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GENESIS AND GEOGRAPHY OF SOILS

The Rate of Peat Accumulation in the Holocene in Kamchatka

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Abstract—The most favorable conditions for peat accumulation in Kamchatka existed during the Atlantic climatic optimum of the Holocene (5000–6000 yrs ago) and in the Boreal period (8000–9000 yrs ago). Less favorable conditions were in the Subboreal period. The growth of peat substrates in Kamchatka in the modern period is estimated at 1.1–1.5 mm/yr. During the earlier stage of the Subatlantic period (except for the last century), it comprised 0.1–0.3 mm/yr. The rate of peat growth in the Subboreal period varied within 0.03–0.08 mm/yr. During the Atlantic optimum, it increased up to 0.08–0.5 mm/yr. During the earlier stage of the Atlantic period, it comprised 0.06–0.2 mm/yr and, during the Boreal period, 0.1–0.6 mm/yr. The most significant variations in the rate of the peat accumulation in Kamchatka are related to changes in the climatic conditions of the peninsula from its western coast to its eastern coast.

Keywords: Kamchatka, volcanic ash, rate of peat accumulation

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INTRODUCTION

Kamchatka is one of the regions of Russia with considerable peat deposits. Peat is a renewable source of energy, and it is interesting to know the rates of its accumulation. However, there are no published data on the rates of peat accumulation in Kamchatka.

At the same time, Kamchatka offers an excellent possibility to study the rates of peat accumulation on the basis of dated layers of volcanic ashes found at certain depths in the peat deposits. These ash layers originated during large and catastrophic volcanic eruptions in the Holocene.

Thus, studying the morphology of peat soils in different climatic regions of Kamchatka and the depths of dated ash layers in these soils [1, 12], we can estimate the rates of peat accumulation in different parts of Kamchatka during the Holocene.

OBJECTS AND METHODS

The velocity of the linear (upward) growth of peat largely depends on the climatic conditions. The relationships between the heat and water balances specify the biological productivity of peat-forming plants and, hence, the rate of peat accumulation. The intensity of the peat accumulation also depends on the position of a given mire in the landscape, on the character of its catchment, and on some other external and internal factors specifying the sedimentation conditions. The horizonation of peat soils and the thickness of their particular horizons are indicative of changes in the climatic conditions during the postglacial period.

According to special investigations [2, 3, 11, 13–15, 17], the beginning of the Subatlantic warming of the climate in Kamchatka dates back to 2200–2300 yrs ago. The Subboreal cooling of the climate in Kamchatka, as well as in the northeast of Russia and in Japan, began about 4500 yrs ago. The Atlantic warming of the climate in Kamchatka took place 6700 yrs ago. The warmest conditions were observed in the middle and at the end of the Atlantic period with a peak about 4800–5000 yrs ago. Five to six thousand years ago, the July air temperatures in Kamchatka were 3–4°C higher than those at present.

The Boreal period was generally cold. However, its beginning was marked by warming of the climate with a peak about 9300 yrs ago.

The rate of the peat accumulation was studied along a latitudinal transect from the western coast of southern Kamchatka (Ust-Bol'sheretsk) to its eastern coast (Petropavlovsk-Kamchatskii), i.e., from the moderately continental climate on the coast of the Sea of Okhotsk to the continental climate in central Kamchatka and to the humid and relatively mild climate on the Pacific coast of the peninsula. The rates of the Holocene growth of the peat were also examined in other areas, including the middle reaches of the rivers flowing to the western coast in central Kamchatka, in the northeast of the peninsula in the lower reaches of the Kamchatka River and in the upper reaches of the Levaya Ozernaya River to the north of the settlement of Klyuchi, and in the extreme northwest of the peninsula (Cape Utkholok) with the transitional (from mar-

itime to continental) type of climate typical of northern Kamchatka (Fig. 1).

Volcanologists have accumulated extensive data on the tephra chronology of Kamchatka (tephra denotes volcanic ashes transported by air) with determination of the absolute dates of the tephra horizons in the soils of Kamchatka and the areas occupied by these layers. The most distinct layers are related to definite catastrophic volcanic eruptions in the Holocene [1, 12].

The rates of the peat growth were judged from the thickness of the peat layers between the dated layers of tephra. In this paper, data on the oligotrophic peat soils are discussed. Such soils predominate among the peat soils of Kamchatka [6, 10].

RESULTS AND DISCUSSION

In all the pits where we could estimate the rate of the linear growth of the peat in the past century (i.e., in pits 520, K17-20, 546, 538, 1105, 8901, and 7 containing the layers of tephra from the recent eruptions of the Ksudach (1907), Avacha (1926), and Shiveluch (1964) volcanoes), the velocity of the peat accumulation was the highest for the Late Holocene and varied from 0.67 to 1.54 mm/yr (Table 1).

Along the latitudinal profile, higher rates of peat accumulation in the recent century are typical of the southwestern and western coastal regions (from 1.06 to 1.54 mm/yr). To the east (in the area of the Nachikino Crossing) and further to the southeastern coast of the peninsula, the rates of peat accumulation in the recent century have been somewhat lower (0.67 to 0.77 mm/yr). This may be explained by the differences in the climatic conditions: wet and relatively warm along the southeastern coast, moderately continental in the central part, and excessively wet (with the coefficient of moistening of 2.5) in western Kamchatka.

In the extreme northeast of the peninsula (pit 7), the recent growth rate of the peat is close to that in southeastern Kamchatka and reaches 0.85 mm/yr.

The peat horizons developed during the entire Subatlantic period (without the recent century) are relatively thick; the rate of the peat accumulation in them varies from 0.03 to 0.37 mm/yr (Table 2).

The interpretation of the data on the thickness of the underlying ancient peat horizons subjected to compaction and partial mineralization after their burying under younger peat layers has its own specificity. It is not quite correct to interpret these data in terms of the rate of the linear growth of the peat deposits because of the probable effect of the compaction and mineralization of the peat [4, 9, 16]. However, we can compare the thicknesses of these horizons in different parts of the peninsula.

As shown above, for the surface peat horizons developed in the recent century of the Subatlantic period, the rates of peat accumulation vary from 0.67 to 1.54 mm/yr. For the previous period of the Subatlantic period, they comprise 0.03 to 0.37 mm/yr.

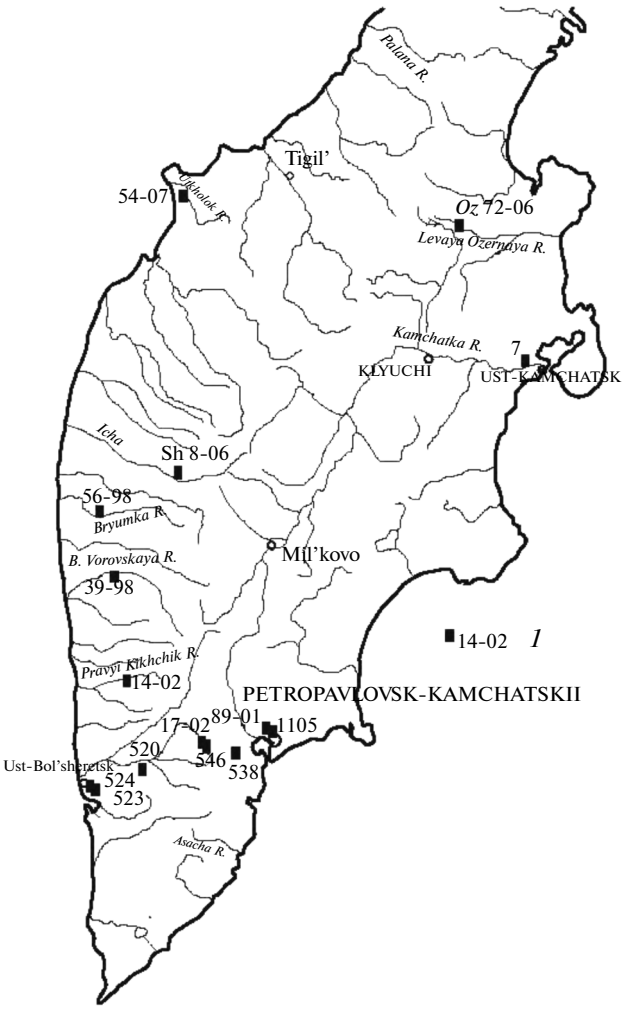

Fig. 1. Schematic map of the studied sites; (*1*) numbers of soil pits.

The averaged data on the thickness of the earlier accumulated peat horizons described in different parts of Kamchatka from the Sea of Okhotsk to the Pacific coast indicate that the lowest rates of the peat accumulation were typical of the cold Subboreal period (0.03 to 0.8 mm/yr); thicker peat layers were formed during the Atlantic period (0.06–0.23 mm/yr) and, especially, during the Atlantic climatic optimum (0.08–0.50 mm/yr).

However, this general regularity is not confirmed for the mires of the eastern coast of Kamchatka (near Petropavlovsk-Kamchatskii), where the variations in the thickness of the peat layers formed in different periods of the Holocene are relatively small; the calculated rates of peat growth vary from 0.12 mm/yr for the Subboreal period to 0.08–0.09 mm/yr for the Atlantic period.

Table 1. The rates of growth of peat layers formed in the periods between strong eruptions of Kamchatka volcanoes in the Holocene

Eruption center, tephra index	Depth of the tephra layer, cm	Approximate age of the tephra, yrs	Time of the peat accumulation between the eruptions	Thickness of the peat layer, cm	Average growth of the peat, mm/yr	Period of the Holocene
SOUTHERN KAMCHATKA						
Ust-Bol'sheretsk, pit 524						
Opala, OP	52*	1410	1410	52	0.37	SA
Khodutkinskii Maar, KhD	69	2670	1260	17	0.13	
Avacha, AV_{2800}	71–72	3008	338	2	0.06	SB
Ksudach, KS_2	144	6890	3882	72	0.19	SB–ATO
Kuril'skoe Ozero, KO	153	8466	1576	9	0.06	AT
Bystraya R., pit 523						
Opala, OP	46–47	1410	1410	46	0.33	SA
Khodutkinskii Maar, KhD	80–81	2670	1260	34	0.27	
Apacha settlement, pit 520						
Ksudach, $KSHt_3$	11	104	104	11	1.06	SSA
Opala, OP	53–55	1410	1410	42	0.30	SA
Ksudach, KS_1	65–66	1774	364	10	0.27	
Khodutkinskii Maar, KhD	92	2670	896	26	0.29	
Avacha, AV_{2800}	93–96	3008	338	1	0.03	SB
Ksudach, KS_2	171–175	6890	3882	75	0.19	SB–ATO
Kuril'skoe Ozero, KO	194–197	8466	1576	19	0.12	AT
Not identified*	212–213	9796	1330	15	0.11	BO
Lake Nachikinskoe, Pit K17-02						
Ksudach, $KSHt_3$	13–15	104	104	13	1.25	SSA
Opala, OP	30–41	1410	1306	15	0.11	SA
Ksudach, KS_1	44–53	1774	364	3	0.08	
Krater Chasha, OPtr	80–81	5450	3676	27	0.07	SB
Avacha, AV_{5300}	87–89	6050	600	6	0.10	ATO
Ksudach, KS_2	119–129	6890	840	30	0.36	AT
Kuril'skoe Ozero, KO	170–174	8466	1576	41	0.26	
Lake Nachikinskoe, pit 546						
Ksudach, $KSHt_3$	16–17	104	104	16	1.54	SSA
Opala, OP	56–66	1410	1306	39	0.30	SA
Ksudach, KS_1	74–84	1774	364	8	0.22	
Avacha, AV_{2800}	95–98	3008	1234	11	0.10	SB
Krater Chasha, OPtr	118–120	5450	2442	20	0.08	
Avacha, AV_{5300}	126–127	6050	600	6	0.10	ATO
Ksudach, KS_2	147–152	6890	840	20	0.24	AT
Kuril'skoe Ozero, KO	161–162	8466	1576	9	0.06	
Not Identified	220–222	9796	1330	58	0.44	BO
Nachikino Crossing, pit 538						
Ksudach, $KSHt_3$	8	104	104	8	0.77	SSA
Opala, OP	12–17	1410	1306	4	0.03	SA
Ksudach, KS_1	22–30	1774	364	5	0.14	
Avacha, AV_{2800}	36–39	3008	1234	5	0.04	SB
Krater Chasha, OPtr	69–70	5450	2442	6	0.02	SB
Avacha, AV_{5300}	83–85	6050	600	30	0.50	ATO
Ksudach, KS_2	102–110	6890	840	17	0.20	AT
Kuril'skoe Ozero, KO	138–140	8466	1576	28	0.18	
Not identified	220–222	9796	1330	80	0.60	BO
Petropavlovsk-Kamchatsksii, pit 1105						
Ksudach, $KSHt_3$	8–9	104	104	8	0.77	SSA
Avacha, AV_{1827}	10	184	80	1	0.12	SA
Opala, OP	19–20	1410	1226	9	0.07	
Ksudach, KS_1	25–29	1774	364	5	0.14	
Avacha, AV_{2500}	48–49	2775	1001	19	0.19	

Table 1. (Contd.)

Eruption center, tephra index	Depth of the tephra layer, cm	Approximate age of the tephra, yrs	Time of the peat accumulation between the eruptions	Thickness of the peat layer, cm	Average growth of the peat, mm/yr	Period of the Holocene
Petropavlovsk-Kamchatskii, pit 8901						
Ksudach, $KSHt_3$	7–8	104	104	7	0.67	SSA
Opala, OP	18–19	1410	1306	10	0.08	SA
Avacha, AV_{1600}	21–23	2434	177	2	0.11	
Ksudach, KS_1	26–29	1774	187	3	0.16	
Avacha, AV_{2500}	38–40	2775	1001	9	0.09	
Avacha, AV_{3300}	52–54	3534	759	12	0.16	SB
Avacha, AV_{3500}	57–58	4000	466	3	0.06	
Krater Chasha, OPtr	77	5450	1450	19	0.13	
Avacha, AV_{5300}	82–83	6050	600	5	0.08	ATO
Ksudach, KS_2	92–97	6890	840	9	0.11	AT
Kuril'skoe Ozero, KO	110–112	8466	1576	13	0.08	
WESTERN COAST OF KAMCHATKA						
Middle reaches of the Pravyi Kikhchik R., pit K14-02						
Ksudach, KS_2	107–109	6890	6890	107	0.16	SA– AT
Kuril'skoe Ozero, KO	137–142	8466	1576	28	0.18	AT
Middle reaches of the B. Vorovskaya R., pit 39-98						
Ksudach, KS_2	96–99	6890	6890	96	0.14	SA– AT
Middle reaches of the Bryumka R., pit 56-98						
Ksudach, KS_2	124–129	6890	6890	124	0.18	SA– AT
Middle reaches of the Icha R., pit Sh 8-06						
Khangar, KhG	161–166	7700	7700	161	0.21	SA– AT
NORTHERN KAMCHATKA						
Upper reaches of the Levaya Ozernaya R., pit Oz 72-06						
Shiveluch, SH_1	14–19	350	350	14	0.40	SA
Shiveluch, SH_2	32–33	970	620	13	0.21	
Shiveluch, SH_3	37–38	1400	430	5	0.12	
Shiveluch, SH_4	55–57	2600	1200	17	0.14	
Northeastern coast of Kamchatka						
Lower reaches of the Kamchatka R., pit 7						
Shiveluch, SH_{1964}	4	47	47	4	0.85	SSA
Shiveluch, SH_1	16–18	970	923	10	0.11	SA
Shiveluch, SH_2	28–32	1400	620	12	0.19	
Ksudach, KS_1	44–52	1774	804	12	0.15	
Northwestern coast of Kamchatka						
Cape Utkholok, pit 54-07						
Shiveluch, SH_2	80–82	970	970	80	0.82	SA

* Peat layer for which the age is established, but the source (the particular volcano) is not determined.

SSA, SA, SB, ATO, AT, and BO are the modern Subatlantic, Subatlantic, Subboreal, Atlantic optimum (temperature maximum), Atlantic, and Boreal periods of the Holocene, respectively. The data on pits 524, 523, 520, 546, 538, 1105, and 8901 are given according to [1]; the data on pit 7 are given according to [8].

It is known that the eastern coast of Kamchatka has the least contrasting temperature and moisture conditions because of the great impact of the Pacific Ocean on the local climate. It is probable that the temperature fluctuations in the Holocene in this part of Kamchatka were relatively low because of the smoothing influence of the Pacific Ocean; as a result, more or less stable rates of peat accumulation were preserved within the coastal lowlands in the southeastern part of Kamchatka throughout the Holocene.

Table 2. Average rates of peat growth in different periods of the Holocene along the latitudinal transect from the western coast to the eastern coast of Kamchatka, mm/yr

Area	Holocene period					
	SSA	SA	SB	ATO	AT	BO
Ust-Bol'sheretsk	–	0.25	0.06	0.19	0.06	–
Apacha	1.06	0.29	0.03	0.19	0.12	0.11
Lake Nachikinskoe	1.39	0.18	0.08	0.10	0.23	0.44
Nachikino Crossing	0.77	0.08	0.03	0.50	0.19	0.60
Petropavlovsk-Kamchatskii	0.72	0.12	0.12	0.08	0.09	–

Dashes mean the absence of data.

The Boreal period of the Holocene with the temperature maximum about 9300 years ago was marked by considerable peat accumulation. Its calculated rates (for the layers of maximum thickness) vary from 0.12 mm/yr near the settlement of Apacha to 0.43 mm/yr near Lake Nachikinskii and to 0.6 mm/yr on the Nachikino Crossing.

In the north of Kamchatka, the rates of peat growth can be estimated on the basis of data on the depths of tephra layers formed in the Late Holocene. For the past 300 years, the average rate of peat accumulation is estimated at 0.81 mm/yr. In the Early and Middle Subatlantic periods, it varied from 0.11 to 0.4 mm/yr.

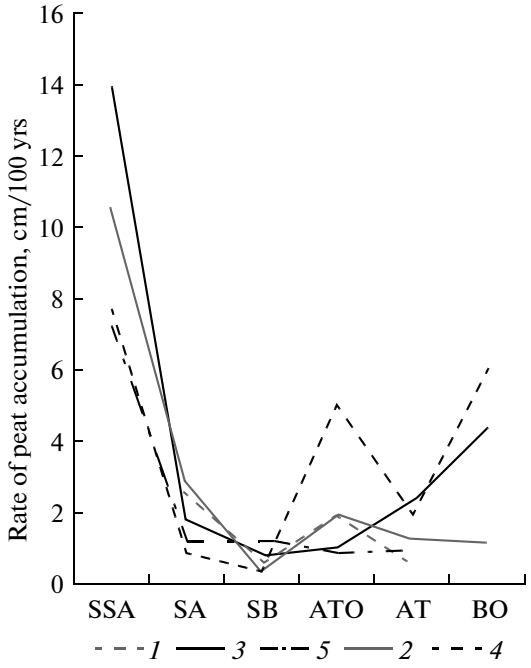

Fig. 2. Peat growth rates in different periods of the Holocene along the latitudinal transect from the western to the eastern coasts of Kamchatka. The studied areas: (*1*) Ust-Bol'sheretsk, (*2*) Apacha, (*3*) Lake Nachikinskoe, (*4*) Nachikino Crossing, and (*5*) Petropavlovsk-Kamchatskii.

Thus, taking into account the thickness of the peat layers formed in different periods of the Holocene, we can say that the optimum conditions for peat accumulation in Kamchatka existed during the Atlantic optimum (5000–6000 yrs ago) and in the Boreal period (8000–9000 yrs ago). Less favorable conditions were observed in the Subboreal period (Fig. 2).

The existence of wet and relatively warm conditions favorable for peat accumulation during the Atlantic period is also confirmed by data on the properties of the specific ocherous (andic) illuvial horizons in the lower parts of the profiles of mineral soils [5]. As a rule, most of the ash-composed horizons (tephra layers) in the profiles of both mineral and organic soils of Kamchatka are characterized by a low degree of alteration [7]. Tephra layers deposited during catastrophic eruptions are clearly seen in the soil profiles; their boundaries are distinct, and the particles composing them are poorly triturated by hand. The meso- and micromorphological features of these layers also attest to the relatively weak transformation of the ash sediments.

Strongly altered volcanic ashes composing the illuvial ocherous (andic) horizons (BAN) in mineral soils have different properties. These horizons are considered to be diagnostic of the type of ocherous volcanic soils. They are composed of ashes from different eruptions; often these ashes were redeposited and, thus, cannot be used for dating purposes. As a rule, however, they represent the ashes formed in the mid-Holocene Atlantic period. Within the thickness composed of these ashes, the labeling tephra layer formed during the caldera-forming eruption of the Ksudach Volcano (4907 BP) is often present. In the soil profile, the ocherous horizons are marked by their bright colors. The ashes composing them are strongly weathered, which can be clearly seen under a microscope. Often, the material of these horizons displays the property of pseudothixotropy: when rubbed in the fresh state, it releases absorbed water. The ocherous horizons are rich in iron (8–10% FeO_3) and aluminum (15–20% Al_2O_3) and in the mobile (oxalate-extractable) forms of these elements. This is explained by the high degree of alteration of the ashes and by the illuviation of mobile sesquioxides from the upper horizons.

As found earlier, the high degree of alteration of ashy material composing the BAN horizons is due to the long period of the presence of this material in the zone of active pedogenesis under the surface organic horizons, i.e., due to the long period of "rest" between strong volcanic eruptions [5].

The relatively warm and wet climatic conditions of the Atlantic period favored the accumulation of thick peat layers. At the same time, they favored more intense weathering of ash sediments in the thickness of the mineral soils with the formation of specific ocher-

ous horizons. The latter are mainly developed within ash sediments deposited in the Atlantic period.

CONCLUSIONS

The maximum rate of peat accumulation in Kamchatka is typical of the modern stage of the Subatlantic period of the Holocene. In the past 100 years, the average rates of peat growth along the western coast of Kamchatka, in the north of the peninsula, and in the south of its central part have reached 1.06–1.54 mm/yr; they have been somewhat lower (0.67–0.77 mm/yr) along the eastern coast of Kamchatka.

The Subatlantic period of the Late Holocene (except for the recent century) is generally characterized by thicker peat deposits in comparison with the older periods. The rates of peat accumulation calculated for the Subatlantic period vary from 0.03 to 0.37 mm/yr. The peat layers accumulated during the cold Subboreal period are the thinnest; the calculated rates of peat accumulation in that period varied from 0.03 to 0.08 mm/yr. More intense peat accumulation took place in the Atlantic period (0.06–0.23 mm/yr) and, especially, during the Atlantic climatic optimum (0.08–0.50 mm/yr).

High rates of peat accumulation were also observed in the Boreal period of the Early Holocene with the temperature maximum about 9300 years ago; thick peat layers accumulated during that period with calculated rates from 0.12 to 0.6 mm/yr.

The existence of more favorable for peat accumulation warm and wet conditions during the Atlantic climate optimum is also confirmed by the formation of specific ocherous illuvial horizons with andic properties in the mineral soils. These horizons consist of the strongly transformed volcanic ashes of Middle Holocene age.

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