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GEOGRAPHY

Radiocarbon Age and Holocene Dynamics of Palsa in the Usa River Valley

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Palsa represent one of the most widespread forms of the permafrost relief. They are abundant in areas of discontinuous permafrost with mean annual temperatures close to zero and sufficiently common in the zone of low-temperature continuous permafrost as well.

An assessment of timing is one of the main problems in the study of palsa. It is assumed that they are relatively ancient structures (older than 4–5 ka) that are now degrading [1, 2]. The aim of this work is to establish the timing of palsa in different geocryological environments in the Usa River valley in the northeastern European part of Russia, where palsa of variable configuration, height, and age are widespread. We studied palsen at three sites (the distance between the marginal Yeletskaya and Usa settlements is more than 250 km) and obtained 49 new radiocarbon dates. The mean annual temperature of ground varies from –0.2 to –1.0°C in the Usa area and from –0.2 to –2.0°C in the Yeletskaya area.

Hummocky peat bogs are among the most suitable objects for radiocarbon dating [3, 4] due to specific features of peat accumulation: conditions favorable for the accumulation of allochthonous organic matter rarely originate during the formation of such peats. This is confirmed by our studies as well: age inversions are practically absent in radiocarbon dates of the studied palsa sections (Table 1). Datings were performed in two laboratories: the Radiocarbon laboratory of the Geological Institute (GIN), Russian Academy of Sciences (based on alkaline leachates) and the Radiocarbon laboratory of the Helsinki University (based on plant remains).

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The starting point of palsa formation as a topographical structure can most objectively be estimated by measuring the radiocarbon age of peat formed at the moment when the palsa surface (more exactly, the surface of seasonal thawed layer at the palsa top) appears above the water table of a surrounding bog). It is also necessary to recognize sediments precisely corresponding to the initial moment of palsa formation. The strategy of our study resided in detailed dating of the palsa-overlying peat and the examination of the botanical composition of peat in order to divide it into the lowmoor (eutrophic) and highmoor–transitional (oligotrophic–mesotrophic) types. It should be noted that the beginning of peat accumulation is responsible for the appearance of palsen. Therefore, the history of peat formation completely corresponds to the history of palsa formation.

Based on the botanical composition of peat, we distinguished the subaqueous (lowmoor peat) and subaerial (highmoor and mesotrophic) stages of palsa development in the Usa River valley. The subaqueous stage is the period of peat formation during inundation conditions, i.e., prior to heaving. On lowmoor bogs corresponding of this stage, background vegetation is mainly represented by sedges (*Carex aquatilis, C. rotundata, C. limosa*, and *C. rostrata*), hypnaceous mosses (*Drepanocladus* and *Calliergon*), some sphagnous mosses (*Sphagnum riparium*), horsetails (*Equisetum*), and buckbean (*Menyanthes trifoliata*). The flooded pools are populated by *Scheuchzeria palustris* and sedges (*Carex limosa, C. pauciblora*, and *C. rariflora*). The subaerial stage corresponds to the period of peat accumulation under conditions of mainly highmoor drainage; i.e., moisture was mostly provided by atmospheric precipitation. Oligotrophic environments favored the development of sphagnous mosses (*Sphagnum* sp.), cottongrass (*Eriophorum vaginatum*), cranberry (*Oxycoccus quadripetalus*), marsh tea (*Ledum palustre*), butterbur (*Andromeda polyfolia*), leather-leaf (*Chamedaphne calyculata*), and bog whortleberry (*Vaccinium uligonosum*). These plants are adapted to the gradual rise of the bog surface, because they develop auxiliary roots when submerging into peat.

Table 1. Radiocarbon dates obtained for palsen in the Usa River valley in the northeastern European cryolithozone of Russia

^{14}C age, ka	Sample no.	Field sample no.	Depth, m	Material and its decomposition degree, %	$\delta^{13}C$, ‰
Settlement of Usa					
Palsa (0.8 m high)					
140 ± 40	GIN-10976	383-YuV/2	0.1	Peat (hypnum), 5	
780 ± 40	GIN-10977	383-YuV/3	0.25	Peat (arboreal–sedge), 75	
1890 ± 80	Hel-4499	383-YuV/4	0.3–0.35	Peat (brown grass–hypnum with wood remains), 60	–28.9
2090 ± 40	GIN-10978	383-YuV/5	0.4	Peat (grass–hypnum), 50–55	
Palsa (2.0 m)					
3690 ± 50	GIN-10979	383-YuV/11	0.4	Peat (grass lowmoor), 65	
Palsa (2.5 m)					
6320 ± 40	GIN-10981	383-YuV/14	0.25	Peat (buckbean lowmoor), 55	
7140 ± 40	GIN-10980	383-YuV/13	0.5	Peat (sedge lowmoor), 85	
Palsa (4.0 m)					
5230 ± 40	GIN-10982	383-YuV/15	0.3	Peat (wood), 75	
6490 ± 110	Hel-4507	383-YuV/16	0.6–0.7	Peat (brown wood), 55	–29.5
6650 ± 50	GIN-10983	383-YuV/18	0.8	Peat (buckbean lowmoor), 60	
Settlement of Nikita					
Palsa (4.7 m)					
90 ± 70	Hel-4500	380-YuV/1	0–0.03	Peat with lichens	–28.0
1130 ± 40	GIN-10621	380-YuV/2	0.03–0.1	Peat (wood–hypnum), 80	
2740 ± 40	GIN-10622	380-YuV/3	0.1–0.15	Peat (wood), 65–70	
4070 ± 90	Hel-4501	380-YuV/4	0.15–0.2	Peat (wood), 55	–29.4
4100 ± 40	GIN-10623	380-YuV/5	0.2–0.25	Peat (wood–grass), 60	
4450 ± 40	GIN-10624	380-YuV/6	0.25–0.35	Peat (wood–grass) with birch wood remains, 70	
5280 ± 100	Hel-4502	380-YuV/7	0.35–0.45	Peat (wood), 60	–29.4
4890 ± 40	GIN-10628	380-YuV/11	0.5	Birch	
6670 ± 40	GIN-10625	380-YuV/8	0.45–0.55	Peat (wood), 65	
7550 ± 50	GIN-10626	380-YuV/9	0.55–0.65	Peat (wood–sedge), 75	
7510 ± 60	GIN-10627	380-YuV/10	0.65–0.75	Peat (equisetum lowmoor), 65–70	
8200 ± 130	Hel-4512	380-YuV/21	0.75	Peat (equisetum lowmoor) with schlieren ice, 55	–29.0
Palsa (3.5 m)					
3590 ± 90	Hel-4503	380-YuV/12	0.12–0.2	Peat (brown frutescent), 60	–28.6
5010 ± 90	Hel-4508	380-YuV/13	0.2–0.3	Peat (wood–equisetum), 45–55%	–27.9
6110 ± 110	Hel-4509	380-YuV/14	0.4	Wood	–25.5
6320 ± 90	Hel-4511	380-YuV/20	0.4–0.5	Remains of large shrubs	–25.4
6730 ± 100	Hel-4510	380-YuV/15	0.55–0.6	Peat, wood, 45–50	–29.9
9180 ± 100	Hel-4504	380-YuV/16	0.8	Peat (wood–equisetum), 40–45	–28.6
Palsa (0.7 m)					
1420 ± 120	GIN-10629	380-YuV/22	0.1–0.15	Peat (sedge–hypnum), 5–10;	
1500 ± 40	GIN-10630	380-YuV/23	0.2–0.25	Peat (sedge–hypnum), 60–65	
2360 ± 90	Hel-4513	380-YuV/24	0.3–0.35	Peat (brown sedge–hypnum), 35	–28.9
3550 ± 40	GIN-10631	380-YuV/25	0.5–0.55	Peat (sedge lowmoor), 35	

Table 1. Contd.

^{14}C age, ka	Sample no.	Field sample no.	Depth, m	Material and its decomposition degree, %	$\delta^{13}C$, ‰
Settlement of Yeletskaya Palsa (4.0 m)					
1040 ± 50	GIN-10968	382-YuV/17	0.15	Peat with frutescent remains, 20	
4800 ± 50	GIN-10969	382-YuV/18	0.3	Peat (wood–sedge), 60	
6190 ± 40	GIN-10970	382-YuV/19	0.6	Peat (sedge), 25–30	
Palsa (3.5 m)					
3100 ± 40	GIN-10971	382-YuV/1	0.05	Peat 9sedge), 80;	
4700 ± 50	GIN-10972	382-YuV/2	0.1	Peat (wood–sedge), 65	
7120 ± 100	Hel-4518	382-YuV/3	0.1–0.15	Peat (wood–grass) with branch remains, 65	–28.9
7420 ± 110	Hel-4519	382-YuV/4	0.15–0.2	Peat (wood–sphagnum), 65–70	–28.1
7560 ± 90	Hel-4520	382-YuV/5	0.2–0.25	Peat (grass–hypnum), with wood remains, 30–35	–28.4
7300 ± 40	GIN-10973	382-YuV/6	0.3	Peat (grass–hypnum), 60	
7760 ± 110	Hel-4527	382-YuV/7	0.35–0.45	Peat (hypnum), 30	–29.3
8100 ± 90	Hel-4528	382-YuV/8	0.45–0.5	Peat (wood), 30	–29.5
7750 ± 40	GIN-10974	382-YuV/9	0.6	Peat (grass lowmoor), 45	
8240 ± 90	Hel-4529	382-YuV/10	0.65–0.75	Peat (grayish brown wood), 40	–30.2
8220 ± 110	Hel-4521	382-YuV/11	0.75–0.8	Peat (grayish brown wood), 60–65%	–29.6
8350 ± 110	Hel-4505	382-YuV/12	0.8–0.82	Peat (frozen)	–27.9
8490 ± 70	GIN-10975	382-YuV/13	0.9	Peat (wood) with sand, 75%	
9750 ± 160	Hel-4506	382-YuV/14	1.15	Peat with schlieren ice	–29.3

Lichen cover (*Cladonia silvatica, Cetraria nivalis*, and *Ochrolechia tartarea*) is formed in the driest habitats [5].

The peat accumulation rate and initiation of different peat development stages were measured based on radiocarbon dates and the thickness of peat layers (Table 2). The lowmoor peat of the subaqueous stage evidently formed at the palsa base level, and the palsa level in the section indicates the value of heaving.

In Swedish Lapland, Zuidhoff and Kolstrup [6] estimated the age of palsen based on four AMS-radiocarbon dates. They consider the data obtained for plant remains from the uppermost interlayer of the hydrophilous peat layer (remains of sphagnous moss and cottongrass) as the starting point of palsa formation, i.e., the transition of the palsa from the subaqueous stage to the subaerial one. Most palsen started growing here in the period of 1520 to 1730 yr B.P. This is evident from the following dates: 390 ± 70 (Sample Ua-13229); 95 ± 65 (Ua-13228); and 105 ± 65 yr (Ua-13230). However, oligotrophic peat found in one palsa contains *Sphagnum* dated at 8150 ± 85 yr B.P. (Ua-13227), indicating that the palsa is older than 8 ka B.P.

Palsen near the settlement of Usa. This lacustrine bog area hosts high (up to 4 m) and low (less than 1 m) palsen. A larch–birch open woodland is developed along its periphery. Two palsen more than 1 m high (with two birches growing on the slope of one palsa) are observed in the central part of the lacustrine bog depression.

In the 0.4-m-thick peat section overlying the relatively young (not more than 2000 yr B.P.) 0.8-m-high palsa, the grass-hypnum lowmoor peat occurring in the depth interval of 0.35–0.4 m is dated back to 2090 ± 40 yr B.P. (GIN-10978) and can be referred to the subaqueous stage. The botanical composition of the peat suggests its formation in subaqeous environments, which is evident from the occurrence of buckbean, sedge, and hypnaceous moss remains. However, the presence of frutescent and birch wood remains suggests that the heaving probably initiated at the beginning of the accumulation of this peat interlayer. Taking into consideration the ephemeral nature of migratory palsen, we can assumed that the formation of the abovementioned palsa was repeatedly interrupted at the initial stage and that its modern shape started to form only during the last century.

The second palsa, about 2 m high and 5 × 13 m in size (Fig. 1a), is located a few meters north of the previous one. At a depth of 0.4 m, it includes a lowmoor grass peat layer with fine-grained sand. The peat includes the remains of birch (*Betula* bark 5%), cottongrass (*Eriophorum*), horsetail (*Equisetum* 10%), sedge (*Carex rostrata* 10%), buckbean (*Menyanthes trifoliata* 50%), grasses, and hypnaceous mosses. It is dated at 3690 ± 50 yr B.P. (GIN-10979), which most likely corresponds to the subaqueous stage. The insufficiently

Table 2. Peat deposit morphology and chronology of palsa evolution in the Usa River valley

Palsa height (above the water table), m	Age of peat deposit, ka (thickness, m)	Age of transition from the subaqueous stage of peat accumulation to the subaerial one, ka (depth, m)	Peat accumulation rate, m/ka	
			subaqueous stage	subaerial stage
Settlement of Usa				
0.8 (0.45)	0.14–2.09 (0.4)	0.1 (0.1)	0.25	<0.1
2 (1.6)	3.7 (0.4)	after 3.7(?)	–	<0.1
2.5 (2.25)	6.3–7.1 (0.5)	after 6.3	0.29	0.04
4 (3.2)	5.2–6.6 (0.8)	6.6 (0.8)	0.6	0.10
Settlement of Nikita				
4.7 (4.0)	0.09–8.2 (0.75)	7.5 (0.65)	0.15	0.08
3.5 (2.7)	3.6–9.2 (0.8)	6.7 (0.6)	0.12	0.05
0.7 (0.35)	1.4–3.5 (0.55)	after 1.4 (0.35)	0.16	<0.1
Settlement of Yeletskaya				
4 (3.4)	1.0–6.2 (0.6)	4.8 (0.3)	0.21	0.06
3.5 (3.0)	9.7–3.1 (1.15)	7.56 (0.25)	0.27	0.08

detailed sampling does not allow a reliable determination of the subaqueous–subaerial transition stage. Nevertheless one can undoubtedly state that the palsa heaving took place not earlier than 3700 yr B.P.

The third palsa, 2.5 m high and 8 × 8 m in size (Fig. 1a), is located 30–40 m northeast of the second mound. Here, sedge peat, which is composed of *Menyanthes trifoliata, Carex chordarrhiza, C. caespitosa,* and hypnaceous moss *Polytrichum strictum*, is replaced upsection by the peat largely consisting of buckbean *Menyanthes, trifoliata*, *Carex chordarrhiza*, and *Equisetum.* Although both these peat interlayers are referred to the lowmoor type, the replacement of the sedge peat by the buckbean variety indicates the beginning of a change in the water and mineral supply regime during the 7.1–6.3 ka B.P. interval. The frosting and heaving took place here not earlier that 6 ka B.P.

The fourth palsa, about 4 m high and 7 × 8 m in size (Fig. 1a), is located 100 m east of the third one. The subaqueous–subaerial transition stage can be distinguished here at a depth of 0.8 m. This event is marked by the replacement of preponderant *Equisetum* and *Menyanthes trifoliata* remains by the wood remains of birch and frutescent forms (*Vaccinium*) that are typical of oligotrophic environments and estimated at 6.65 ka B.P. (Table 1). The palsa surface commenced to heave in the 6.5–6.0 ka B.P. period. The buckbean lowmoor peat gave way to wood remains, including pine, willow, and birch. The peat accumulation rate was significantly high (0.6 m/ka) during the subaqueous stage and equal to 0.1 m/ka at the subaerial stage.

It seems that the heaving process in the area of the settlement of Usa was particularly intense after 6.5–6.0 ka B.P. and the palsen grew up to 2–3 m high. Some older palsen began to disintegrate by that time. The heaving process reactivated in the period of 3.7–2.1 ka B.P. and continues up to the present day to form younger palsen 0.35–1.6 m high.

Palsen in the area of the Settlement of Nikita. This area hosts both large (up to 5 and even 8 m high) and small (up to 1.5–2.0 m high) palsen (Fig. 1b)

We scrutinized a 4.7-m-high palsa located 0.3 km north of the Nikita railway station. This palsa is overlain by a 0.8-m-thick peat layer. The lower interlayer (interval 0.8–0.65 m) was formed in an bog and is dated at 8.2–7.5 ka B.P. It was replaced upsection by the interlayer with a high content of wood remains, probably indicating a partial draining of the area owing to the beginning of heaving at about 7.5 ka B.P. At the beginning of this process, the palsa surface was populated, along with arboreal forms, by sedges *Carex caespitosa, C. chordorrhiza, C. diandra*, and horsetails, which occur here in interpalsa depressions resembling eutrophic swamps. Hence the subaerial stage lasting about 7.5 ka was marked by the accumulation of 0.65 m of mainly wood peat. It seems that the palsa growth rate during the initial phase was sufficiently high and could reach the value of approximately 4 m/ka. Subsequently, it decreased to about 0.08 m/ka. The peat located at a depth of 0.25–0.35 m contains the remains of buckbean *Menyanthes trifoliata*, sedges (*Carex chordorrhiza* and *C. diandra*), and horsetail *Equisetum*, which is evidence of the partial thawing and subsidence of the palsa at about 4.5 ka B.P. Later, the palsa began to grow again and rose up to the modern size. It can be considered as a stable palsa that ceased to grow but did not begin to disintegrate, which is confirmed by the development of the lichen cover on its surface.

The second palsa 3.5 m high is 1.5 km south of the Nikita station. The exposed section contains a 1.0-m-thick peat layer. Its botanical composition suggests that the palsa surface was previously covered by arboreal

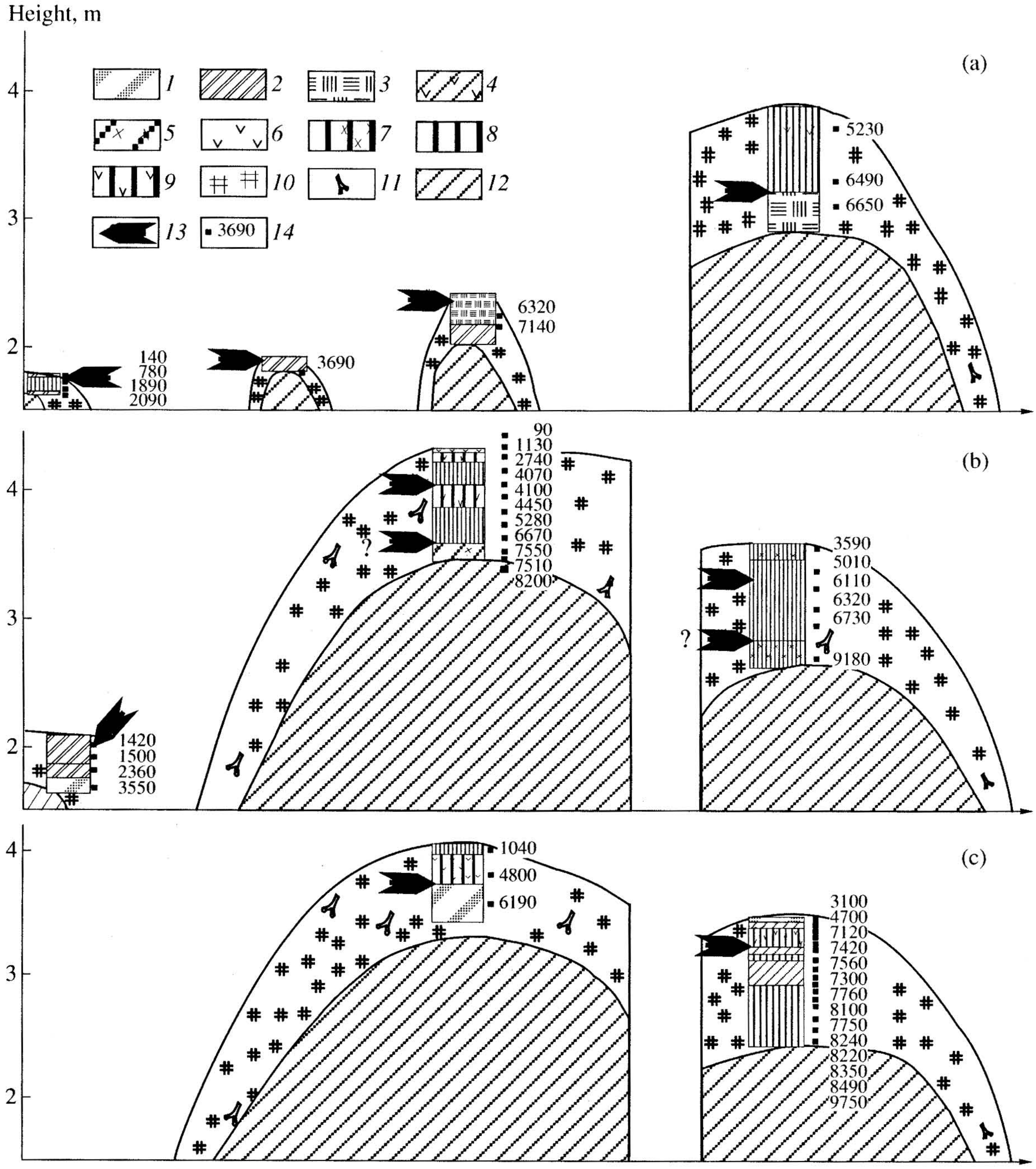

Fig. 1. Sections of palsen near the settlements of (a) Usa, (b) Nikita, and (c) Yeletskaya. (*1*) Peat (sedge lowmoor); (*2*) peat (sedge–hypnum); (*3*) peat (buckbean lowmoor); (*4*) peat (grass lowmoor); (*5*) peat (equisetum lowmoor); (*6*) peat (highmoor); (*7*) peat (wood–equisetum; (*8*) peat (wood); (*9*) peat (grass–wood); (*10*) peat; (*11*) wood remains; (*12*) loam; (*13*) assumed starting point of heaving; (*14*) radiocarbon dates (yr).

vegetation and then flooded. Therefore, we refer the black near-bottom wood-equisetum peat with *Betula* remains to the flooding (subaqueous) stage. This stage (9.2–6.7 ka B.P.) is marked by the accumulation of lowmoor peat and the disappearance of arboreal vegetation due to swamping of this previously dry area. A 0.2-m-thick peat layer accumulated during this period. The subaqueous peat accumulation rate was about 0.1m/ka. The palsa was formed 6.7 ka B.P. The peat accumulation rate was 0.05 m/ka during the subaerial stage marked by arboreal forms. Judging from the occurrence of horsetail remains in the peat at the depth of 0.2–0.3 m, the palsa was partially thawed approximately 5 ka B.P. and then restored.

The third small palsa (0.7 m high) is located 100 m north of the previous mound. Based on the study of its botanical composition, one can recognize a peat layer that corresponds to the stage of the palsa surface oscillation above the bog during the replacement of the lowmoor sedge peat by the sedge-hypnum variety including buckbean and gramineous forms. This transition is noted in the depth interval of 0.55–0.35 m and dated at 2.36–3.35 ka B.P. (Table 1). Practically the entire peat layer of the palsa accumulated under conditions of enhanced flooding, which is evidenced from the botanical composition of peat (*Equisetum, Menyanthes trifoliata, Carex limosa, C. caespitosa, C. diandra, C. chordorrhiza, C. vesicaria, Calliergon*, and *Drepanocladus*). This means that this palsa was also quite unstable after 2.3 ka B.P. It probably thawed and subsided several times to turn into a low rise or a hummock and then to heave again. This pulsating mode gave way to a more stable one after 1.5–1.4 ka B.P.

Palsen located near the settlement of Nikita differ in are age. A transition from the lowmoor peat to the subaerial stage variety and, consequently, heaving of the palsen occurred during 7.5–6.7 and 3.3–1.4 ka B.P. The palsa surface rose by 4–2.7 m as a result of heaving that commenced 7.5–6.7 ka B.P. Later, this process stabilized and palsen grew slowly. The slow heaving of young palsen, which commenced 3.3–1.4 ka B.P. and is continuing now, resulted in the rise of their surface by about 0.35–0.7 m.

Palsen in the area of the settlement of Yeletskaya. The hummocky peatbog is located 1.5 km northeast of the settlement of Yeletskaya. Several palsen were examined in detail in this area.

The first palsa 4 m high and 6 × 7 m in size is overlain by 1.15-m-thick peat (Fig. 1c). The heaving commencement and subaqueous stage termination are observed at a depth of 0.3 m. This level is dated at 4.8 ka B.P. The subsequent subaeral stage lasted less than 5 ka, and peat with *Vaccinium* sp., *Chamaedaphne calyculata*, and *Carex vesicaria* accumulated at an average rate of 0.06 m/ka.

The botanical composition of 0.9-m-thick peat overlying the second palsa (3.5 m) indicates that its surface was initially covered by arboreal vegetation (*Betula*) and then was flooded, which is evident from the occurrence of *Equisetum* remains. In the 0.25–1.15-m depth interval, we distinguished a subaqueous stage peat that marks the development of a lowmoor bog. As a result of subaqueous development, arboreal vegetation was replaced by the lowmoor herbaceous variety (*Menyanthes trifoliata, Carex diandra*, and *C. chordorrhiza*). This stage is dated at 9.7 to 7.56 ka B.P. Formation of the palsa started at probably 7.5 ka B.P., and the peat accumulation rate averaged 0.08 m/ka. The palsa summit also includes a lowmoor sedge peat, which probably indicates a partial thawing at about 4.7–3.1 ka B.P. It can be assumed that the heaving near the settlement of Yeletskaya was most intense during 7.7–6.2 ka B.P., which resulted in the rise of palsa tops by 3.0–3.4 m above the bog surface.

In general, the beginning of heaving process in the Usa River Valley could be most intense in the period from 7.5 to 6.2 ka B.P. Subsequently, some palsen experienced partial thawing, whereas others continued slowly growing or remained stable. Substantial activation of the heaving occurred 3.7–1.4 ka B.P. and resulted in the intense formation of younger palsen that continue to grow until now. At present, new palsen are growing in some draining areas.

It seems that the heaving is controlled by both general climatic changes and local factors, because the peat accumulation rate, commencement of the heaving process, and duration of subaqueous and subaerial stages may differ even within a single palsa, although a great body of data allows us to distinguish periods of intense heaving and attenuation of this process. The surficial thermokarst-related reorganization of mature palsen results in abrasion and subsidence of some of them, whereas their draining is followed by the formation of new palsen.

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