

# Radiocarbon Chronology and Dynamics of Palsas in the Russian European North

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## Abstract

Palsas in frozen mires of the Russian European North (near Usa, Abez, Nikita, Eletskiy, and Khanovey settlements and the Bugry station) were studied and  $^{14}\text{C}$  dated. During the Holocene, the paleodynamics of these palsas were not similar. Some of them actively grew even during the Holocene optimum. Their current state even within the same massif can be both degradational and stable and aggradational and pulsating.

**Keywords:** European North; Holocene; palsa; stratigraphy; radiocarbon age.

## Introduction

Palsas (frost mounds of a maximum height of about 10 m with an icy core composed of peat or peat-overlying mineral deposits) are widely distributed in Northern Europe, Asia, and northern North America.

Palsas are one of the most prevalent forms of permafrost terrain. Most frequently they are found in districts with higher annual mean temperatures (about zero) in areas of continuous and sporadic permafrost, but they are also frequently found in colder continuous permafrost (Åkerman 1982, Washburn 1983, Vasil'chuk & Lakhtina 1986, Vasil'chuk & Vasil'chuk 1998, Vasil'chuk et al. 2008). They are almost always found in the northern regions where peatlands are present and are usually developed in areas with long winters and a thin snow cover.

The beginning of the formation of a palsa as a landform can be determined by radiocarbon dating of deposits formed at the time when the heave surface appeared above the water surface of the surrounding bog. The time of heave can be reliably determined by the identification of the deposits that were accumulated in the palsa stratigraphy during this initial period of heaving.

Recent studies have observed significant and relatively rapid changes in the distribution of permafrost and palsas during the second half of the 20<sup>th</sup> century and the beginning of the 21<sup>st</sup> century in Northern America and Europe. These changes showed a reduction of area occupied by palsas in arctic and subarctic peatlands, and are usually considered to have occurred in response to global climatic changes. At the same time, there are data revealing that the growth and dynamics of individual palsas are associated with local factors that influence the hydrology. These may include river channel migration, changes in lake configuration, and even the activity of beavers (Lewkowicz & Coultish 2004). There are data on the current growth of palsas and the range of expansion in both the south and the north of the cryolithozone (Vasil'chuk et al. 2008).

According to studies by Yu.K. Vasil'chuk, the mechanisms of palsa formation can be varied (Fig. 1). For some palsas, hummocks are formed in bogs during the development of vegetation. During freezing, the moisture is supplied to hummocks from all sides, and heave results. Freezing gradually penetrates deeper peat, clayey silt, and clay. During freezing, shrinkage of the ground surrounding the hummock takes place due to desiccation. On the contrary, the hummock continues to heave as a result of the supply of

additional water and moisture migration to the freezing front under conditions of negative temperatures and low long-term gradients. This leads to the formation of segregated ice schlieren. However, this is only one of the possible scenarios for palsa development. Palsa formation within depressions with high moisture content and active peat accumulation (Fig. 1a) is also very common. A combination of palsa formation mechanisms at the place of a hillock and in a depression can also be noted within a single palsa massif. Moreover, the ice content of a palsa formed in the moistened depression can be significantly higher than that of a palsa primarily formed at the hummock (Fig. 1b).

Yu.K. Vasil'chuk (1983) carried out a detailed study of the ice content and cryogenic structure of palsas in the north of West Siberia near Azovy settlement. Based on those results, he noted that the total thickness of ice lenses is often 3–4 m less than the height of a palsa above the depressions.

Moreover, a great number of cavities and hollows with a total volume of up to 20% of the surrounding permafrost volume were found in ice-rich palsa sections. Similar cavities and hollows were earlier observed by N.G. Bobov (1960) in palsas of Central Yakutia. A.P. Gorbunov's observation (1967) is very valuable as well. He noted that intensive air (and even paper sheets) suction into a borehole occurred in the process of drilling one such palsa at the Tian Shan. This unambiguously indicates the presence of cavities with vacuum.

## Radiocarbon Dating of Palsas

The authors obtained 75 new radiocarbon dates for the peat covering palsas in the Usa River basin of the Bolshezemelskaya tundra (near Usa, Abez, Nikita, Eletskiy, and Khanovey settlements and Bugry Station).

A palsa 3.2 m high (Fig. 2) near Bugry Station was selected for dating. The peat accumulation began here about 8.6 ka BP. Freezing began 2.3–2.1 ka BP, and this palsa was formed as a result.

Several palsas of various ages were studied in detail and dated near Usa settlement. A small palsa (height of 0.8 m, Fig. 2B a) was the youngest; the hypnum peat at the depth of 0.1 m is 140 years old. In the section of a palsa that is about 4 m high, the buck-bean valley peat at the depth of 0.8 m is 6.65 ka BP, and at the depth of 0.3 m the peat is 5.2 ka BP (Fig. 2B d). This palsa is the most ancient.

Radiocarbon dating of a 3-m-high palsa near Abez settlement was carried out on eight samples of peat taken

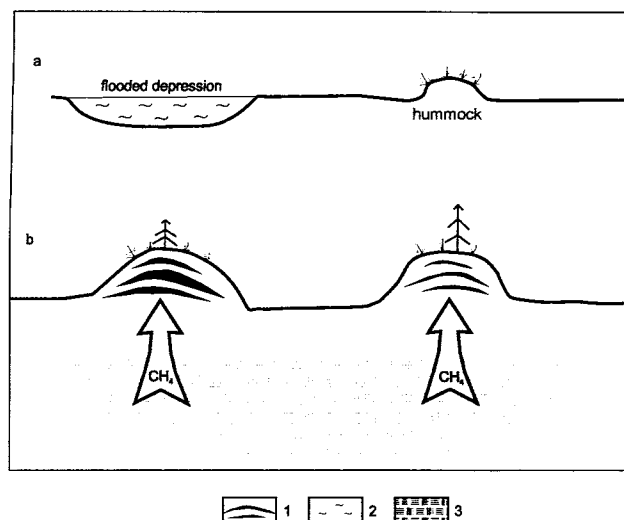


Figure 1. Scheme of palsa formation during heaving of the flooded depression and of the hummock, and further growth of palsa and their ice content with supply of methane from below that contribute to floatation of palsa. 1 – ice lenses, 2 – water, 3 – organic mass (the source of methane).

from the axial part. It showed that the accumulation of peat began there at 5.6 ka BP. The accumulation of peat ended at 2.7 ka BP, which was established by <sup>14</sup>C dating of transient moss-grass peat sampled from the depth of 0.1 m (Fig. 2C). Two similar radiocarbon dates were earlier obtained by Evseev (1976) from the base of the peat in a palsa near the same village (5.7 and 5.5 ka BP).

The transition from the peat formed 8.2–7.5 ka BP under conditions of a forest horsetail bog (within the depth interval 0.80–0.65 m) to the peat with a high content of wood remains (which probably indicates partial desiccation of the site) about 5.3 ka BP (Fig. 2D b). This is found at 0.65 m depth in the section of the 4.7-m-high palsa near Nikita settlement.

A palsa 3.5 m high (Fig. 2D c) was studied 1.5 km to the south of this settlement. Remains of a large bush and wood at the depth of 0.4–0.5 m was dated at 6.3–6.1 ka BP and indicate the subaerial conditions of peatland development.

A small 0.7-m-high palsa is composed of lowland peat (Fig. 2D a). It began to heave at 1.5 ka BP.

A 4-m-high palsa near Eletskaya settlement is covered by peat 1.15 m thick (Fig. 2E a). The wood-sedge peat from the depth of 0.3 m has an age 4.8 ka BP and represents the initiation of heaving. The second 3.5-m-high palsa is covered by peat about 1 m thick (Fig. 2E b). Massif drying as a result of heaving occurred at 7.42–7.12 ka BP.

A 2.5-m-high palsa (Fig. 2F) was dated near Khanovey settlement. Peat at the base started accumulating 8.8 ka BP. Remains of aquatic plants indicate that peat accumulation here occurred in eutrophic conditions. Peat from 0.6 and 0.5 m depths was dated at 8.5 and 7.5 ka BP, respectively. Peat in the depth range 0.3–0.1 m is much younger, between 3.75 and 3.85 ka BP. A recent date was obtained for the palsa's top.

Radiocarbon dating of three samples taken from the slope of this palsa demonstrated that the peat here is much younger than in its axial part and has an age of 2.9–2.8 ka BP. The peat thickness here does not exceed 0.25 m. Moreover, dating inversion is noted here (a date of 3.5 ka BP between 2.9 and 2.8 ka BP). This is a result of peat sliding

downward from the earlier formed palsa, or of filling of cavities formed during heaving. Younger ages from modern to 480 years were obtained for the palsa basis and for the flooded depression around it.

Radiocarbon dating allows us to state that palsa formation could occur in different Holocene periods (including the present), both in different geocryological zones and within a single massif. This is indicated by the changes in peat composition and its accumulation rate. This allowed us to reconstruct the initial events of heaving and palsa formation from different massifs (Fig. 2).

## Dynamics of Palsa Development in the Holocene

It is assumed that the Holocene optimum covering about two thirds of the first half of the Holocene was a period of general permafrost degradation and decay of most palsas. But our research showed that this is not absolutely true.

H. Seppa and colleagues (Välliranta et al. 2010, Salonen et al. 2011) studied the changes in the woody vegetation during the Holocene at palsa massifs in the Bolshezemelskaya tundra and the Pechora River basin. They assume that the expansion of the natural areas of woody vegetation (spruce, birch) occurred in this region (currently located at the treeline and outside it) during the Holocene optimum. The vegetation grew here as isolated sparse forests since the beginning of the Holocene (Välliranta et al. 2010).

During the Holocene optimum, which is defined here between 8.0 and 3.5 ka BP, the summer mean temperature in tundra was 3°C higher than present (Salonen et al. 2011). Spruce forests were growing at that time around the Khariney Lake located 150 km to the north of the modern treeline. The temperature decreased about 3.5–2.5 ka BP, which led to an active aggradation of permafrost and intensive palsa growth, as well as wood vegetation extinction. The most ancient remains of the vegetation dated about 2.5 ka (Salonen et al. 2011).

Radiocarbon dating allowed us to define the beginning of heaving and the dynamics of palsas in the Holocene in the areas near the Bugry Station and Usa, Abez, Nikita, Eletskiy, and Khanovey settlements.

Calculations show that the heave processes within the areas are caused both by general climatic changes and local factors. Peat accumulation rate, periods of heaving, and the duration of the subaerial and the subaquatic phases can be different within the same massif.

Nonetheless, the stages of the intensification and relative decrease of heave processes can be identified based on the large amount of data. Permafrost did not degrade and, on the contrary, the formation of new palsas could begin during the Holocene optimum even within the southern part of the cryolithozone. Intensive peat accumulation as a result of high summer temperatures and the same winter severity (locally more severe than present) during the Holocene optimum were the main factors in this phenomenon, which at first glance can seem to be a geocryological contradiction.

The studied palsas are described in more detail below.

### Bugry Station

It was found that at the initial stage the growth of a small palsa 0.8 m high near the Bugry station repeatedly ceased. It

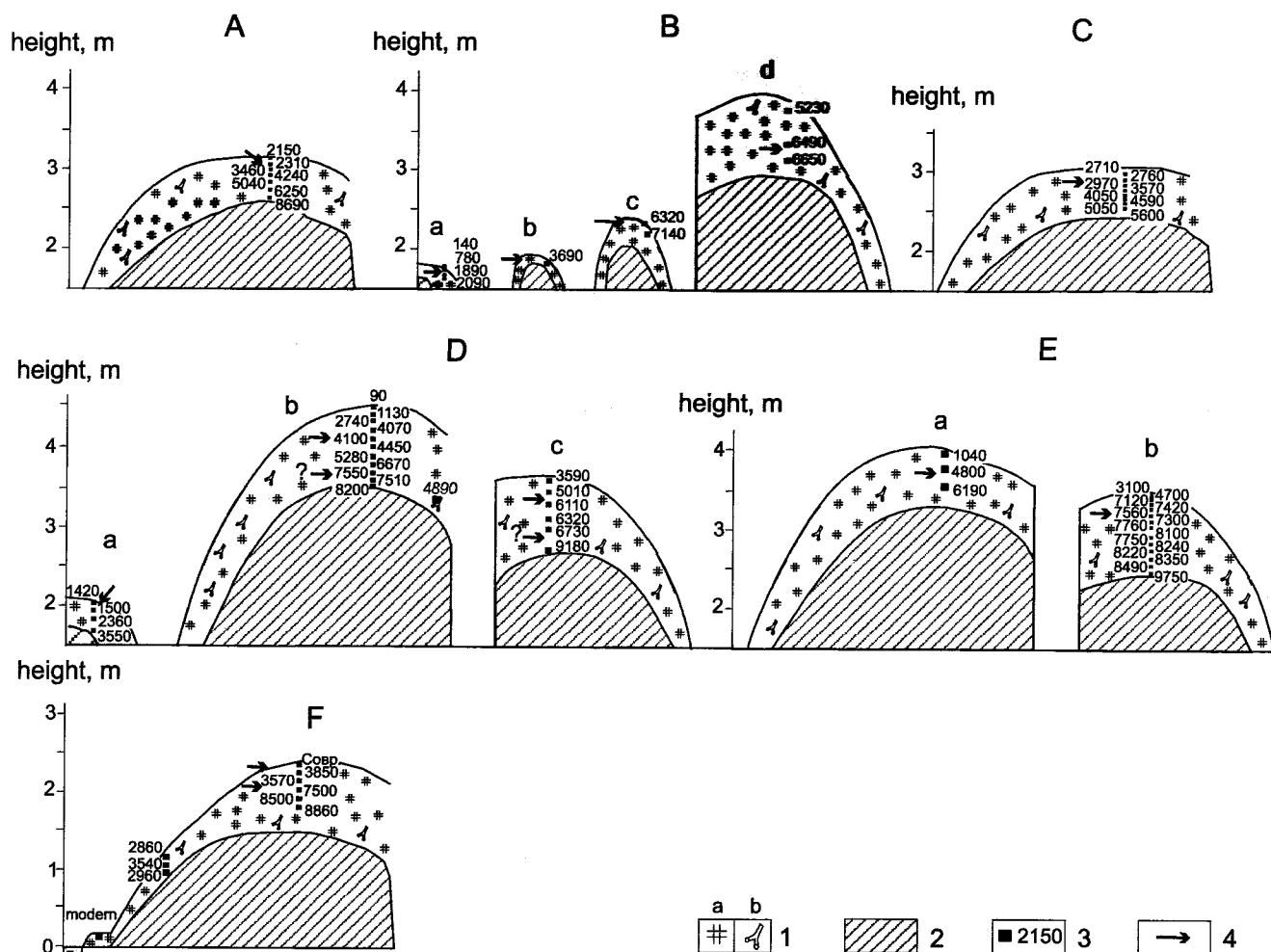


Figure 2. Radiocarbon dating of palsas in the Bolshezemel'skaya tundra (Vasil'chuk et al. 2003, 2008): A – Bugry station, B – Usa settlement, C – Abez settlement, D – Nikita settlement, E – Elets'kiy settlement, F – Khanovey settlement. 1 – peat (a) and tree branch (b), 2 – clayey silt, 3 – radiocarbon dates, 4 – heaving event.

was evidently formed during the past century, since the age of the sample from 0.1 m depth and that of the sedge-hypnum peat from the surface is approximately 140 years (Fig. 2A).

The formation of another palsa about 2 m high started not earlier than 3.7 ka BP. Since a sedge-hypnum peat bed is at the surface, it can be assumed that the heaving process was quite fast. This is associated with the fact that the high-bog peat did not have enough time to form. Since there is no lichen cover the palsa, it can be assumed that heaving occurred not long ago (within the past 100 years).

Change of sedge lowland peat 7.10 ka BP (at 0.5 m depth) to lowland buck-bean peat 6.32 ka BP is found in the section of a 2.5-m-high palsa. This indicates the activation process in the change of the water-mineral supply regime between 7.1 and 6.3 ka BP. According to radiocarbon dates and peat composition, heaving occurred here not earlier than 6 ka BP.

The formation of a palsa about 4 m high began not earlier than 6.5–6.0 ka BP. At the same time, the buck-bean lowland peat was replaced by the woody peat with residuals of pine, willow, and birch. The peat accumulation rate during the subaquatic phase was quite high at 0.06 cm/yr. According to the correlation of dates and the peat layer thickness, the transition to the subaquatic phase was completed about 5 ka BP. At that time peat accumulation and palsa growth ceased completely.

#### Usa Settlement

The heaving process near Usa settlement was most intensive after 6.5–6.0 ka BP. The palsa rose above the surface by 2–3 m. Some of the palsa formed at that time is beginning to decay. However, the active heaving process started again 3.7–2.1 ka BP and is still going on. The uplift of the younger palsa surface is 0.35–1.60 m (Fig. 3A).

#### Abez Settlement

The formation of a palsa near Abez settlement started about 2.7 ka BP. This is identified by a transition to the young (i.e., quickly freezing) transient moss and moss-grass peat with the remains of *scheuchzeria*, herbs and cowberry (Fig. 3B).

#### Nikita Settlement

The formation of a 4.7-m-high palsa near Nikita settlement started about 7.5 ka BP, according to replacement of the lowland bog peat by peat with high content of woody remains. This probably indicates partial site drying (Fig. 3C). Heaving took a long time, according to the peat accumulation rate. The transient phase was completed about 2.7 ka BP. Buck-bean (*Menyanthes trifoliata*), sedge (*Carex chordorrhiza*, *C. diandra*), and horsetail (*Equisetum*) remains are found at the depth of 0.25–0.35 m. This indicates the partial thawing and

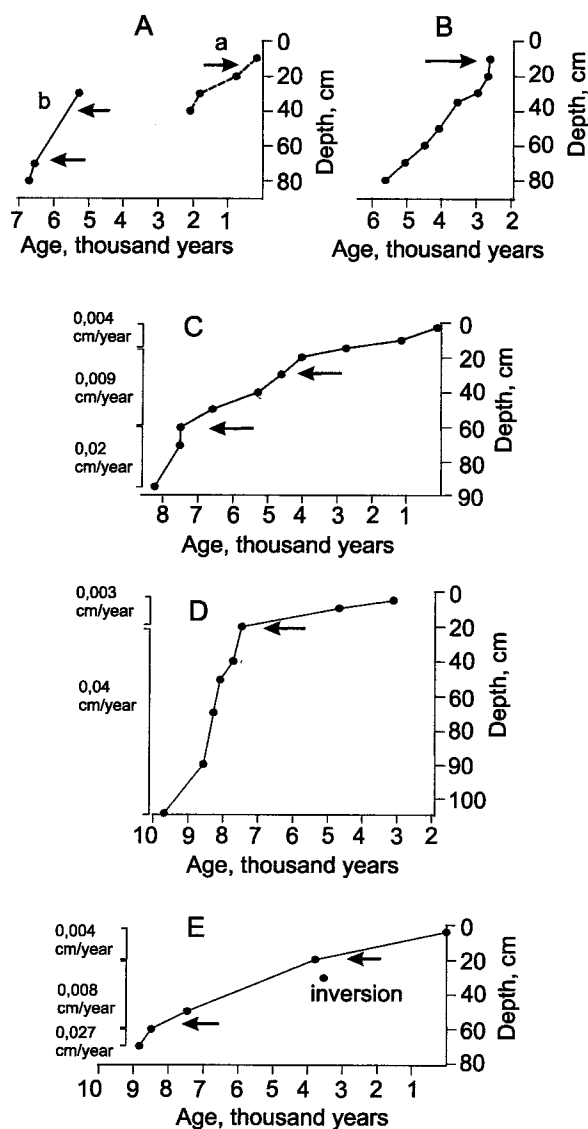


Figure 3. Assumed heave events (shown with arrows) and the rate of peat accumulation in palsas of the Bolshezemelskaya tundra: A – Usa settlement, B – Abez settlement, C – Nikita settlement, D – Eletskiy settlement, E – Khanovey settlement.

subsidence of the palsa about 4.5 ka BP. Later it recovered again and grew until reaching its current size. A 3.5-m-high palsa started forming about 6.7 ka BP. This is identified by replacement of black woody-horsetail near-bottom peat with remains of wood and large bushes.

Partial thawing of the palsa probably occurred about 5 ka BP, according to horsetail remains in the peat at the depth of 0.2–0.3 m. Then the palsa recovered again (not earlier than 3.6 ka BP). A 0.7-m-high palsa composed of peat accumulated in conditions of intensive flooding of the site began growing about 2.3 ka BP. This was defined by replacement of sedge lowland peat with sedge-hypnum peat containing buck-bean and herbs. The heave was extremely unstable; it evidently thawed and subsided repeatedly and it is most probable that only a low hillock or a hummock remained after the subsidence. Then it froze and heaved again. But after 1.5–1.4 ka BP this pulsating state was transformed to a more stable one.

### *Eletskiy Settlement*

The beginning of heaving and termination of the subaquatic phase of palsa development was identified in the section of the 4-m-high palsa near Eletskiy settlement at a depth of 0.3 m, dated at 4.8 ka BP. The next subaerial phase lasted for about 5 ka.

The formation of a 3.5-m-high palsa evidently occurred at 7.5 ka BP. The rate of peat accumulation during the subaquatic phase was 0.27 m/ka (Fig. 3D). The peat accumulation rate during the subsequent subaerial phase was 0.08 m/ka. Sedge lowland-type peat is found on the palsa top. This can indicate a partial thawing of the palsa 4.7–3.1 ka BP.

It can be assumed that the heave process near Eletskiy settlement occurred most intensively about 7.7 ka BP, when the palsa grew by 3.0–3.4 m.

### *Khanovey Settlement*

Dating of the peat from the palsa near Khanovey settlement showed a long gap in peat accumulation or a steep slowing down of the peat formation process between 7.5 and 3.5 ka BP. This testifies to the massif's freezing and the formation of a comparatively low palsa. Peat accumulation resumed for a short period about 3.5 ka BP. Since a recent date was received for the palsa top (the peat accumulation is still going on), it is evident that the palsa uplifted above the surface not long ago (Fig. 3E).

The distribution of radiocarbon dates in the palsa section (more ancient in the axial part and younger on the slope) demonstrated two important points. Firstly, this landform is properly identified as a palsa. It is not a residual that formed as a result of erosion of an initially flat peatland. The followers of the hypothesis of the erosional origin of palsa in this area agreed. It was also acknowledged by the researchers who recognized heaving as the main mechanism of palsa-like forms. They thought that in the Bolshezemelskaya tundra this process takes place in more southern areas, while the heave terrain forms that occurred in the North near Vorkuta, under the conditions of colder ground temperatures, were referred to as residual large-block forms generated as a result of erosion in frost cracks. Secondly, both the initial period of heaving 7.5 ka BP and the time of secondary additional heaving approximately 3.5–2.8 ka BP are clearly observed here. At the time of initial heaving, a small palsa several meters in diameter and probably no more than 1.0–1.5 m high was formed. At the time of secondary heaving, a palsa more than 3 m high and more than 45 m in diameter was formed from the initially small one. It covered the surrounding flooded depression where peat accumulation occurred 2.8 ka BP, but then stopped after heaving.

### *Usa River Valley*

Palsa mires in Usa River valley developed in several stages. A 3.5- to 5.0-m-high palsa was formed 7–6 ka BP. The height of the peatland surfaces at that time reached 2.25–4.00 m. Smaller palsas were formed 3.5–2.0 ka BP. Their height was 0.35 m.

## Conclusions

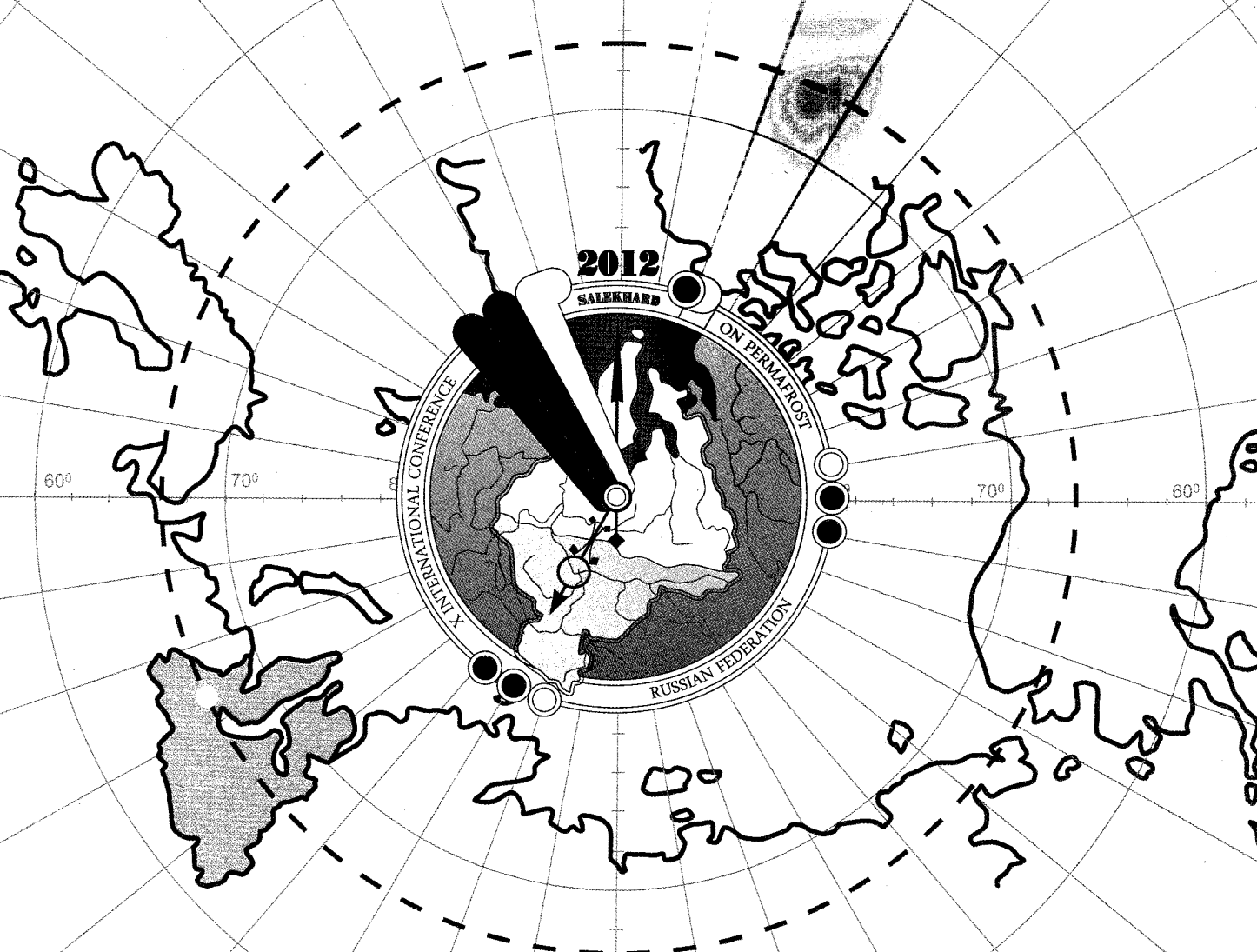
- 1) Palsas are found in the European North both in areas of continuous permafrost and in areas of discontinuous or sporadic permafrost.
- 2) The southern limit of palsa formation in the European North coincides with the southern permafrost boundary: it is approximately 67°50'N for the Kola Peninsula and southward from 66°20'N for the Bolshezemelskaya tundra. The northern limit reaches 68°10'N in the Nenets Autonomous Area and 67°30'–68°00'N in the Bolshezemelskaya tundra and extends far into the zone of cold continuous permafrost.
- 3) Permafrost did not always degrade and, on the contrary, the formation of new palsas could have begun during the Holocene optimum, even within the southern part of the cryolithozone. This occurred due to intensive peat accumulation as a result of high summer temperatures and winter severity during the Holocene optimum.
- 4) Some palsas have a cyclic development; thermokarst impacts the surface of earlier formed palsa, which leads to the abrasion and subsidence of some of them, and subsequent massif drainage is completed with the formation of a new palsa.

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