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The Holocene palaeoecology of the palsa mire near Igarka (Yenisei Siberia)

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Abstract. The paper presents a new paleoecological evidence covering the last 6500 years based on detailed AMS radiocarbon dating, plant macrofossils, loss on ignition and macroscopic charcoal records from a 8 m long peat sequence, obtained from the palsa mire situated near Igarka (Yenisei Siberia). The obtained data show that the peatland initiation, development of the perennial frost mound and local vegetation history were strongly influenced by the Holocene climatic fluctuations and permafrost dynamics. The main stages of palsa uplift occurred at about 5360 cal yr BP and 2250 cal yr BP and coincided with the periods of cooling in the Russian Arctic region. According to the radiocarbon dating and plant macrofossil analysis of the upper part of peat sequences the peat accumulation rate in the palsa decreased significantly during the last 2000 years. Nevertheless, we consider that the rate of the peat vertical growth could be underestimated due to the disturbance of the frost mound, water erosion and wildfires.

1. Introduction

The permafrost zone of Siberia is extremely vulnerable to environmental changes [1]. Among the best possible lines of evidence for the impacts of paleoclimate changes on ecosystems in circumpolar regions as a model for better understanding their modern dynamics are the results of multiproxy studies of lakes and peatlands. Our paleoecological study is focused on one of the palsa mires located at the eastern edge of the West Siberian Lowlands in the forest-tundra ecotone. Perennial frost mounds, often called as palsas and peat plateaus [2], are the dominant landscape type in the northern part of West Siberia occupying up to 70% of watershed area in the permafrost zone [3, 4]. Being climatically sensitive landforms on permafrost peatlands, palsas are unique natural archives that contain information about changes in vegetation, climate and environment during the Holocene.

Active studies of palsas near Igarka took place in the middle of the last century [5, 6, 7]. The vegetation of different types of the mires near Igarka were described by Katz [8]. The first pollen and plant macrofossil data from palsa with radiocarbon age of about 8000 years BP were obtained by Piavchenko [9]. A review of available data on the regional vegetation, peat stratigraphy and the Holocene dynamics of palsas was presented by Vasilchuk *et al.* [10].

Our study provides new paleoecological evidence for the last 6500 years based on plant macrofossils, loss on ignition and charcoal records from an 8 m long peat sequence, obtained from the perennial frost mound. The records presented are the first high-resolution data on macroscopic fossil plants supported by detailed radiocarbon dating. The main goal of the study is to reconstruct peat inception, vegetation history and peatland development in the study area and compare the data obtained with the available information on the main stages of climate change in the Holocene in the Arctic region of Russia.

2. Study area

The Bolshaya Graviyka mire (N 67°31’53.77’ E 86°38’05.65’) is located about 10 km northeast of the town of Igarka in the Turukhansk district of the Krasnoyarsk region. The mire occupies the gently undulating moraine plain of the Ermakov (Late Pleistocene) glaciation close to the border between moraine plain and the late Pleistocene fluvio-glacial and alluvial valley, which is nowadays inherited by the valley of the Graviyka River, the right tributary of the Yenisei River. As follows from the landscape map of the study area (figure 1), palsas are very typical landforms within the moraine plain, since plastic clay deposits contribute to the penetration of water into peat and the rise of a perennial frost mound [10].

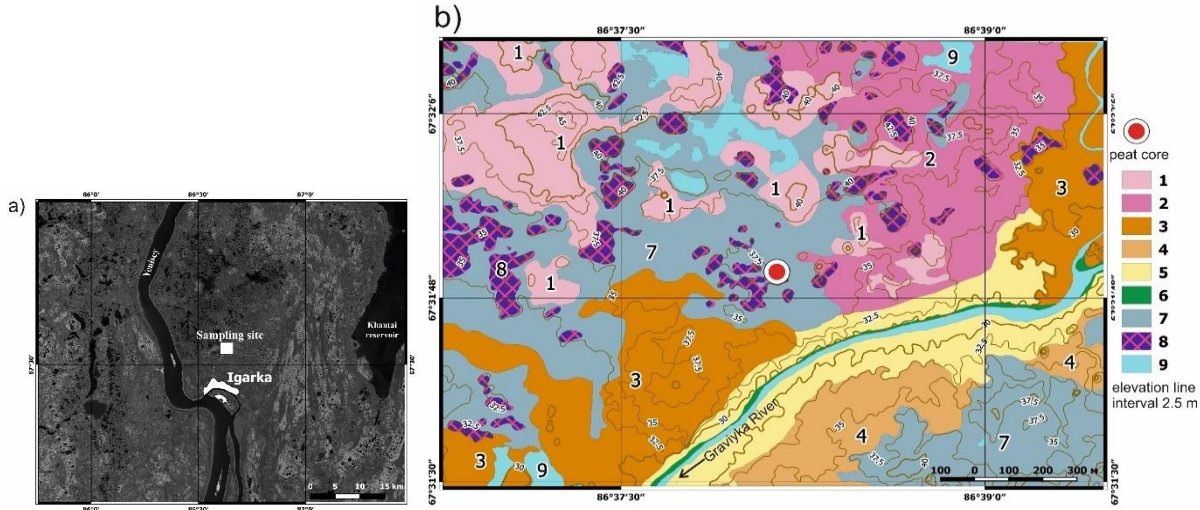

Figure 1. Location of the study area and the sampling site: a) Location of the study region; b) Landscape map of the study area and position of the peat core. The topography of the study area was derived from ArcticDEM [11]. Legend: 1. Moraine plains, undulating, moderately drained, composed of the Ermakov (Late Pleistocene) diamicton, covered by *Pinus sibirica*-*Picea*-*Larix* forests on turbic cryosols; 2. Moraine plains, gently inclined, poorly drained, composed of the Ermakov (Late Pleistocene) diamicton, covered by *Larix* forests on histic cryosols; 3. Fluvio-glacial plains, gently inclined, moderately drained, composed of the Ermakov (Late Pleistocene) sand, pebbles and siltstones, covered by *Picea*-*Larix* with *Betula* forests on turbic cryosols; 4. Fluvio-glacial plains, flat, poorly drained, composed of the Ermakov (Late Pleistocene) sand, pebbles and siltstones, covered by *Larix* forests on histic cryosols; 5. 1st floodplain terrace of the Graviyka River, gently inclined, well drained, composed of alluvial sands and pebbles, covered by *Picea*-*Larix*-*Betula* forests on turbic cryosols; 6. Floodplain, flat, poorly drained, composed of alluvial sands, pebbles and boulders, covered by hydrophilous vegetation on alluvial soils; 7. Wetlands; 8. Perennial

frost mounds; 9. River channel and lakes.

According to the Köppen-Geiger climate classification, the climate of the study is sub-Arctic (or subpolar) with long, usually very cold winters, and short, cool summers [12]. The mean annual air temperature is -7.8°C, the mean annual precipitation is 647 mm. The region belongs to the area of continuous permafrost. The vegetation is represented by open larch and spruce-larch woodlands with admixture of *Pinus sibirica* Du Tour and *Betula pendula* Roth. The soil cover is formed by turbic cryosols and histic cryosols.

The peat core was obtained from the central intact part of the perennial frost mound (>4.5 m height, 50-100 m width) surrounded by flat wide hollows (200-300 m). The surface of the mound is covered by lichen (70%) and feather mosses (20%) combined with bare peat. The local vegetation is formed by *Betula nana* L., *Ledum palustre* L. and *Rubus chamaemorus* L.

3. Material and methods

The field work and peat coring were carried out at the end of August 2020. The core was extracted from the frost mound using a portable drilling station equipped with a motor piston corer. The seasonally thawed layer of permafrost at the coring site was 52 cm. The obtained core, 860 cm in length, consisted of peat deposits (845 cm) intercalating with ice lenses, underlain by dense dark gray clay with plant remains. The sampling interval for plant macrofossil and macro-charcoal analysis and loss on ignition measurements varied from 0.5 to 5.0 cm (2.8 cm on average) depending on the amount of ice and peat material in the samples. An additional core 120 cm in length was taken from the unfrozen hollow adjacent to the palsa under study using a Russian peat corer.

The bulk peat samples (18 samples) from the palsa peat core and 3 samples from the additional core (table 1) were dated by AMS radiocarbon analysis in the Laboratory of Radiocarbon Dating and Electronic microscopy of the Institute of Geography of the Russian Academy of Science (Moscow) and the Center for Applied Isotope Studies of the University of Georgia (USA). The ^{14}C dates were calibrated using the Calib 8.2 software and the calibration dataset Intcal 20 [13]. The age-depth model for peat core (figure 2) was developed using the "Bacon" package [14] in the R language environment [15].

The samples for plant macrofossil analysis were disaggregated with water and washed through a 250 μm mesh sieve. The plant remains were identified using a binocular microscope at 200x magnification following Katz *et al.* [16]. LOI was determined following the procedures outlined by Dean [17] by combusting dried samples at 550 C. The samples for macroscopic charcoal analysis were prepared according to the method of Mooney and Tinner [18] using a 125 μm μm mesh sieve.

4. Results and discussion

4.1. Chronology and peat accumulation rate

The results of radiocarbon dating show that organic reach deposits accumulated in the Bolshaya Graviyka mire since 5500±20 ^{14}C yr BP/ 6350±20 cal yr BP (IGAN$_{AMS}$ 8350). The radiocarbon date 5425±20 ^{14}C yr BP/ 6240±40 cal yr BP (IGAN$_{AMS}$ 8349) obtained at the lower boundary of the peat sequence (at 845 cm depth) suggests the peat inception at the end of the mid-Holocene climate warming. The latter was revealed by paleoclimatic reconstructions based on pollen records from Lama Lake in the Putorana Plateau [19] located about 200 km northeast from our study area. According to these data, the temperature reached its maximum between 7200 and 5200 cal yr BP, and climate warming promoted the mire growth.

At present, an exceedingly small number of radiocarbon dates are available for the basal peat layers from the Yenisei Siberia. For Igarka region, only two dates have been reported: 8210±250 ^{14}C yr BP / 9090±500 cal yr BP [9] and 7330±80 ^{14}C yr BP / 8170±160 cal yr BP (KRIL-118) [9]. Two radiocarbon dates 7940±80 ^{14}C yr BP / 8800±200 cal yr BP (KRIL-134), 6800±70 ^{14}C yr BP / 7675±110 cal yr BP (KRIL-133) were obtained for the peat initiation in palsas close to the town of Dudinka, situated 200 km to the north from the study area [10]. A series of dates from perennial frost mounds in the northeastern East European Plain, in the Polar Urals, and on the Tazovsky and Taimyr peninsulas provide an age estimate for the onset of peat accumulation between 11000 and 6000 cal yr BP [10, 20, 21] that is consistent with the period of the most active peatland initiation in the high latitudes of the Northern Hemisphere [22, 23]. Although the Bolshaya Graviyka mire is somewhat younger than previously studied peatlands in the region, its age falls into the range for the dates of basal peat layers in the permafrost zone of northern Siberia.

The radiocarbon dates obtained for the peat sequence in the studied palsa with a step of 50 cm show a uniform increase in age with depth (figure 2), except for few inversions. Bearing in mind the radiocarbon date 1930±20 ^{14}C yr BP / 1850±40 cal yr BP (IGAN$_{AMS}$ 8354) obtained at the depth of 15 cm, it can be assumed that the 8-meter-thick peat sequence was accumulated for 4000 years. This exceptionally high peat increment is obviously overestimated due to the expansion of peat by ground-ice lenses [10, 24]. According to Konstantinova [7], the volume of ice in perennial frost mounds in the study region varies from 60 to 90%. We observed in the field several ice layers up to 5 cm thick in the peat core, as well as a lot of inclusions of ice crystals in the peat.

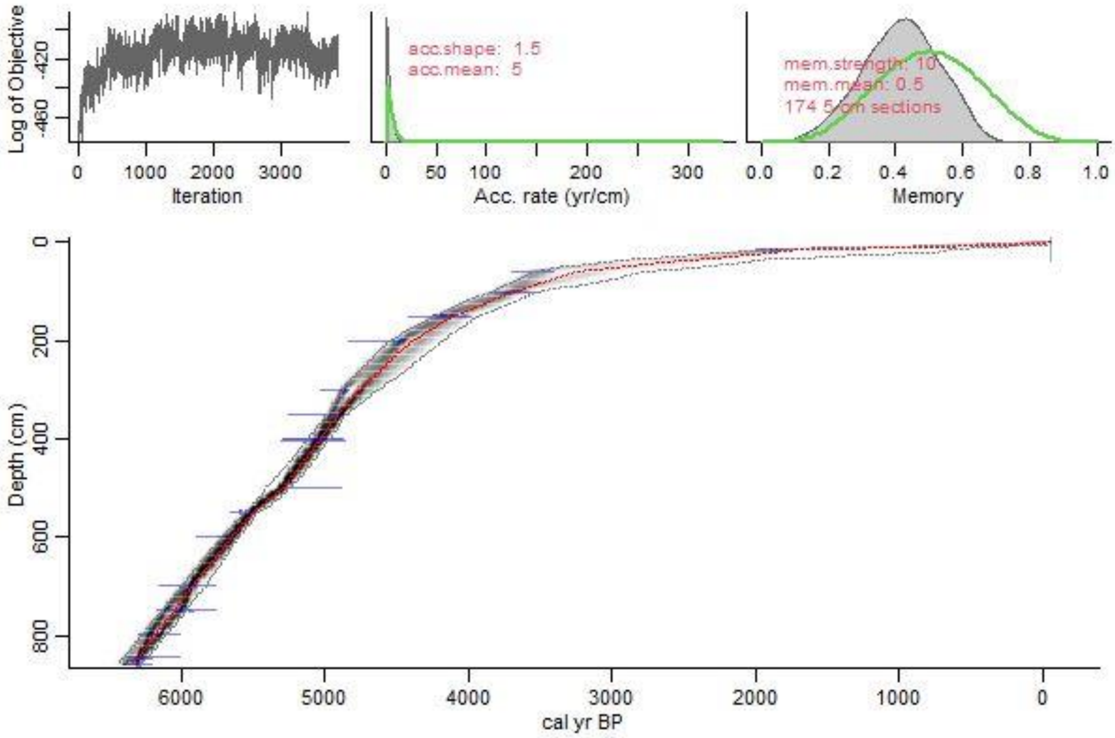

Figure 2. Age-depth model for the peat core from the perennial frost mound in the Bolshaya Graviyka mire.

The Radiocarbon age of the peat sample from the depth of 120 cm in the additional core located in unfrozen hollow adjacent to the palsa under study is 4150±20 ^{14}C yr BP/4690±50 cal yr BP (IGAN$_{AMS}$ 8353), which corresponds to peat accumulation rate of 0.25 mm/year. This is in accordance with the average Holocene peat growth rate in unfrozen hollows in the northern part of West Siberia, reaching 0.39 mm/year [25].

The age of about 1850 cal yr BP determined for the peat sample taken at the depth of 15 cm implies an incredibly low peat accumulation rate over the last 2000 years and may also be underestimated as a result of peat disturbance due to water erosion of the palsa surface and wildfires, the signs of which were revealed from plant macrofossil and macroscopic charcoal analysis. The damage of the uppermost peat layers in perennial frost mounds and peat plateaus is a common feature of peatlands in Northern Europe

[26, 27]. A series of radiocarbon dates obtained from the peat bogs in the Bolshezemelskaya tundra (northeastern European Russia) showed that radiocarbon age of peat at the depth of 15-20 cm was 1040±50 yr BP (GIN-10968), 1420±40 yr BP (Le-11252) and 1920±100 yr BP (Hel-3798) [10, 20, 26], and even 3100±40 yr BP (GIN-10971) at the depth of 5 cm [20]. However, some studies showed that undisturbed perennial frost mounds in this region can be also found [10].

During the last 2000 years, the peat accumulation rate in the palsa under study was 0.075 mm/year and in the adjacent hollows it varied from 0.19 to 0.28 mm/year. According to Bleuten and Lapshina [25], the peat vertical growth in peat bogs in the northern West Siberia decreased significantly during the late Holocene compared to the previous epochs and varied from 0.09-0.10 mm/year in frozen mounds, to 0.13-0.21 mm/year in thawed hollows, and up to 0.48 mm/year in young sphagnum hummocks Our data confirm the earlier assumption [24, 25, 28] about the suppression of the process of peat accumulation in frozen peat bogs over the past two millennia. However, we assume that the peat accumulation rate can be underestimated due to the disturbance of peat sequences.

4.2. The Holocene palaeoecology of the palsa mire

The results of LOI, plant macrofossil and macroscopic charcoal analysis (figures 3, 4) from the Bolshaya Graviyka mire allow us to identify 5 main phases of palsa mire history and evolution.

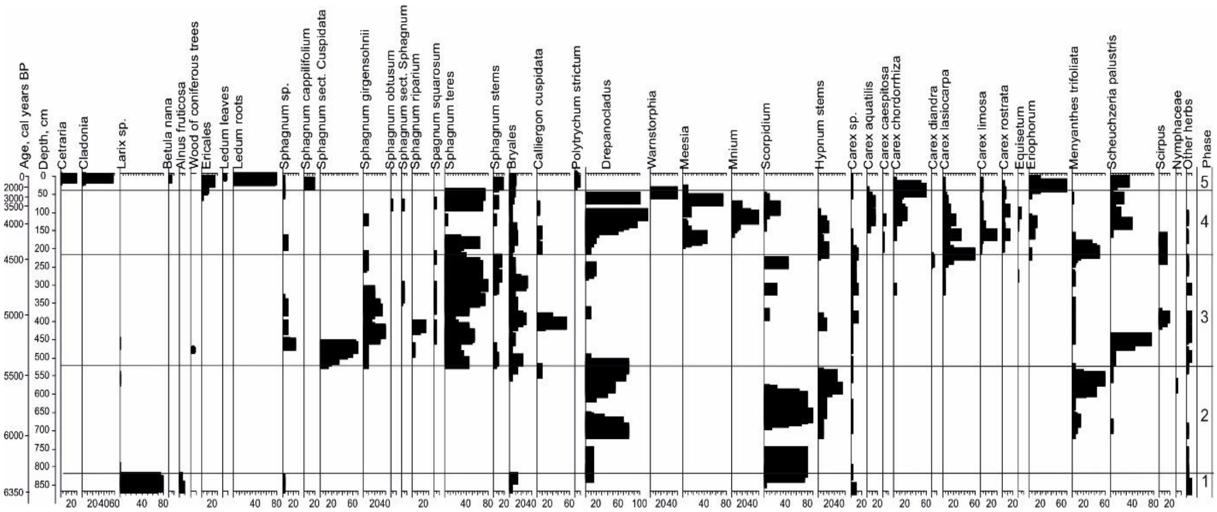

Figure 3. Plant macrofossil diagram for the peat core from the perennial frost mound in the Bolshaya Graviyka mire.

Phase 1 (860-845 cm, 6350-6240 cal yr BP). The layer of dense gray clay underlying the peat, with abundant *Larix* sp. and *Alnus fruticosa* wood remains, contains abundant macroscopic charcoal particles (from 200 to 700 particles/cm^3). This suggests an active paludification processes of wet larch forest after a fire. The organic matter content in the clay layer ranged from 13 to 20% (figure 3). The remains of bryozoan (*Cristatella mucedo*, *Plumatella*-type) indicate the excessive surface humidification with shallow small lakes, and possibly thermokarst.

Phase 2 (845-516 cm, 6260-5360 cal yr BP) is characterized by highly humified minerotrophic peat (figure 4) composed of the remains of feather mosses (*Drepanocladus aduncus* (Hedw.) Moenk., *Hamatocaulis vernicosus* (Mitt.) Hedenäs., *Scorpidium scorpioides* (Schimp.) Limpr.) with admixture of the remains of *Menyanthes trifoliata* and sedges. According to the existing ecological data [29, 30], these plants require excessive moisture conditions typical for the initial (subaquatic) stage of palsa development [10].

The LOI values increase sharply to 94% at the lower boundary of the peat sequence and range between 93% and 98% throughout the entire peat core, except for the interval of 720-708 cm, where the organic matter content sharply reduces to 60-70%. An increase in mineral fraction content in the peat could be a result of the injection of the underlying clay by permafrost processes or it may be due to amplification of soil disturbance in the adjacent area. The peak of macro-charcoal concentration (up to 860 particles/cm^3, figure 4) detected at these depths evidence high fire activity. Except for this period, the macroscopic charcoal concentration in peat is extremely low (1-4 particles/cm^3), and at several depths charcoal is completely absent.

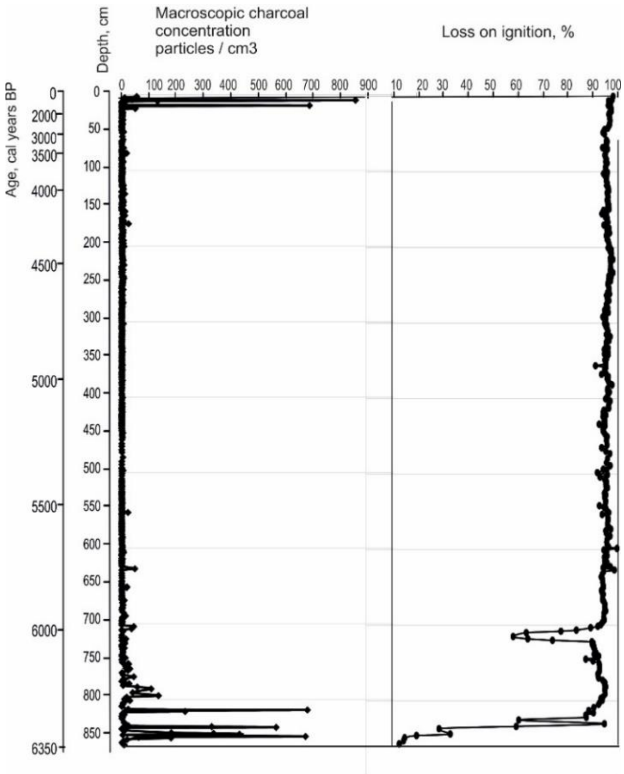

Figure 4. Macroscopic charcoal concentration and Loss on ignition in peat core from the perennial frost mound in the Bolshaya Graviyka mire.

Phase 3 (516-220 cm, 5360–4465 cal yr BP). This stage is distinguished by the accumulation of the low and medium decomposed *Sphagnum* peat (phase 3a, 516-413 cm, 5330-5060 cal yr BP; phase 3c, 377-220 cm, 4970-4465 cal yr BP) and highly decomposed herbal - feather mosses peat with remains of *Calliergonella cuspidata* (Hedw.) Loeske and *Scirpus* sp., (stage 3b, 5060-4970 cal yr BP). The plant macrofossil assemblages of *Sphagnum* peat are formed mainly by *Sphagnum teres* (Schimp.) Ångstr. (60-80%), demanding sufficient mineral nutrition [31, 32, 33] and growing usually in open reach and very rarely in poor fens. The remains of *Sphagnum girgensohnii* Russow and *Sphagnum squarrosum* Crome. in the peat layer are not abundant. Some remains of brown and feather mosses and herbs were recorded.

The appearance of *Sphagnum* mosses in the plant macrofossil assemblages indicates significant changes in moisture conditions in the mire at 5360 cal yr BP probably due to the uplift of the peatland surface by permafrost. *Sphagnum* mosses sustain to palsa development insulating ground-ice lenses [34]. The modern field observations on palsas suggest that perennial frost mounds aggrade under cold and dry climatic conditions that enable deep freezing of the peat bog [35]. Paleoclimatic reconstructions based on palynological data from Lama Lake in the northwestern Putorana Plateau [19] show a noticeable temperature decrease after 5200 cal yr BP that promoted palsa development. Alteration in the dominance of sphagnum and feather mosses in plant macrofossil assemblages may be evidenced by partial thawing and subsidence of the palsa surface between 5050 and 4970 cal yr BP, and its subsequent rise.

Phase 4 (220-231 cm, 4970-2250 cal yr BP). The increase in the abundance of *Carex* (*C. chordorrhiza* Ehrh. ex L.f., *C. lasiocarpa* Ehrh., *C. aquatilis* Wahlenb.) in plant canopy at the beginning of this period (subphase 4a, 220-51 cm, 4970-2960 cal yr BP) suggests lower surface wetness in the mire compared to the previous time interval. In addition to the high abundance of Carex species, plant macrofossil assemblages are characterized by alternating peaks of brown and feather mosses (*Drepanocladus sp., Scorpidium scorpioides, Mnium cinclidioides* Hedw., *Meesia trifaria* Crum.) and *Sphagnum teres.* The abundance of arctic aquatic moss *Warnstorfia exannulata* (Guemb. in B. S. G.) Loeske) [36] at a depth of 51-46 cm (4b, 2960-2800 cal yr BP) indicates very high surface wetness of the mire, probably, due to the thawing of the palsa surface. At the depth of 46-31 cm (subphase 3c, 2800-2250 cal yr BP) *Warnstorfia* peat is replaced by peat consisting mainly of *Carex* (*Carex chordorrhiza, Carex rostrata* Stokes).

The beginning of phase 5 (subphase 5a, 31-16 cm, 2250-1700 cal yr BP) is marked by a dramatic shift in moisture conditions in peatland as evidenced by the appearance of *Eriophorum vaginatum* L., *Scheuchzeria palustris* F. Muell. Thus, the transition from the subaquatic stage of palsa development to the subaerial one occurred 2250 cal yr BP and could be a sign of permafrost aggradation in this area [26].

Based on a large data set on plant macrofossil records and radiocarbon dates from perennial frost mounds in northern West Siberia Vasilchuk *et al*. [10] determined that the uplift of most palsas occurred within the time range from 4900 to 1370 ^{14}C yr BP (5600 – 1290 cal yr BP) and was highly dependent on local hydrological conditions, topography and vegetation cover. According to our records, the uplift of the palsa under study coincided roughly with the climate cooling in the Arctic [37] at about 2500 cal yr BP that was clearly traced in the paleoclimatic reconstructions by chironomid assemblages from lakes in the western Putorana Plateau [38] and pollen data from lakes in Taimyr Peninsula [39]. Reconstructions of summer temperatures based on tree-ring chronologies [40] and studies of pathological disturbance of *Larix sibirica* wood in Yamal Peninsula [41] also indicated a significant cooling in the Arctic since 2700-2500 cal yr BP.

The upper part of the peat sequence in the palsa under study is formed by reddish-ochre dry peat (subphase 5b, 11-6 cm, 1700-300 cal yr BP), permeated with vegetation roots and buried stems of ericoid dwarf shrubs. The plant macrofossil assemblages composed mainly of *Ledum palustris* (90%) with participation of *Cladonia*, *Cetraria* (5%) and *Polytrichum strictum* (5%) indicate dry environmental conditions. The uppermost 6 cm of peat profile are dominated by lichen *Cladonia* and *Cetraria* (up to 90% in total) with rare remains of *Betula nana* and *Ledum palustris,* suggesting extreme dry conditions in recent period and a visible degradation of the top of the palsa, probably due to fire impacts. During our field observations, the charcoal fragments and charred wood were found at the depth of 10-11 cm (about 1000-1100 cal yr BP). The concentration of macroscopic charcoal particles in the peat at the depths of 10-6 cm ranges from 39 to 870 particles/cm^3, which reveals the presence of fires both in the mire itself and within the surrounding area.

5. Conclusions

The results of radiocarbon dating, plant macrofossil and macroscopic charcoal analysis of the Bolshaya Graviyka mire situated close to Igarka gave us a unique possibility to examine the mid- to late Holocene palaeoenvironmental changes in the frozen peatland in this very remote and poorly investigated area in Yenisei Siberia, which is very important for better understanding the landscape processes in the Arctic and Subarctic regions. Our main conclusions are as follows:

1. The peat inception in the Bolshaya Graviyka mire occurred at about 6200 cal yr BP during climate warming that promoted peatland growth.

2. Our results suggest that the Holocene climate changes had significant impact on permafrost dynamics in the peatland area, especially at the initial stage of palsa development. According to the

obtained data, the initiation of the palsa occurred about 5360 cal yr BP and its significant uplift corresponded to 2250 cal yr BP. These events coincided with the main periods of cooling in the Russian Arctic region.

3. Radiocarbon dating and plant macrofossil analysis of the upper part of peat sequences in the Bolshaya Graviyka mire indicated suppression of peat accumulation in the palsa during the last 2000 years, but it is most likely that the uppermost peat layer has been lost due to water erosion and fires.

Acknowledgements
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