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Validity of radiocarbon ages of Siberian yedoma

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ABSTRACT

The ice wedges are considered as key subjects for ^{14}C aging of yedoma, as there are no any exchange processes between the environment and the ice wedges. Syngenetic sediments contain allochthonous organic admixtures which originated at a distance from its present position. The main problem of radiocarbon dating within permafrost is the uncertain reliability of the ^{14}C ages. To establish the age of ice wedge formation the strategy for the most authentic radiocarbon age selection for syngenetic sediments is considered on the base of a model of yedoma accumulation and distribution of reversal material by flood and aeolian transport. The re-working of organic material discussed in terms of cyclic syngenetic sedimentation of yedoma.

The advantages and the complications of ^{14}C dating of organic inclusions from ice wedges by the accelerator mass spectrometry (AMS) are discussed applying to the search of true age organic material, which is simultaneous to ice-wedge formation. Radiocarbon ages of different organic materials from the same samples are compared, it is demonstrated that the difference between ages of the fractions from the ice wedges consists of about 9 kyr in Seyaha ice-wedge complex in Yamal Peninsula and about 5 kyr in Bison yedoma, Kolyma River valley. The principle of the choice of the youngest ^{14}C age from the set and from the layer is proposed for yedoma.

1. Introduction

The objective of this paper is to consider the problem of ^{14}C dating of syngenetic permafrost sediments taking into account accumulation of old organic material in syngenetic permafrost conditions. In accomplishing this objective, the paper provides a model of yedoma development and describes the distribution of reworked material related to the flood and aeolian transport. The main hypothesis of the paper is as follows: 1) in order to yield ^{14}C age of the yedoma is required selection the youngest ages from every stratigraphic unit; 2) the syngenetic ice wedges contain the organic material simultaneous to their time formation; 3) resulting comparison of the ^{14}C ages from ice wedges and their host sediments may be done at the base of the model of yedoma formation.

Here we discuss the ^{14}C dating of syngenetic permafrost sediments in particular yedoma. Permafrost that forms at the same time as continued cold-climate sedimentation and causes the base of the active layer to aggrade upwards is termed syngenetic. This sedimentation may be alluvial, colluvial (i.e. slump or gravity-induced), aeolian, or lacustrine in nature. By definition, syngenetic permafrost is of the same age (approximately) as the sediment in which it is formed [12]. Typically, syngenetically frozen sediments are silty, or loess-like (up to 70–80% silt fraction), and ice-rich (the soil gravimetric content may exceed 100–200%). Syngenetic freezing also occurs in aggrading fluvioeolian sands and in sandy, even gravelly, floodplain deposits. Syngenetically frozen sediments usually contain rootlets, buried organic-rich horizons, and may exhibit a rhythmically organized (i.e., layered) appearance. The main locations where syngenetic permafrost is forming today are in the alluvial and deltaic environments of Arctic North America (e.g., Colville and Mackenzie Rivers) and in northern Siberia (e.g., Lena, Yenisei, Yana, Indigirka and Kolyma Rivers). The thickness of contemporary syngenetic permafrost usually does not exceed a few meters. Late Pleistocene-age syngenetic permafrost occurs mainly in the continuous permafrost zone of central and northern Siberia and in the valleys and lowlands of the never-glaciated parts of northwestern Arctic North America. In all these regions, uninterrupted periods of long continued cold-climates, combined with sediment aggradation on lower valley-side slopes and on broad alluvial floodplains, led to the formation of permafrost that is several hundred meters thick. This permafrost is polygenetic in which the upper part is syngenetic and the lower part is epigenetic [12]. Yedoma is silt-dominated deposits up to 50 m thick with wide and tall ice wedges [19,66,67,68]. The Late Pleistocene environment of Northern Eurasia and Northern America was extremely favorable to accumulation of ground ice and formation of syngenetic permafrost,

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which formed synchronously with sedimentation in unglaciated areas. As a result, extremely ice-rich permafrost (termed “yedoma”) had been originated and now it remains one of the most prominent feature of the periglacial environment in the Arctic.

Many studies of yedoma cryostratigraphy have been undertaken in Russia [21,32,46,51–56,66,67,79–80], relatively few studies of a similar detailed nature have been undertaken in the permafrost lowlands of Arctic North America [19,28,41,44,82,83]. One of the first study, devoted to syngenetic accumulation had been done by Gallwitz [14,15] in the Germany paleopermafrost area. He described a section in the Elbe River valley and distinguished several loess layers with intercalated levels of ice wedge casts and reworked loess. Numerous ^{14}C ages of bulk samples have been obtained in Russia over the last 50 years, most of them from the ice-rich yedoma deposits of central Yakutia, Chukotka and the Siberian coastal lowlands. The results of ^{14}C dating very often can not be used due to irregular vertical distribution of ^{14}C ages in exposure. 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 ages for permafrost sediments.

At first, it was assumed that ^{14}C ages from permafrost usually rejuvenated as it took place in the non-permafrost areas. Even small amounts of modern carbon (which is everywhere) very easily create apparently finite ages when one is near the limit of the technique. Graphic and dramatic example of this can be seen in Pigati et al. [45]. Bird and co-workers [3] have clearly demonstrated that ^{14}C ages of old samples that are obtained using standard chemical and extraction techniques often underestimate true ^{14}C ages by 8–10 kyr or more.

As it was shown by Nilsson et al. [34] and Turetsky et al. [62], the main sources of carbon which are likely to contaminate contemporaneous carbon pools with modern carbon are assumed to be young roots, rootlets and rhizomes penetrating down into older, underlying peat, and humic acids and other dissolved organic carbon which leach downwards in percolating ground-waters [4]. According to Wallén [76], up to 90% of photosynthetically fixed CO_2 is allocated to roots; they transfer current atmospheric carbon dioxide to deeper layers and may be observed to penetrate up to 2 m in certain environments [50]. Nilsson et al. [34] reported that most root biomass does not penetrate deep enough into older peat to affect significantly radiocarbon ages.

As to permafrost area, young roots may to grow within active layer. Dissolved organic carbon, in particular humic and fulvic acids, may originate either from decomposition of plant matter or from root exudation. However, this young organic material does not penetrate into the underlying permafrost, and even more so in the ice wedges. Younger organic materials may be incorporated in older sediments in syngenetic permafrost within active layer only. In rare cases, younger organic materials may be incorporated in older sediments in syngenetic permafrost. This could happen, and does happen with pore waters through the active layer that accumulate at the top of the permafrost table, but for the most part these waters would not be able to carry organic material with it or through cryoturbation, or when macrofossils (wood, seeds, bones etc.) submerged into semi-liquid sediments of the lakes or ponds. 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 age based on tritium concentrations. Our data show that usually the tritium concentration in syncryogenic sediments is very low less than 1–10 TU [72].

It was supposed that the contamination with modern ^{14}C is the main factor for obtaining invalid ^{14}C ages. However, while this is correct for an open system, the array of syncryogenic permafrost sediments is not a true open system. 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.

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 syngenetic accumulation. These factors favoured the re-deposition of ancient organic material in permafrost. Therefore, it is possible to find both animal bone that is older than the sedimentation, weathered wood, and older and younger plant detritus in the same layer of the peat. Abnormally old ^{14}C ages together with younger ones are often obtained from lacustrine and marine sediments. This is especially true for areas of active accumulation of redeposited material [5,8,39,48,59]. 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 ages of the logs are about 3.2–4.7 kyr BP, while one log is not older than 80 yr BP [11]. All the dated logs belong to the genus *Picea* that does not grow in this area. We can expect an error of more than three thousand years if we try to determine the formation time of the beach sediment of Victoria Island in correspondence with the ^{14}C ages of the wood.

Stanley [59] 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 ages 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 age of one shell is 10,160 ± 25 ^{14}C yr BP and the ^{14}C age of the other very similar shell is 30,900 ± 100 ^{14}C yr. Other archaeological findings from this cave are about 10,000 yr [49].

Foraminifera shells can also be aged with reversals because both younger and older material are involved in foraminifera shells. Broecker [5] proposed to compare the ^{14}C ages 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 ages or reversals of ages between different fractions of the same sample are not an exception but rather the rule. At first, anomalous ^{14}C ages were obtained from the syngenetic polygonal ice wedge complex at Cape Barrow [7]. The syngenetic sediment of yedoma aged as no older than 8300 yr. Two ^{14}C ages of sedge remains and lemming pellets obtained from the ice wedge. The age from the lateral part of the ice wedge is 14,500 yr BP, and the ^{14}C age in the centre of the ice wedge is 8200 yr BP. It is clear that the older age obtained from a mixture of uneven-aged organic material.

Abbot and Stafford [1] 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.

^{14}C reversals have been obtained in the Fox Permafrost Tunnel also. Some reversals are associated with bones, which 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 ages obtained from the same horizon, which is about 15 kyr, from 27,790 to 43,300 ^{14}C yr BP [17].

Nelson et al. [33] studied the problem of permafrost sediments with allochthonous organic material 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 separated into different size fractions and each fraction aged separately. The results ranged from 13.25 to 30.26 kyr BP, as follows: the > 2-mm fraction of peat dated to 13,250 ± 100 ^{14}C yr (USGS-2046A); the 1–2-mm fraction was 17,730 ± 110 ^{14}C yr (USGS-2046B); the 0.5–1.0-mm fraction was 24,740 ± 320 ^{14}C yr (USGS-2046C); the 0.25–0.5-mm fraction was 30,260 ± 530 ^{14}C yr (USGS-2046D); and the < 0.25-mm fraction was 20,360 ± 190^{14}C yr (USGS-2046E). The age 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 [33]. 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 could 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 reversal is more than 7000 yrs. As a result of the methodical study by Stuckenrath et al. [60], it was possible to achieve a number of ages without reversals 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. Schuur et al. [57] also show that older carbon is stored in the active layer.

As the main problem of radiocarbon dating within permafrost is the uncertain reliability of the ^{14}C ages, it is very difficult to interpret the totality of these data. 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. Hence the youngest age of organic material in this case, even the youngest dating only indicating the maximum age of the syngenetic sediments.

Cyclic character of syngenetic permafrost sediment accumulation, alternation of subaerial and subaqueous regime, multi redeposition 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 [67,68] 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 accumulation, d) evaluation of AMS ^{14}C dating of organic micro-inclusions in the ice wedges; e) comparison of the ^{14}C ages 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 ages. The comparison of the ages from the same layer and various sets of ^{14}C ages may also be used for evaluation of the ^{14}C ages from the permafrost.

Hunt [18] having analyzed ^{14}C ages yielded for high-resolution record of ecosystem change near Niukluk Lake for the last 13.5 kyr BP on the Seward Peninsula, Western Alaska within permafrost area shows that too old ages should be rejected because organic material may have been washed in during disturbance events (flooding), i.e. in subaqueous conditions. The other too old age was rejected also due to an age reversal, which is most likely due to dating of selected brown moss stems, which can take up old C.

Morse and Burn [31] even do not presented radiocarbon data for the rate of surface aggradation of syngenetic ice-wedge polygons, outer Mackenzie Delta, western Arctic coast, partly because of the potential for contamination in an alluvial setting.

Successful method of ^{14}C dating in permafrost-affected areas demonstrated by Zazula et al. [83,84]. Representative of their depositional context fragile macrofossils (flowers, seeds, leaves and seed capsules) and formation of coherent ecological assemblages herbaceous xerophilic taxa from glacial environments), are selected for the purposes ^{14}C dating achieving duplication and assessing different types of material (needles, beetles and seeds).

Radiocarbon ages from study of Eagle River meltwater channel and braid delta, northern Yukon have demonstrated that coarse, woody materials consistently over-estimate the ages of the sediments they are used to date. All sediments occur in rapidly aggrading forms with no evidence for a significant hiatus in deposition. Radiocarbon ages on woody plant macrofossils and spruce needles are non-finite, while radiocarbon ages on macrofossils from herbaceous plant taxa and insects with 'steppe-tundra' ecological affinity from the upper part of the delta range from 15,840 ± 90 to 21,600 ± 1300 ^{14}C yr BP. It was stressed that these ages must be considered within the context for potential depositional histories including extensive preservation and reworking. Bulk samples from the region could yield artificially old ^{14}C ages by containing any number of well-preserved macrofossils of varying age. The composite samples potentially contain macrofossils of differing ages that will produce a composite age older than the youngest component [23,24]. Thus, permafrost syngenetic sediments and ice wedges are characterized by significant 'reservoir' effects, the magnitude of which is likely to be highly variable and not easily and independently constrained for ancient permafrost. The youngest age from this point may be maximum limit age for the syngenetic sediment or ice.

2. Foundations for permafrost ^{14}C dating strategy

2.1. Cyclic model of thick syngenetic ice wedge formation

In the permafrost area, thick syngenetic ice wedges are the dominant form of the ice (Fig. 1). Ice wedges are formed because 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 [67,68]. 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 me-

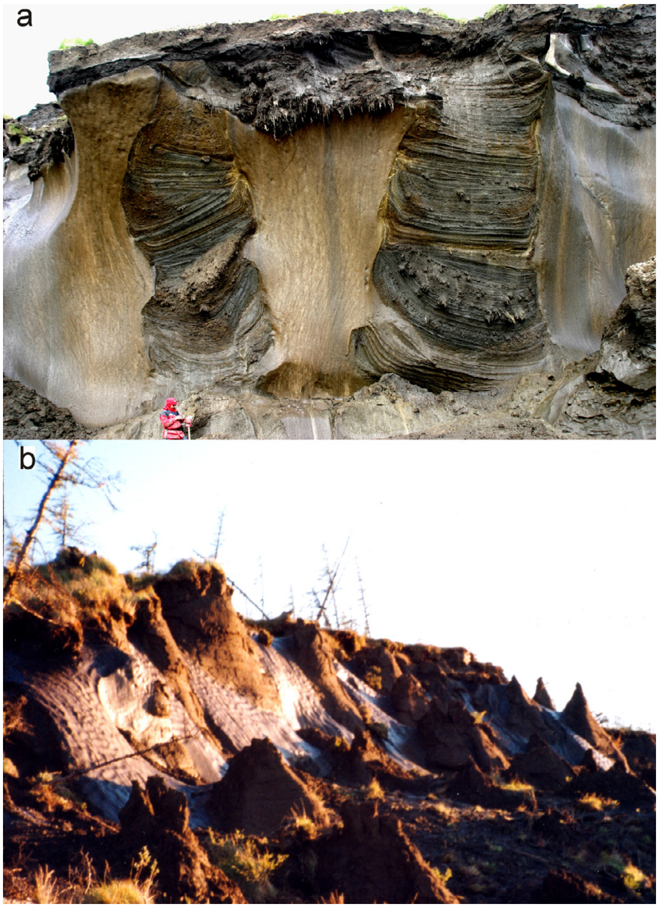

Fig. 1. Yedoma of a – Bolshoy Lyakhovsky Island (73°20′ N, 141°45′ E). Photograph by V. Tumskoy and b – Duvanny Yar (68°37′ N, 159°08′ E). Photograph by Yu. Vasil'chuk.

ters. Macrocycling, as a rule, is out of the frame of the radiocarbon method.

For syngenetic ice wedges two stages can be distinguished (Fig. 2): 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 [68]. 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 stage. 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. In yedoma sequences fluvial inputs, colluvial inputs (also aeolian inputs) are fixed, they correspond to subaqueous stage; aggradation of peat, soil formation and aeolian inputs also occur at subaerial stages.

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 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 yedoma sediments and ice wedges are discontinued according to the stage changes. Cyclic structure of the syngenetic sediments with ice wedge in Fox Permafrost Tunnel reveals by horizontally laminated silts containing thin, sub-parallel organic-rich horizons, which may be interpreted as poorly developed paleosoils [27], i.e. paleosoils fixed several short subaerial stages.

2.2. Modern re-distribution of organic material at subaqueous syngenetic conditions

One of the main prerequisites for more careful consideration of reworked organic material is the participation of ancient organic material in modern alluvial, marine and lacustrine sediments in permafrost areas. This was clearly demonstrated by ^{14}C dating of organic remains collected directly under the Seyaha yedoma exposure [71,72]. Organic material of the exposure is aged from 36.8 to 11,62 kyr BP. 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. It is similar to peat layers in yedoma exposure and often identified as the autochthonous type, although these peat layers may be allochthonous in many cases. The sample of the peat under exposure of Seyaha yedoma (Fig 3), which has been collected in 2016 season aged 12,950 ± 100 ^{14}C yr (Le−11,409). Of course, the ^{14}C age of the similar but buried peat is not synchronous with sedimentation. 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 reworked material can be very large at the accumulative coastal areas far from abraded shores. This evidenced 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 [63]. The percentages of the tree pollen in coarse sand were significantly higher (by 25-50%) than in fine sand (Fig. 4). 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 because of thermal abrasion and is older than the sediment. Presence only 10% of dead carbon in modern age sample gives oldering of the age about 800–2000 yrs [2,36]. However if the same 10% of dead carbon to add into the sample of 30–28 kyr, so, the age of the sample will be older by about 60–80% (our interpretation Olsson's [36] curves). In real situation in permafrost during syngenetic accumulation, the participation of old organic material may consist of 90–95%.

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 [61]. The fresh-looking peat sampled at the beach near Sabler Cape is dated 13,600 ± 400 ^{14}C yr (GIN-1529), while at a distance of several hundred meters at a rather flat low surface of Fus

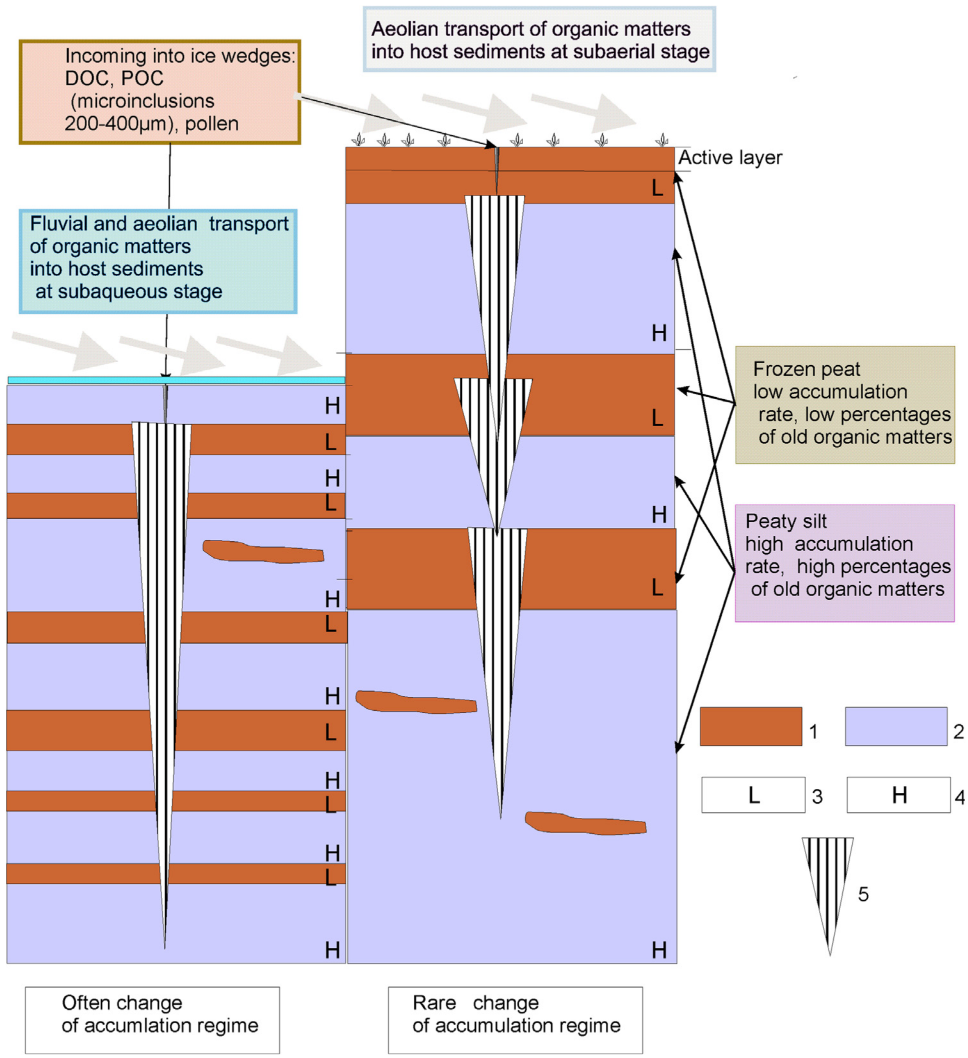

Fig. 2. The scheme of cyclic model of thick syngenetic ice wedge formation: 1 – deposits of subaerial stage (often soil or peat); 2 – deposits of subaqueous stage (often silt or sandy loam); 3 – low content of old organic matters; 4 – high content of old organic matters.

Cape the peat sample is dated 2860 ± 150 ^{14}C yr, and a peat sample from the beach between these points is 7400 ± 60 ^{14}C yr (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. 5). It may be suggested that the content of old organic matter in the sample near Fus Cape is approximately 30%, and near Sabler Cape is approximately 80% or slightly more (according our interpretation of Olsson [36] curves).

The ^{14}C age of this layer of beach sediments after a short time does not objectively correspond to the time of accumulation. Nevertheless, the youngest age is closest to the actual time of sedimentation from the series of ages from this horizon.

2.3. Possible age reversal at the subaerial stage

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

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 [10,16,25]. 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 an *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. 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" [81,82]. Earlier in Alaska, the seeds of *Lupinus arcticus* Wats. from lemming burrows were also successfully germinated. They were aged about 10 kyr BP. The organic material in the burrows is always autochthonous and ^{14}C ages 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

Fig. 3. Exposure of the Seyaha yedoma (70°25′ N, 72°38′ E) (a), organic detritus washed out by thermal abrasion on the modern beach deposited in scalloped form (b). Photograph by Yu. Vasil'chuk.

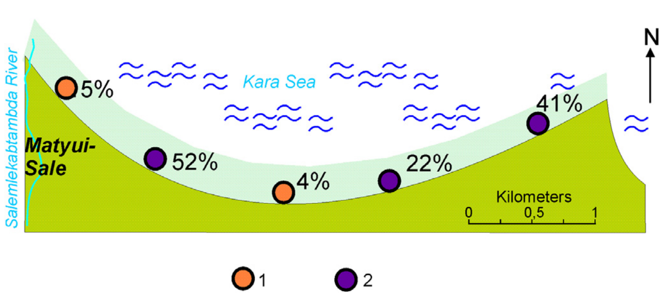

Fig. 4. Sampling points (a) and percentage variations of tree pollen (b) depending on the grain size of sediments at the modern beach in the Salemlekabtambda River mouth, on the coast of Mamont Peninsula (71°59′ N, 76°22′ E), North Gydan Peninsula [63]: 1 – fine sand, 2 – coarse sand.

Mamont Peninsula. The ^{14}C age of the small twigs in the burrow is 8630 ± 60 ^{14}C yr (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 about 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 ^{14}C yr (Beta-157,195) in the Duvanny Yar cross-section. This is a very high concentration of ancient pollen for the Kolyma valley region [63]. 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-

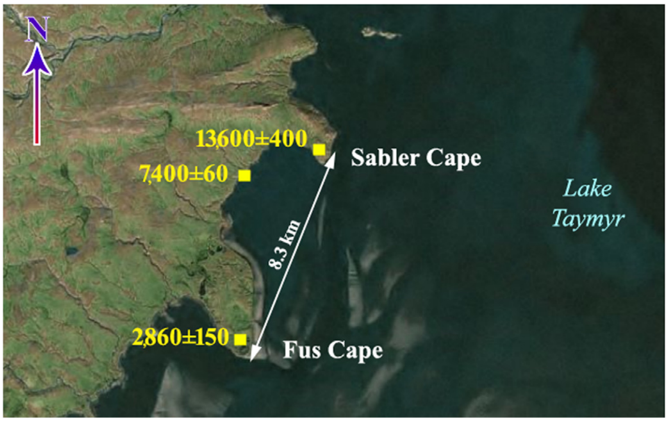

Fig. 5. Variation of ^{14}C ages in freshly deposited organic material in different parts of the modern beach of Taymyr Lake (74°33′ N, 100°32′ E).

deposition. As shown by Payette [40], 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 ^{14}C yr BP. But ^{14}C dating of the peat demonstrated normal distribution of the ^{14}C ages: 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. [85] and Walter et al. [77] in the permafrost area. Therefore, methanotrophic bacteria, which provide *Sphagnum* mosses with carbon [26], 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 ^{14}C yr BP in July mineral soil samples and from 1525 to 8300 ^{14}C yr BP in August samples [35].

Consequently, the reversals of ^{14}C ages in syngenetic deposits may occur in subaerial environments where methane releases from underlying peat.

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 [67,68]. As syngenetic ice wedge is a closed system, microbial activity is excluded in the ice. The dating of organic microinclusions from ice wedges allows to obtain the age of the ice wedge directly. However, results of the AMS ^{14}C dating of organic inclusions (particulate organic carbon - POC) in ice wedges have demonstrated that the problem of an inhomogeneous concentrate also occurs.

The comparison of the ^{14}C ages of different fractions from the samples of organic material in the syngenetic ice wedges of a 24-meter terrace near the village of Seyaha demonstrates that the ages of the organic micro-inclusions (more than 200 µm) are the youngest (Table 1). The concentrations of tritium in the ice 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 aged as 14,550 ^{14}C yr, and at a depth of 12 m as 14,720 ^{14}C yr BP. The ages of alkaline extracts (dissolved organic carbon - DOC) from the same samples are respectively 19,920 and 23,620 ^{14}C yr BP. Thus, the differences of 5 kyr and 9 kyr between the ages 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 ages of pollen concentrates from the same samples also demonstrate reversals. The ^{14}C age of the upper sample was older than the alkali extract from the same sample and older than the ^{14}C age of the lower sample. Admixture of "dead" carbon is evidenced 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 ^{14}C yr r BP, in order to obtain the age 25,200 ^{14}C yr BP, it is evident that most of the Quaternary pollen is re-deposited from older sediments. This is confirmed the participation of the penecontemporaneous organic material in the sedimentation process in a period of intense accumulation of ice wedges.

In the Lower Kolyma River, in the Bison exposure a mismatch of ^{14}C ages from different fractions of ice-wedge samples obtained (Table 1). All the alkali extracts are older than the micro-inclusions (by more than 400 µm) from the same sample. The ages of the micro-inclusions are from 32,600 yr to 26,460 ^{14}C yr BP. A ^{14}C age reversal is marked at 7.6 m from the micro-inclusions ages. The age of 32,600 ^{14}C yr BP at this depth is older than the age at 11 m (30,500 ^{14}C yr BP). The reversal of ^{14}C ages is obtained from ^{14}C dating of pollen concentrate at the top sample. The youngest age of pollen concentrate between all fractions is obtained at 4 m. Based on the choice of the youngest age 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 analyzing the peculiarities of the pollen spectra, 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 rather should contain penecontemporaneous components due to the low pollen productivity of the tundra vegetation. The ^{14}C ages of pollen concentrate from ice wedges which accumulated in forest regions are the youngest compared with the ages of the micro-inclusions (POC) and alkaline extract (DOC) because the concentration of contemporaneous pollen is tens of times greater than in the tundra.

Absolute dating of ice wedges show substantial age reversals [37,38,47]. In some cases the alkali extracts (DOC) may be younger than the organic micro-inclusions (POC), as has been shown by Lachniet et al. [27] 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 to 11.17 kyr younger than the particulate organic carbon contained within the same wedge. This indicates that the POC is detrital in origin. A buried ice wedge system and the sediments enclosing a permafrost ice wedge studied in the tunnel near Barrow [30]. The Late Pleistocene age of the site is indicated by AMS ^{14}C ages 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. Several ^{14}C age reversals have been found in Yedoma Ice Complex and taberal Yedoma Ice Complex at the Oyogos Yar coast [38].

Here we would like to discuss the problem appeared in ^{14}C dating of permafrost syngenetic sediments with ice wedges (yedoma), but we take into account that there are many sources of uncertainty or error that combine to set the practical upper limit of ^{14}C dating of terrestrial samples, such as: incomplete removal of secondary (contaminant) carbon species during chemical pretreatment, atmospheric carbon that is introduced to the original sample during extraction, graphitization, and/or storage, and uncertainties associated with AMS measurements.

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 (Lab ID)	^{14}C data of alkaline extract (DOC)	^{14}C data of pollen	Calibrated age (yr b2k)- the maximum limit ages
Seyaha outcrop, Ob bay coast, Yamal Peninsula, tundra					
363-YuV/27	+20.2/1.8	**14, 550 ± 100** (GrA-10,538)	19,920 ± 130 (GrA-9847)	25,200 ± 150 (SNU01-214)	***16,029–15,523***
363-YuV/87	+ 10.0/12.0	**14, 720 ± 100** (GrA-10,539)	23, 620 ± 160 (GrA-9848)	22,400 ± 100 (SNU01-215)	***16,235–15,687***
Bison outcrop, Lower Kolyma River, northern taiga					
378-YuV/195	+18.0 / 2.6	**26,460 ± 350** (GrA-16,803)	27,790 ± 400 (GrA-16,793)	31,400 ± 500 (SNU02-128)	***29,230–27,906***
378-YuV/90	+ 16.6 / 4.0	29,500 ± 500 (GrA-16,802)	32,00 ± 650 (GrA-16,785)	**26,200 ± 300** (SNU02-147)	***29,037–27,755***
378-YuV/100	+13.0/ 7.6	32,600 ± 700 (GrA-16,808)	36,00 ± 1000 (GrA-16,792)	**28,200 ± 600** (SNU02-150)	***31,630–29,205***
378-YuV/102	+ 13.0 / 7.6	**30,750 ± 550** (GrA-16,804)	33,500 ± 75 (GrA-16,788)	35,600 ± 800 (SNU02-124)	***33,924–31,886***
378-YuV/146	+9.6/ 11.0	**30,500 ± 550** (GrA-16,805)	> 38 400 (GrA-12,891)	43,600 ± 1100 (SNU02-125)	***33,695–31,705***

*The valid ages are marked in bold, the same ages were determined as yr b2k using OXCal 4.2.4. (Bronk Ramsey [6]) and shown by bold italic.

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 and calibrated ages (95.4% probability) for its different organic fractions.

Field Number	Height (m a.s.l.) / Depth, m	Conventional ^{14}C age of bulk sample (**yr BP**) & Lab ID	Organic fractions	AMS ^{14}C age, yr BP & Lab ID	δ^{13}C value (‰)	Calibrated age* (yr b2k)
316-YuV/9	14.0 / 34.0	44,200 ± 1100 (GIN-4003) – hot alkaline extract	Seed fragments	45,700 ± 1200 (SNU01-077)	−32.4	45,029
			Herb remains and detritus	39,000 ± 1300 (SNU01-079)	–	43,781–39,297
			Thin white twigs without crust	40,500 ± 500 (SNU01-078)	−25.6	43,068–41,235

*Calibration using OXCal 4.2.4. (Bronk Ramsey [6])

2.5. Comparison of the ^{14}C ages from various materials from the same samples

The principle of the preference for the youngest age from a series at the same depth [69,70] 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 ages older (45,7 kyr BP) and younger (39.0 kyr BP) than the bulk sample were obtained (Fig. 6 and Table 2). As shown by further measurements, the youngest age does not correspond to the true age, because the AMS age of an insect cornea from a sample occurring at 4 m below is 34.9 kyr BP. We suppose that, of these six ages, the closest to the true time of accumulation is the youngest age 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 age of a dwarf birch (*Betula nana*) twig extracted from the sample is 31.2 kyr BP. Of course, the age of the twig is closer to the real-time accumulation of these yedoma [67].

A comparison of the results for plant detritus and alkali extracts from the same sample was made in the GIN radiocarbon laboratory [61]. 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 age of the second alkali extract from the same sample is 32,500 ± 400 (GIN-3479 gII); 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 (GIN-3475 gI), and the second alkaline extract was 23,300 ± 400 yr (GIN-3475 gII). It is likely that material that is more ancient 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 [9], while ^{14}C ages of insects and woody material have different ages in the same deposit [24].

3. Comparison of ^{14}C ages in yedoma sediments

Analysis of available series of ^{14}C ages of syncryogenic sediments - yedoma of the Russian Arctic, as obtained by the authors [64,66,67,68,69,70,71,72,74] and published elsewhere [13,37,38,42,52–56,61,78–80] has revealed the important role of ancient reworked material in syncryogenic permafrost sediments throughout the Russian Arctic, as well as offering the principle of choosing the youngest age as the most reliable.

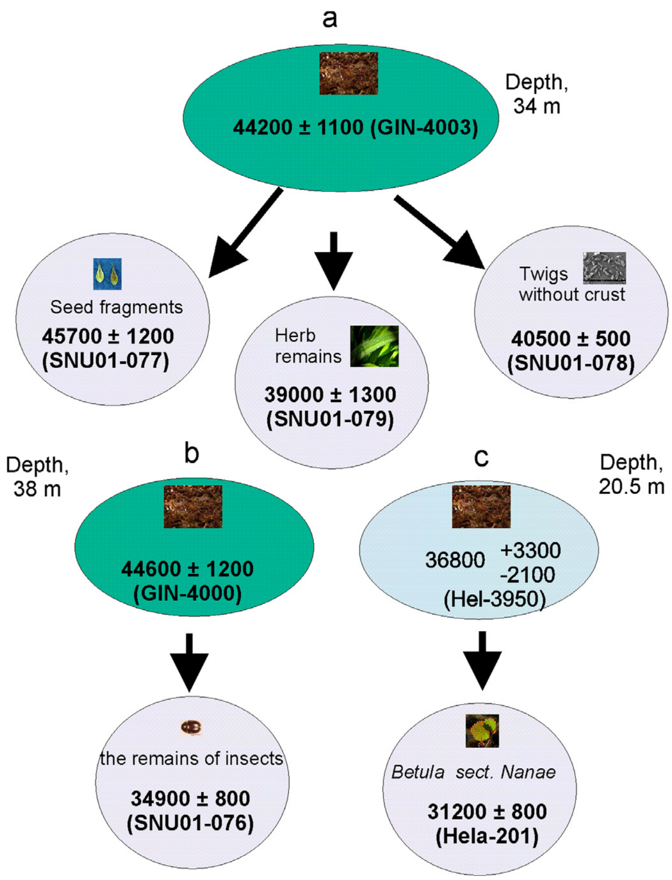

Fig. 6. ^{14}C ages of bulk samples consisting of mixed organic material and homogeneous organic material extracted from bulk samples: a - b: samples from different depths of Duvanny Yar yedoma outcrop (68°44′ N, 159°12′ E), c – sample from the bottom part of Seyaha yedoma (70°25′ N, 72°38′ E).

Nelson et al. [33], Zazula et al. [83,84], Schuur et al. [57], Kennedy et al. [24], Lachniet et al. [27], Hunt [18], Opel et al. [38] also evaluated the ^{14}C ages from the position of contamination with old carbon in syngenetic permafrost.

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 [64,67] and therefore to assess the reliability of the radiocarbon ages.

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 [66,67,68]. As an example, we have discussed the most representative sections of the Kolyma Lowland - Duvanny Yar and a cross-section in the delta of the Lena River - Mamontova Khayata [75].

The choice of valid ^{14}C ages based on yedoma model as two-component system such as ice wedges and host sediments (Fig. 7). At first stratigraphic units identified as subaerial or subaqueous. It is possible to select youngest age sequence from every subaerial unit, than to distinguish the youngest age sequence from all kind organic materials and compare it with ages obtained from sediments of subaqueous origin. The ages of the ice wedges as the other component of the yedoma are setting to subaerial units. At this step, it is necessary to find the correspondence between the youngest ages of the fractions from every sampling block of the ice wedge and the ages from subaerial units. Result sequence of maximum limit ages may be yielded.

Mamontova Gora. We would like to discuss the ^{14}C aging of the 50-m-high terrace exposure at Mamontova Gora (63°1′10″N 133°55′47″E), located at the left limit of the Aldan River 310 km from its mouth, central Yakutia as an example of applying of the principle of the choice of the youngest ^{14}C ages. At least two terraces of 50-m and 80 m in height reveal at the place. There is thick inset of lacustrine sediment with twigs and fragments of tree trunk in the upper part of the terrace exposures. Large ice wedges occur in this sediments, their visible height is about 5–7 m. The wood remains were aged numerously. One of the first age series have been presented in Markov [29, p. 4, 5, 163] for the upper part of 50-m terrace section. These dates are on samples from depths of 1–8 m but not from one continuous section or from one locality; therefore, the depth below the surface does not define stratigraphy. The dates and sample depth reported are: 26,800 ± 600 ^{14}C yr BP., 5.5 m; 40,600 ± 500 ^{14}C yr, 3 m; and 44,000 ± 1900 ^{14}C yr, 8 m. The age 26.8 kyr of well-decomposed wood was recognized as invalid [29]. In an attempt to better understand the stratigraphy of the loess-like silt, Pewe in 1973 collected carefully located organic samples in a vertical section at Mamontova Gora [42]. The radiocarbon ages on the 1973 samples ranged from about 42,000 to 46,000 ^{14}C yr BP for the upper 12 m. Pewe and Journaux supposed [43, p.42] that " the sediments may be 20,000 years old, whereas at this depth at another locality, the age may be 40,000 years". We studied vertical section of lacustrine loess-like sediments with large syngenetic ice wedges and obtained ^{14}C ages of the wood remains from 42 to 35 kyr BP also [65], and considered them to be reworked. The situation cleared up when ^{14}C AMS ages of POC from ice wedges have been obtained (Fig. 8). Series of seven ^{14}C ages showed that ice wedges formed from 17 to 13 kyr BP. Accumulation of lacustrine sediments completed in the basins located on the high terraces about 13 kyr BP and subaqueous stage of yedoma accumulation changed with subaerial one. Apparently the ^{14}C age 26,800 ± 600 yr BP at 5.5 m should be considered valid, and the older ^{14}C ages of the wood remains most likely are reworked.

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 ages were obtained from this site [20,32,66,67,68]. However, these series of ages could not be compared directly. The yedoma at Duvanny Yar on different profiles from different outcrops is aged by stratigraphically consistent age series in the upper parts of the profiles, with the ages monotonically increasing back to about 36 000–38 000 cal BP (about 31 000–33 000 ^{14}C BP). But, in the lower parts, the age-height pattern appears confusing, with ^{14}C ages at roughly the same heights covering extremely wide intervals (from about 31 000 to > 50 000 ^{14}C BP). However, one interpretation of such old ages is that they record a considerable admixture of old allochthonous material. Based on the ages from microinclusions and alkali extracts from ice wedges, Vasil'chuk et al. [73,74] concluded that most of the dated material has been reworked, and proposed that the most representative ages for silt deposition were the youngest ^{14}C ages obtained in each horizon (Table 3). Subsequently, an age of 36,900 ^{14}C BP at a height of 8.5 m above sea level (asl) was considered a reliable indicator of the age of some of the lower part of the yedoma, because similar ages have been obtained for the same depth interval: 29,900; 30,100; 31,100; and 35,500 yr ^{14}C BP [16,66,67]. From the youngest series of ages, the lower 25–30 m of yedoma may date from 40,000–35,000 ^{14}C BP; a high concentration of old organic material is characteristic of this part of the section and leads to irregular results from ^{14}C dating. Some investigators [20] have suggested that the lower 10 m of the cross-section at Duvanny Yar are older than 50,000–40,000 ^{14}C BP. This interpretation, however, is distinctly younger than the age model proposed for the lower part of this composite section in the Murton *et al* [32]. because 47 ^{14}C ages from a composite stratigraphic section, supplemented

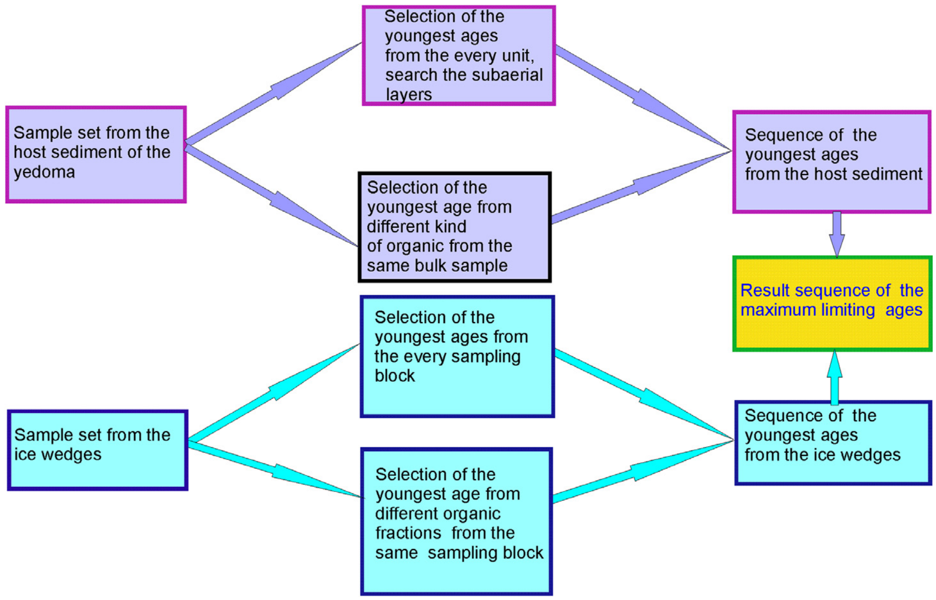

Fig. 7. Strategy of valid ^{14}C age choice in syngenetic permafrost allowing to yield a sequence of the maximum limit ages.

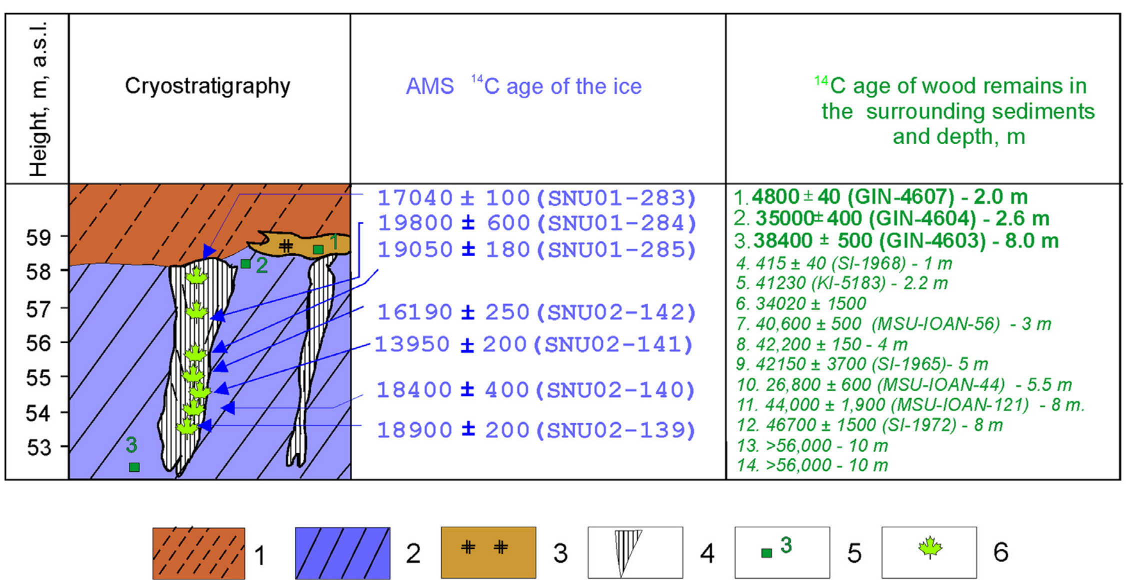

Fig. 8. Field sketch, cryostratigraphy and ^{14}C age of the Ice complex Mamontova Gora (62.94°N, 134.07°E) exposed along the Aldan River, Central Yakutia, Russia. AMS ^{14}C dates of organic micro-inclusions from ice wedges - from Vasil'chuk et al. [74]; ^{14}C dates of wood from surrounding sediments: 2–3 from Vasil'chuk [65]; 4, 9, 12 from Péwé et al. [42]; 7, 10, 11 from Markov [29]; 5, 6, 8, 13, 14 from Katasonov and Solov'ev [22]: 1 – sandy loam, 2 – peaty silt; 3 – peat; 4 – sampling point of the wood; 5 – sampling point of the particular organic carbon.

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

Radiocarbon age (^{14}C BP)	Laboratory Number	* Calibrated age (yr b2k)- the maximum limit ages	Height (m) asl	Organic Material
13,080 ± 140	EP–941,555	14,135–13,299	ca. 51	Soil
17,850 ± 110	MAG-592	19,976–19,331	ca. 42	Dispersed plant material
28,600 ± 300	GIN-3867	31,524–29,745	18.0	Mammoth bone
29,900 ± 400	GIN-4588	32,813–31,396	10.0	Black peat
35,400 ± 900	GIN-3996	39,927–36,420	7.5	Dispersed plant material

*Calibration using OXCal 4.2.4. (Bronk Ramsey [6]).

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 Yu. Vasil'chuk).

Radiocarbon age (^{14}C BP)	Laboratory Number	* Calibrated age (yr b2k)- the maximum limit ages	Height (m) asl	Organic Material
10,840 ± 50	KIA-11,441	10,855–10,732	about 36	Peat
17,160 ± 90	KIA-9195	19,021–18,507	30.0	Dispersed plant material
28,470 ± 160	KIA-6716	31,041–29,816	22.2	Wood
35,860 + 610/–570	KIA-6707	39,756–37,272	16.0	Herb
41,990 + 1050/–930	KIA-8168	45,956–41,510	10.0	Lemming coprolite from the ice wedges
42,630 + 980/–870	KIA-6701	Date probably out of range - 42,630 + 980/–870 BP	8.8	Herb
54,930 + 4280/–2780	KIA-12,509	Date probably out of range 54,930 + 4280/–2780 BP	0.2	Dispersed plant material

*Calibration using OXCal 4.2.4. (Bronk Ramsey [6])

by three OSL ages revealed good stratigraphical order, suggesting continuous silt deposition. The ^{14}C age model for yedoma deposition extends from 19 000 ± 300 cal BP at 36.7 m above river level (arl) to around 50 000 cal BP or beyond at 4.3 m arl. The three OSL ages range from 21.2 ± 1.9 kyr BP near the top of the yedoma to 48.6 ± 2.9 kyr BP near the bottom, broadly consistent with the ^{14}C age model [32]. As the yedoma has a dome shape thus organic material eroded from the higher central part may have accumulated in inverse order in the lower sections of marginal areas, enriched by old organic material. Different sections of the large yedoma body reveal at various times. Thus, only reliable material should be dated, such as layers of autochthonous peat or seed caches within fossil rodent burrows.

Mamontova Khayata. ^{14}C dating of yedoma sediments in the Bykovsky Peninsula, Lena River delta, is very indicative. Fartyshev obtained the first series of ages [66]. These ages have a very good correlation. The bone age is 22 kyr BP, grass roots around the bone are 21.6 kyr BP. Ages of 28.5 kyr and 33 kyr BP were obtained beneath the bone. A series of inversion ^{14}C ages: 21,630 ± 240 yr ^{14}C (LU-1328), 22,070 ± 410 yr ^{14}C (LU-1263), 28,500 ± 1690 yr ^{14}C (LU-1329) and 33,040 ± 810 yr ^{14}C (LU-1330) were obtained in the upper part of the exposure.

Later, Slagoda [58] yielded a younger series of ^{14}C ages as follows: 32,200 ± 930 yr ^{14}C (IM-748), at a depth of 20 m, 19,800 ± 500 yr ^{14}C (IM-753) at a depth of 20 m, 22,000 ± 1600 yr ^{14}C (IM-752) at a depth of 17 m, 20,836 ± 500 yr ^{14}C (IM-749) at a depth of 15 m, and 15,100 ± 750 yr ^{14}C (IM-748) at a depth of 9 m.

New 70 conventional and 20 AMS ^{14}C ages including ages from the ice wedges were obtained in the work of a Russian–German team at the exposure [52]. These ages, 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 et al. [52] came to this conclusion based on the oldest ^{14}C age of the wood as 58,400 + 4960/−3040 yr ^{14}C (KIA-6730) at 2.7 m above sea level (asl).

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 age of the plant remains from the 0.2 m asl is 54,930 + 4280/−2780 yr ^{14}C (KIA-12,509). The bone in situ at 14 m asl is aged about 32 kyr BP; that is, the bone is younger than the plant remains around the bone. By the way, the age of lemming coprolite from the ice wedges at 10 m asl is 41,990 + 1050/–930 yr ^{14}C (KIA-8168). This is one possible indication of a younger age of these layers.

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

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 ages. However, the principle of the choice of the youngest ^{14}C age from the data set in the particular horizon allows us to obtain an adequate un-inversion maximum limit age series of these complicated heterochronous complexes.

4. Conclusions

The strategy of valid ^{14}C age's choice in syngenetic permafrost includes several points such as:

- *Re*-working of organic matter in the permafrost is common. Syngenetic sediments contain allochthonous organic material that originated at a distance from its present position. Significant impact on the radiocarbon age has old organic matter, the magnitude of which is likely to be highly variable and not easily and independently constrained for syngenetic ancient permafrost.
- There needs to be a careful cull of the manifestly more ancient ^{14}C ages, and especially the ages beyond the range of radiocarbon dating, which usually correspond to re-worked organic material within yedoma. The possibility of ^{14}C age rejuvenation in permafrost exists also, within active layer only. The permafrost deposits may be at stable state throughout many thousand years. The youngest ^{14}C age from the data set in the particular horizon is the closest to the actual time of accumulation and freezing of the yedoma sediment.
- The cyclic model of ice wedge formation is useful for allocating the isotopic, palynologic and other data on a chronological scale and for evaluation of organic material for the dating, as reliable ^{14}C ages are most likely in the layers belonging to the subaerial stage.

- As syngenetic ice wedge is a closed system, microbial activity is excluded. The aging of organic microinclusions from ice wedges allows obtaining the age of the ice wedge directly.
- Radiocarbon dating of organic micro-particles, pollen and spores, using AMS has allowed to indicate of secondary contamination with ancient organic material and therefore to assess the reliability of the radiocarbon ages.
- The principle of the choice of the youngest ^{14}C ages is more suitable for syngenetic permafrost if contamination with modern carbon will be excluded at the sampling and pretreatment.
- Especially negligible the rejuvenation role in syngenetic ice wedges, because younger carbon could not contaminate the ice wedges which already completed its accumulation.
- Using a principle of the choice of the youngest ^{14}C ages, it is possible to clear the age of Mamontova Gora yedoma; formation of this ice complex began about 17 kyr BP and ended about 13 kyr BP.
- Based on the principle of the choice of the youngest ^{14}C ages from every strata, it was possible to show 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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