollen in the coarse sand.





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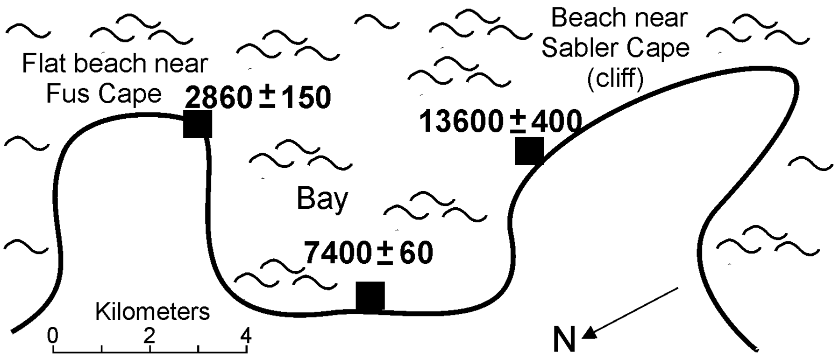


**Figure 4.** Age variation in freshly deposited organic material in different parts of the modern beach at Taymyr Lake (74°33′ N, 100°32′ E).





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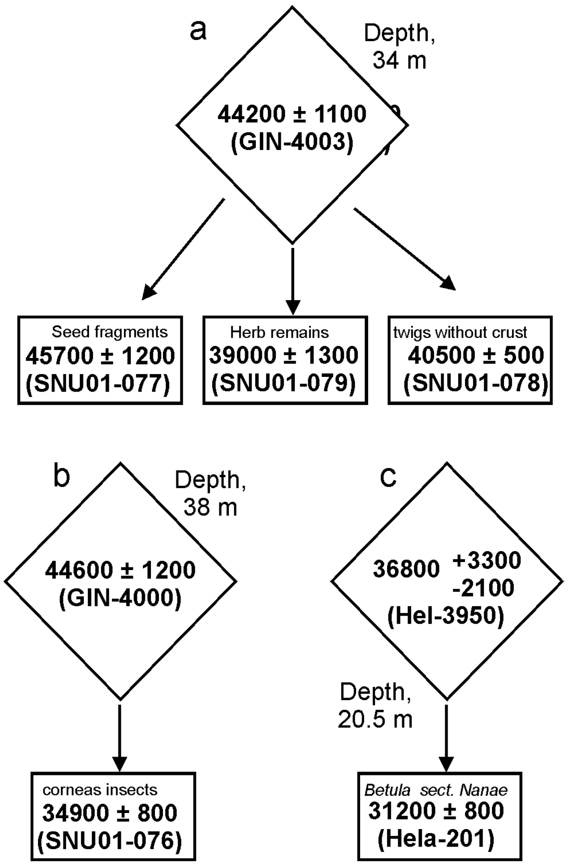


**Figure 5.** $^{14}C$ dating of bulk samples consisting of mixed organic material (in diamonds) and homogeneous organic material extracted from bulk samples dated by $^{14}C$ AMS (in boxes): **(a, b)** samples from different depths of Duvanny Yar yedoma (68°44′ N, 159°12′ E) outcrop, **(c)** sample from the bottom part of Seyaha yedoma (70°25′ N, 72°38′ E).





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