

Detailed reconstruction of the functional state of the Central Yamal khasyrey as a response to local conditions and regional climate changes in the late Holocene

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Abstract. In this article, data of reconstruction of the dynamics of plant communities, water regimes, geocryological conditions, and peat accumulation of the khasyrey of Central Yamal Peninsula located in the tundra of Western Siberia by traditional paleoecological methods on the basis of detailed studies of the botanical composition, degree of decomposition, density, ash content and $\delta^{13}\text{C}$ in the cellulose of peat cut pulp age about 1300 cal. BP are considered. It has been shown that the khasyrey has a sensitive response on century and decadal scales to climate change and the lake regime level. Moreover, the stages of khasyrey functional state are in a good agreement with similar data on mires of the forest zone of Western Siberia and the solar activity periods.

1. Introduction

Predictions of the natural landscape changes made on the basis of high-resolution paleoclimatic and paleoecological reconstructions are topical in light of current climate changes. The forecasts for the most sensitive natural landscapes of arctic and subarctic regions are of special interest. At the present time the processes of permafrost degradation have become active. It creates difficulties in the development of these regions and the threat of mass ejection of CO_2 and CH_4 contained under the permafrost. Long-term sets of data of high-resolution paleoecological reconstructions based on highly sensitive complex of indicators are needed to develop the forecasts. The information about detailed paleoecological studies of mire functional state of Western Siberia tundra is absent.

Studies of permafrost including stratigraphy, dynamics and genesis of palsa are actively carried out around the world [1]. Determination of the optimal environmental conditions for the development of cryogenic processes in soils remains relevant to this day. The palsa in the tundra and forest tundra of Western Siberia are confined mainly to the drained lake basins – khasyreis. The khasyreis are one of the main landscapes of these areas. Periodic filling and draining of lakes cause frequent changes of water regimes and geocryological conditions of khasyreis. The development of khasyreis as well as the permafrost mires occurs cyclically [1, 2]. However the extent of the climate impact on the change of khasyreis functional state in subzones of the permafrost zone is different and isn't known.

The characteristics of tundra zone Holocene paleoclimate are not clarified until the end. The characteristics of mean annual temperature and precipitation amount are practically absent. The high-resolution data of summer temperature have been reconstructed by dendrochronological method for the south of the Yamal Peninsula [3].



The goal of current work is to carry out a reconstruction of paleophytocoenosis, water regimes and cryogenic conditions of khasyrey of Central Yamal as a response to changes of the level of the lake waters and regional climate of the late Holocene according to the detailed data of complex studies of peat deposits.

2. Objects and methods of investigation

The study area is located in the central Yamal Peninsula in the continuous permafrost zone with temperatures from -5 to -7 °C [4] on the border of the typical and southern tundra. In winter, temperatures drop to -59 °C. Summer is short and moderately cool. In July, the temperature may rise up to +30 °C. Indicators of the mean annual temperature (from -1.0 to -9.5 °C (1924-2009)) and mean annual precipitation (315-903 mm (1966-2010)) considerably vary [5].

The khasyrey is located on the III-rd terrace of the Central Yamal near Sokhonto Lake (69°08'57,17" N, 70°15'57,67" E). It has a diameter of 300-350 m. Low center of khasyrey is busy by paludification depression and lake with depth of 2-2.5 m and with erosional stream. The rest of the khasyrey is above a decrease on 2.5 m and busy by polygonal-flat-palsa mire with flat cannels and convex polygons of 3-5 m. *Betula nana*, *Ledum decumbens*, *Vaccinium vitis-idaea*, *Rubus chamaemorus*, *Eriophorum scheichzeri*, *Carex rariflora* grow in polygons. *Sphagnum majus*, *S. balticum*, *S. squarrosum* and *Polytrichum juniperinum*, *Dicranum angustum*, *Oncophorus wahlenbergii*, *Aulacomnium palustre* form a rarefied moss cover on the polygons.

Peat monolith with size of 17.5x20x80 cm from the edge of the khasyrey has been selected and divided into samples of 3.5-0.5cm increments. Research of botanical composition of peat macrofossil by microscopic method, research of decomposition degree (*R*) by centrifugation method, of ash content (*A*) and dry bulk density of peat (*P*) and its organic matter (*OM*) have been carried out. The isotopic composition of carbon $\delta^{13}\text{C}$ in peat cellulose was determined on the equipment, consisting of a DELTA V Advantage isotope ratio mass spectrometer and Flash EA 2000 elemental analyzer (TomTsKP SB RAS) at the Institute of Monitoring of Climatic and Ecological Systems, SB RAS (Tomsk, Russia). Radiocarbon dating has been made by liquid scintillation method using a radiometer-spectrometer Quantulus 1220 (TomTsKP). The calculation of calibrated age was performed on the program CALIB 7.0.4. [6] using the IntCal13 and MARINE13 data set [7] (Table 1). The comparison of $\delta^{13}\text{C}$ in peat cellulose with the reconstruction of summer temperatures in Yamal has been made to revision of obtained dates [3].

Table 1. Radiocarbon dates and calibrated ages of peat samples from Khasyrey section.

Depth (cm)	Age (^{14}C year B.P.)	Material	Laboratory code	Calibrated age (year B.P.)	
				2 δ range	median value
13.5–16	113 ± 0.8%	Peat	IMCES–14C805	118–65	91.5
26.5–28	286 ± 67	Peat	IMCES–14C789	501–267	384
35.5–39	639 ± 86	Peat	IMCES–14C847	709–514	611.5
43.5–45.5	761 ± 51	Peat	IMCES–14C785	786–651	718.5
70–72	1156 ± 122	Peat	IMCES–14C861	1299–899	1099
79–80	1377 ± 75	Peat	IMCES–14C782	1415–1172	1293.5

The calculations of the vertical growth rate (VGR) of peat (mm per year), of the dry peat accumulation rate (PAR), its organic matter (OMAR) and mineral matter (MMAR) ($\text{g}\cdot\text{m}^{-2}$ per year) are given. The reconstruction of paleophytocoenosis by species composition of plant remains of peat has been performed. The calculations of steps of humidification (*SHd*) [8] and index of humidity (*IHd*) of paleoecotops [9] have been made by standard methods of ecological scales by peat botanical composition for quantitative estimation of the hydrologic regime change of the paleoecotopes. The

values of *SHd* and *IHd* have been assigned to some subarctic plants, which is absent in [8, 9]. The belonging of these species to certain ecological groups in relation to the humidification conditions [10, 11] was taken into account. Characteristics of peat properties as additional indicators of hydrological regime were applied. Secondary changes of peat properties have been determined by the absence of an agreed change of *R*, *P*, *SHd*, *SHd* and VGR along depth of peat deposit. The reconstruction of permafrost conditions was performed by the paleosuccessions [1] and peat properties [12]. Paleoprocesses of frost-heave in peat deposit were diagnosed by presence of remains of plant species, which are characteristic for a transition of mire surface from the subaqueous to subaerial condition. The beginning of permafrost degradation was investigated by the appearance of remains of more hydrophilic plants in the peat. The abundance of remains of diatoms seaweed is accepted as an indicator of the presence of thermokarst pool in the past. During wet and/or warm climate periods symptoms of drying of khasyrey surface are evidences about lake drainage.

Climatic conditions for khasyrey development stage have been determined by climate reconstruction data of the forest zone of Western Siberia [13–15], by data of average summer temperatures of the South of the Yamal Peninsula [3] and paleoecotops (by use $\delta^{13}\text{C}$). The paleoclimatic curves [13–15] have been digitized and calibrated.

Revealed the zonal features of the dynamics and clarify paleoclimate characteristics of khasyreya development stages by using data on the dynamics of the marshes of the forest zone of Western Siberia [16–19] and the solar activity [20].

3. Results and discussion

The khasyrey peat deposit has a depth of 80 cm (Figure 1) and consists of numerous thin layers of transitional peats, that are differed sharply from each other by botanic composition и properties (*R* – 5–35 %, *A* – 6.2–43.1 %, *P* OM – 25–240 g dm⁻³).

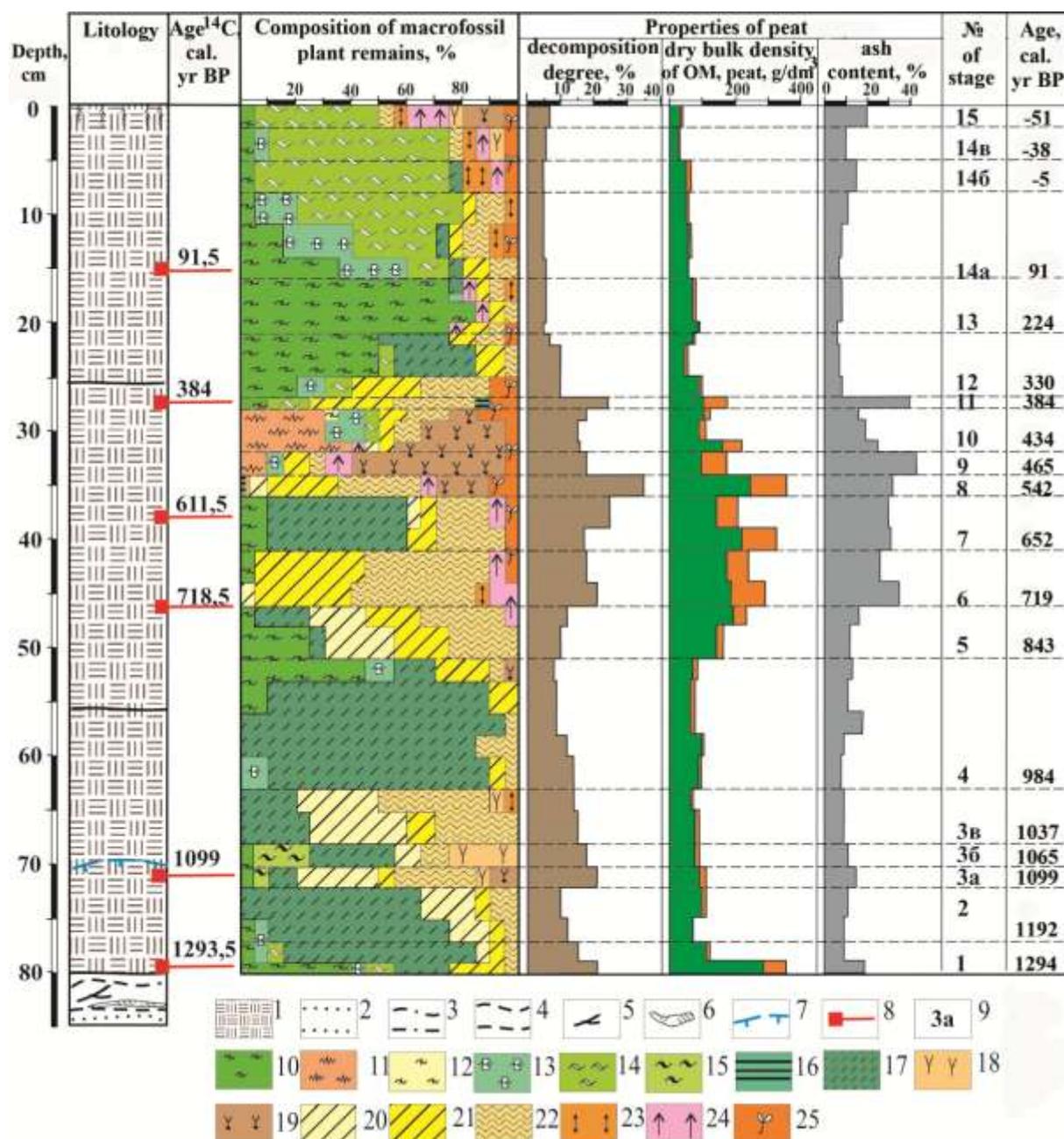


Figure 1. Lithology, botanical composition and properties of peat of Khasyrey cutting.

Symbols: 1) peat; 2) sands; 3) laminated sandy loam; 4) laminated loam; 5) peat lenses of moss; 6) introduced by water plant remains; 7) the upper limit of the frozen peat (28.08.2014); 8) sampling locations on radiocarbon dating; 9) borders of khasyrey formation stages; plant remains in the peat: 10) *Sphagnum squarrosum*, 11) *S. lenense*, 12) *S. angustifolium*, 13) *S. balticum*, 14) *S. majus*, 15) *S. platyphyllum*, 16) *S. riparium*, 17) *Warnstorfia fluitans*, *Drepanocladus sp.*, *Calliergon sp.*, 18) *Aulacomnium palustre*, *Meesia triquetra*, 19) *Polytrichum juniperinum*, *Dicranum angustum*, *Oncophorus walhenbergii*, 20) *Carex rariflora*, 21) *C. rotundata*, 22) *Eriophorum sp.*, 23) *Betula nana*, 24) *Ericaceae*, 25) *Rubus chamaemorus*.

Three layers differ markedly in their properties. The upper layer (0–26.5 cm) has been formed by Sphagnum peat with low indexes of properties ($R_{av} - 6\%$, $A_{av} - 10.2\%$, $P_{av} OM - 65\text{ g dm}^{-3}$), the

middle layer (26.5–50.5 cm) has been formed by grass, grass-moss and shrub-moss peats with higher indexes of properties ($R_{av} - 16\%$, $A_{av} - 27.6\%$, $P_{cp} - 215 \text{ г/дм}^3$), bottom layer (50.5-80 cm) has been formed by Hypnum and grass-Hypnum with lower indexes of properties ($R_{av} - 13\%$, $A_{av} - 12.1\%$, $P_{av} - 111 \text{ г дм}^{-3}$). The most frequent abrupt changes of botanical composition and properties of peat are characteristic of the middle layer. The peat extracted from the depth 0.7 m was frozen (Figure 1). Sandy loams, loamy sands with plant remains and silty sands lie below the peat.

Chronology of peat accumulation is based on 6 calibrated radiocarbon dates. Using satellite imagery Landsat [Google Earth <http://www.google.com/earth/explore>] from different years it has been revealed that the last wet stage of the khasyrey ended between 2003 and 2008. Age–depth and age–cumulative mass models have a convex shape (Figure 2a), which is typical for mires of continental regions in North America [21] and climatogene type mires of forest zone of Western Siberia [16-19].

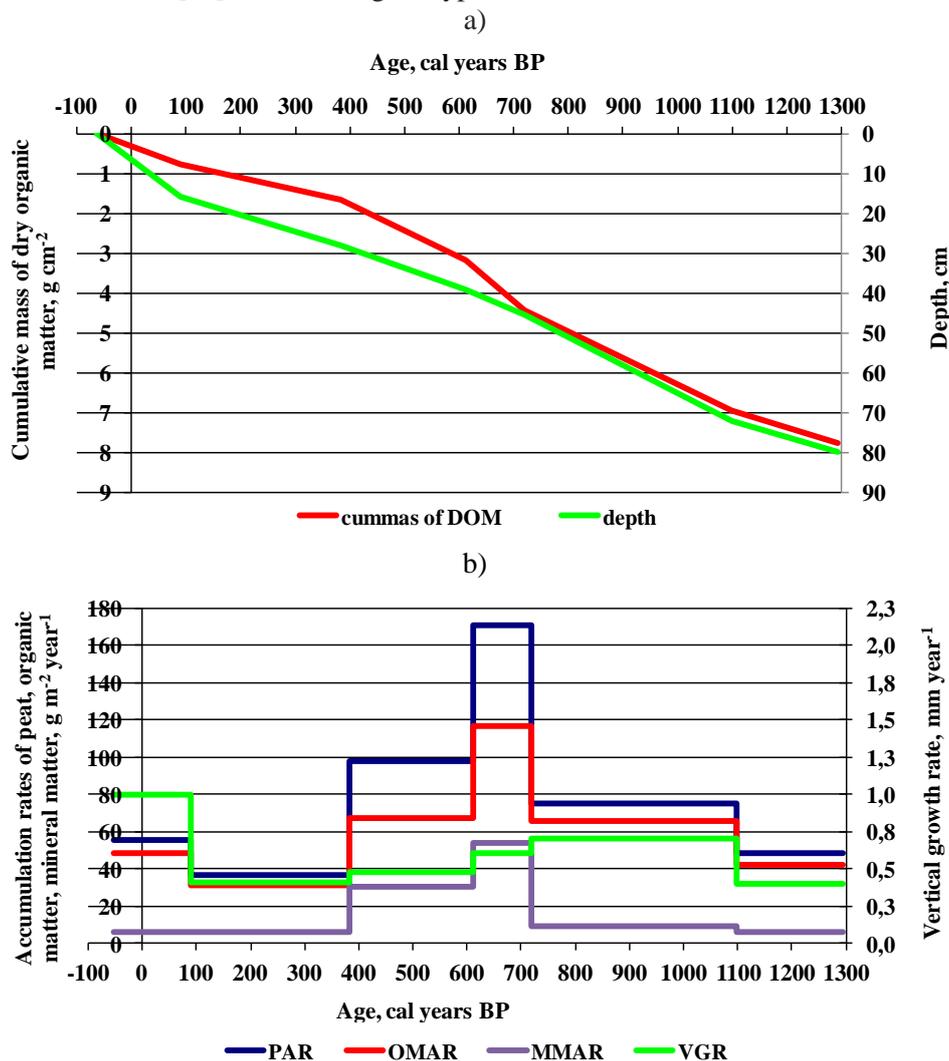


Figure 2. Relationship between: a) age and peat depth, cumulative mass of peat organic matter, b) age and vertical growth rate, peat, organic matter, mineral matter accumulation rate for the Khasyrey peat section.

This form (Figure 2a) is caused by differences of primary productivity of paleophytocoenosis, water paleoregimes and paleoconditions of water-mineral nutrition and, consequently, by differences of vertical growth rate and accumulation of peat OM in different periods of formation of khasyrey

(Figure 2b). However these models do not have a plateau due to the absence or short duration of peat accumulation interruptions.

The vertical growth rate (VGR) is $0.59 \text{ mm year}^{-1}$. In different layers it varies from 0.4 to 1.0 mm per year. The long-term accumulation rate of OM peat (OMAR) is $57.2 \text{ g}\cdot\text{m}^{-2}$ per year and varies mainly from 31.1 to $116.6 \text{ g}\cdot\text{m}^{-2}$ per year in different layers. High values of the dry peat accumulation rate (PAR) in layers are caused by high ash content of the peat. High ash content of the peat and, respectively, rate of mineral matter accumulation (OMAR) (54.2 and $30.8 \text{ g}\cdot\text{m}^{-2}$ per year) are characteristic for middle layer (26.5-45.5 cm, 719-330 cal. BP).

$\delta^{13}\text{C}$ varies in layers from -28.7 to -23.9 ‰ . One can clearly see from the Figure 3 that extremes and trends of $\delta^{13}\text{C}$ curve are consistent with extremes and trends of summer temperature curve (T summer) [3] during the period from 5 to 1135 cal. BP. The difference of ages of their Extreme does not exceed 60 years. Different ages of $\delta^{13}\text{C}$ and Tsummer extremes (1153 and 1240 cal. BP) in the bottom layer of peat deposits (Figure 3) are probably due to some rejuvenation of ^{14}C radiocarbon date.

Negative signal of $\delta^{13}\text{C}$ during the modern warming (since 1988) evidences about significant anthropogenic influence on $\delta^{13}\text{C}$ in the atmosphere. Extremes and trends of $\delta^{13}\text{C}$ curve and solar activity (SA) are consistent during period from 5 to 719 cal. BP (Figure 3). Negative signals of $\delta^{13}\text{C}$ are characteristic for the minima of Wolf, Sporer, Maunder and Dalton of the LIA [20], positive ones - for warming between these minima. The maximum positive signal of $\delta^{13}\text{C}$ (952-791 cal. BP) is due to the influence of high summer temperatures during a period of low solar activity.

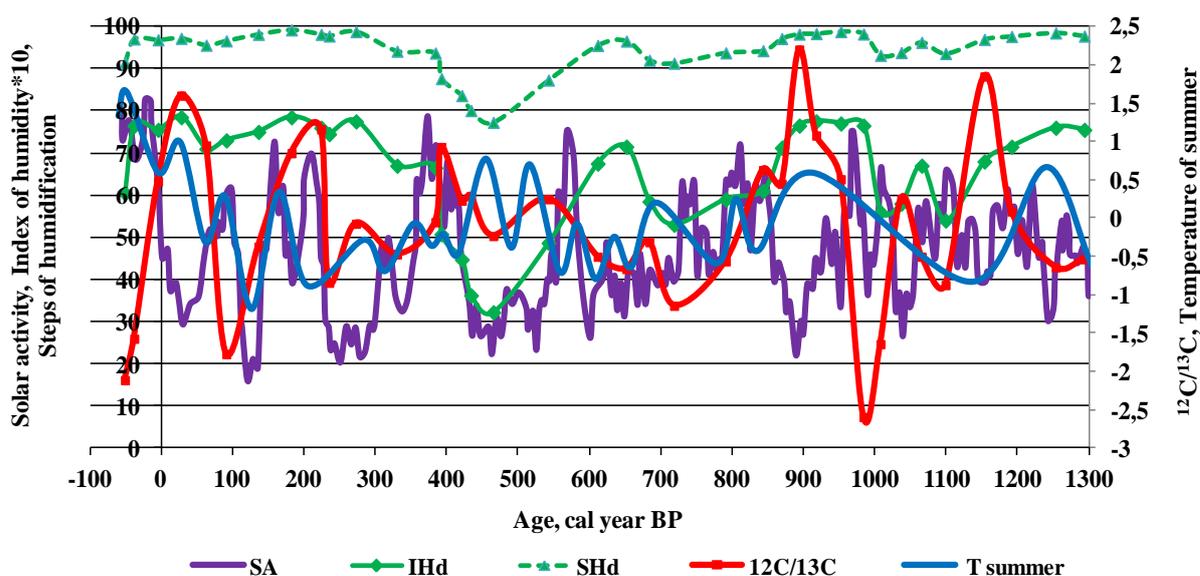


Figure 3. Paleogidrological regime dynamics and $\delta^{13}\text{C}$ in the cellulose of peat of khasyrey cutting, paleoclimatic curves of summer temperatures on the Yamal Peninsula [3] and curves of the solar activity [20] (summer temperature data are presented as the mean deviation from the windows of 100 years after smoothing, solar activity data are smoothed windows of 22 years).

Paleoclimatic curves of average annual temperature and annual precipitation for the forest zone of Western Siberia [13-15] have insufficiently high resolution and contradictory data for some time periods. This is due to the small number of radiocarbon dates and errors of peat layers ages calculation due to a lack of data on their bulk density. Therefore, we had to accept the extremes of different curves that coincided with *SHd* and *IHd* extremes to analyze the impact of climate on the khasyrey dynamics.

Main peat founders were subhydrophytic and hydrophytic grass: *Carex rotundata*, *C. rariflora*, *Eriophorum scheichzeri*, aerohydrophytic and subhydrophytic mosses: *Warnstorfia fluitans*, *Sphagnum squarrosum* and *S. majus*. Change of the water regime have impacted mainly the change of

the ratio of the abundance of these grasses and mosses, as well as on the presence of plant-mesophytes. Seven large phases of khasyrey development and fifteen stage-change with six sub-stages have been identified as a result of reconstruction of phytocenoses, water regimes and permafrost conditions of khasyrey (Figure 1). Stages and sub-stages have intraspecific (13-77 years) and rarely a century (93-140 years) scale.

I phase (1294-1099 cal. BP) - corresponds to an overgrowing of lake by floating in a seasonal freezing conditions. Lying lake sediments below likely were not in the frozen state. The phase has ended by overflow and drainage of the lake due to thermal erosion of its coast in a sharp century warming. 1 stage (from 1294 cal. BP) - greatly drowned moss community from *Sphagnum squarrosum* and *Calliergon stramineum* in conditions of the end of dry cooling. Stage 2 (from 1192 cal. BP) - the most drowned Hypnum moss community from *Warnstorfia fluitans*, which has postponed the peat with minimal *R*. The climate humidity has increased. At the end of the stage the abundance of *Carex rariflora* has increased.

II phase, 3 stage (1099-984 cal. BP) corresponds to a mean flooded sedge-cotton grass-Hypnum moss plant community. The decrease of mire water and lake level took place under conditions of dry cooling [15] and the most cold summers (according to the $\delta^{13}\text{C}$ analysis). A severe desiccation occurred at 3a and 3b substages: about 1099 (a sharp increase in *R*, *A* and presence of *Oncophorus walhenbergii*), and 1008 cal. BP (traces of fire and the presence of dwarf birch). It is likely that a well-drained conditions of khasyrey is due to the formation of low palsa. High palsa were formed in the forest zone of 1123-1010 cal. BP [17, 18]. More flooded moss community with *Warnstorfia fluitans*, *Sphagnum platyphyllum* и *Meesia triquetra* have been formed on 3b sub-stage in the conditions of increased summer temperatures (according to the $\delta^{13}\text{C}$ analysis).

III phase, 4 stage (984-843 cal. BP) corresponds to a strongly flooded *Hypnum* moss floating with *Warnstorfia fluitans*. A significant increase of water table is due to the wet warming [13-15]. At the end of stage (since 869 cal BP) - more drained sedge-moss plant community due to the lake drainage. The beginning of wet period of 997-860 cal. BP have been dated on the mires of the forest zone [16, 17, 19]. This stage corresponds to the Medieval Maximum, which have manifested differently in different regions, including ~ 1050-650 cal. BP in the Polar Urals [22] and 1100-800 cal. BP on the eastern Taimyr and Putoranah [23].

IV phase (843-434 cal. BP) corresponds to progressive draining of the lake drainage, and cryogenic processes in peat and underlying mineral deposits in a predominantly dry cooling. Succession of plants and significant increase of *R*, *P* and *A* of peat evidence it. A high ash content of peat indicates on the arrival of aeolian sand from watershed areas without vegetation in the summer, and on the diluvium with the spring melt waters. The phase is divided into 5 stages.

Fifth stage (since 843 cal. BP) corresponds to a mean flooded sedge-cotton grass-moss plant community with *Warnstorfia fluitans* и *Sphagnum squarrosum*. The decrease of water table have been strengthened by lake drainage under conditions of climate change from wet warm to the dry cold one.

Sixth stage (since 719 cal. BP) corresponds to a low flooded sedge-cotton grass plant community with *Carex rotundata*. Mosses disappear. *Betula nana*, *Ericaceae* and *Rubus chamaemorus* appear. *R*, *P* and *A* of peat increase. The climate was dry cold [13-15] with low summer temperatures (according to the $\delta^{13}\text{C}$ analysis). The freezing and the short-term formation of palsa have probably happened. The end of this phase coincides with the start of the Wolf minimum (670-610 cal. BP).

Seventh stage (since 652 cal. BP) corresponds to more flooded sedge-cotton moss community with *Drepanocladus aduncus*, *Warnstorfia fluitans* и *Sphagnum squarrosum*. An increase of water content under conditions of a short wet warming [13] and increase of summer temperature (according to the $\delta^{13}\text{C}$ analysis) took place. An increase of water content (559 cal. BP) has been also identified in middle taiga mire [16]. Perhaps it was warming between the Wolf and Sporer Minimum.

Eighth stage (since 542 cal. BP) correspond to well-drained sedge-cotton grass community with *Betula nana*, *Rubus chamaemorus* and *Polytrichum juniperinum*. Significant surface drying occurred in the conditions of cooling and climate aridity [13-15]. The formation of permafrost and frost-heave of the whole area have begun. A high flooding of preceding stage contributed to this.

Ninth stage (since 465 cal. BP) corresponds to maximum drained community with *Betula nana*, *Rubus chamaemorus*, *Polytrichum yuniperinum* и *Dicranum angustum*. Icy veins and polygonal mires were formed under conditions of cooling extremum. In the Arctic (from the Urals to the Taimyr Peninsula) 470 cal. BP period was adopted as the year of the beginning of the LIA [24]. The formation of permafrost and polygonal mire coincides with the Sporer Minimum (530-410 cal. BP), which is one of the most continuous and cold sub-periods of the LIA [25]. The growth of continental climate and high summer temperatures [3] favored the cryogenic process. However, the summer temperatures of khasyrey ecotope remained low (according to the $\delta^{13}\text{C}$ analysis) due to the presence of permafrost. 615-465 cal. BP was a period of active formation of high palsa in the mires of the forest zone [16-19].

V phase (434-330 cal. BP) correspond to a permafrost degradation, formation and overgrowth of thermokarst pool, firstly under decrease of climate continentality (summer temperatures decrease according to [3] and the $\delta^{13}\text{C}$ isotopic analysis), then - under decrease of humid warming [13-15].

Tenth stage (since 434 cal. BP) corresponds to more flooded moss community with *Rubus chamaemorus*, cottongrass, *Carex rotundata* and the soil cover of the *Sphagnum lenense* with impurity of mesophytic and hydrophytic mosses. The depth of seasonal thawing of peat deposits have increased. First the height of the polygons decreased and then thermokarst lake was formed. The sudden disappearance of *S. lenense* and high abundance of diatoms peat algae at the depth of 28.5 cm confirm this. Most likely, the filling of the khasyrey lake by water by degrading of permafrost of surrounding upland have begun at the end of this stage.

Eleventh stage (since 384 cal. BP) corresponds to less watered sedge-cotton grass community that was formed at overgrown lakes. The beginning of increase of watering and overgrown of thermokarst lakes (362-304 cal. BP) has been dated in the mires of the forest zone [18, 19].

VI phase (since 330 cal. BP) correspond to a flooding of the basin, a functioning of the lake (depth of slightly more than 2 m), a formation of strongly watered moss and *Sphagnum* moss floating mostly under conditions of humid warming and cooling [26]. At this stage, the upper limit of permafrost (to a depth of 0.5 m) has decreased. A top of the ice veins have thawed partly and flat-palsa mounds have formed on the place of landfills as a result of thermokarst and erosion. A peat accumulation in thawed state under conditions of relatively high levels of mire water and seasonal freezing have happened.

Tewlfth stage (since 330 cal. BP) corresponds to a strong flooded community of sedge-cotton grass-sphagnum moss and moss floating with *S. squarrosom* and *Warnstorfia fluitans* under conditions of a humid periods of climate: warm and then cold (Maunder Minimum, 305-235 cal. BP).

Thirteenth stage (since 224 cal. BP) corresponds to a strong flooded mesotrophic sphagnum community with *S. Squarrosom* under conditions of warm and cold humid periods of climate (Dalton Minimum, 160-115 cal. BP).

Fourteenth stage (since 91 cal. BP) corresponds to a strong flooded cotton grass-sphagnum moss plant community with *Betula nana* and oligotrophic *Sphagnum majus* mainly under conditions of directed warming later than the LIA. Probably the reduction of the seasonal thawing depth at the end of Dalton Minimum helped to the transition to a more oligotrophic stage of development.

VII phase, 15 stage (since -51 cal. BP to 2014) corresponds to a poorly flooded dwarf birch-shrub-moss plant community with *S. Majus* and impurity of mesophytic and hydromesophytic hypnum moss, under conditions of a sharp decrease of khasyrey surface humidity as result of the lake drainage.

4. Conclusions

Thus, a detailed investigation and radiocarbon dating of khasyrey peat deposits have made it possible to obtain data of the dynamics of intra century and century scale of its functional state. A sensitive response of investigated khasyrey on the climate changes of the upper Holocene has been identified. Seven large stages and fifteen stages with six sub-steps of intra century and century scale of changes of the functional state of khasyrey were revealed for 1350- year period of khasyrey formation. Paleoecotopes were most humid in 952-843 and 273- -51 cal. BP, during humid periods of warming and cooling. Paleoecotopes were maximum drained in 1099-1065 and 1037-984, 719-652, 542-434 cal. BP, during periods of the dry cooling. Khasyrey surface desiccation was occurring during periods

of wet warming due to the drainage of the lake between 1192 and 1099, 869 and 843 cal. BP, 2003 and 2008. The probability of the short-term formation of low palsa during periods of dry cooling (1099-1065, 1008-984 and 719-652 cal. BP) is high. The formation of polygonal mire was happening in the dry sub-period of the LIA in about 542-434 cal. BP. Permafrost degradation began in the humid warm sub-period of the LIA in about 434 cal. BP. Partial melting of the ice veins with formation of flat-palsa mire happened in 330 cal. BP. The optimal conditions for the formation of palsa and polygonal ice veins in khasyrey of tundra zone were created at increase of continentality of climate and summer temperatures during periods of dry cooling.

Good consistency of the dynamics of water regimes and permafrost conditions of hasyryea and mires of the forest zone of Western Siberia with the data of reconstructions of regional climate and solar activity indicates to the climate conditionality of cyclical character of khasyrey development of Western Siberia tundra. Climate influence was direct through the hydrothermal regime, and - indirect through a thaw-permafrost state of peat deposit and the level regime of the lake. It was lake drainage in Medieval Maximum, who reduced the stage of high watering khasyrey significantly.

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