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RADIOCARBON DATING OF BURIED HOLOCENE SOILS IN SIBERIA

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ABSTRACT. We have constructed a detailed chronological description of soil formation and its environments with data obtained on radiocarbon ages, palynology, and pedology of the Holocene buried soils in the forest steppe of western and central Siberia. We studied a number of Holocene sections, which were located in different geomorphic situations. Radiocarbon dating of materials from several soil horizons, including soil organic matter (SOM), wood, peat, charcoal, and carbonates, revealed three climatic periods and five stages of soil formation in the second part of the Holocene. ^{14}C ages of approximately 6355 BP, 6020 BP, and 5930 BP showed that the longest and most active stage is associated with the Holocene Climatic Optimum, when dark-grey soils were formed in the forest environment. The conditions of birch forest steppe favored formation of chernozem and associated meadow-chernozem and meadow soils. Subboreal time includes two stages of soil formation corresponding to lake regressions, which were less intense than those of the Holocene Optimum. The soils of that time are chernozem, grassland-chernozem, and saline types, interbedded with thin peat layers ^{14}C dated to around 4555 BP, 4240 BP and 3480 BP, and 3170 BP. Subatlantic time includes two poorly developed hydromorphic paleosols formed within inshore parts of lakes and chernozem-type automorphic paleosol. The older horizon was formed during approximately 2500–1770 BP, and the younger one during approximately 1640–400 BP. The buried soils of the Subatlantic time period also attest to short episodes of lake regression. The climate changes show an evident trend: in the second part of the Atlantic time period it was warmer and drier than at present, and in the Subboreal and Subatlantic time periods the climate was cool and humid.

INTRODUCTION

Soil evolution provides clues for the reconstruction of Holocene environments and prediction of future climate changes. Radiocarbon (^{14}C) dating is a powerful tool for the investigation of genesis, geography, and evolution of soils. We studied several sections of Holocene deposits in forest steppe zones of western and central Siberia, and dated paleosols by the ^{14}C method (Figure 1). This allows us a deeper insight in the history of the Holocene climates and soil dynamics.

METHODS

Recently, there has been a broad discussion of the methods of sample pretreatment and the interpretation of ^{14}C soil dating results (e.g., Chichagova 1985; Chichagova and Cherkinsky 1987; Scharpenseel 1971; Polach and Kostin 1971; Orlova and Panychev 1993; etc.).

To separate soil organics for dating, we use Turin's method (see Arslanov and Kozyreva 1976). Soil organic matter (SOM) is divided into the following fractions: 1) free humic acids—fulvic acids, 2) humic acids bound with Ca and R_2O_3 mobile species—fraction I, 3) humic acids bound with R_2O_3 stable forms (more firmly attached to the mineral fraction)—fraction II, 4) humin; and 5) soil remnant.

We sift a dry soil sample, ranging from 3 to 20 kg, through a sieve (minimal cell size = 0.25 mm) without grinding so as not to contaminate the sample with plant or animal organic remnants. Then we mechanically remove foreign material (e.g., seeds, grass roots, insect remains). The sample is inspected further under a binocular microscope, and placed into 20-L glass vessels; we then add 0.1 N NaOH solution at room temperature. To precipitate clay particles, we add 40 g of Na_2SO_4. Distilled water is added to each container to bring the volume up to 10 L. The mixture is stirred several times during the day, and left overnight. The next day, the solution is siphoned and precipitated by adding concentrated H_2SO_4 and heated to 80 °C. The precipitate is collected, filtered with a Bûchner funnel containing a double glass-fiber filter, washed in distilled water, and dried at 105 °C. The remaining soil is decalcified with 0.1 N H_2SO_4, or with 0.1 N HCl solution in the case of car-

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bonate soils. Then it is washed with distilled water until no Ca^{2+} appears in the filtrate. The decalcified soil is treated 2–3 times with 0.1 N NaOH at room temperature. The alkaline solution is siphoned, and humic acids are precipitated by adding 0.1 N H_2SO_4. Humic acids are then dried for production of benzene. This fraction I of humic acids is bound with Ca and mobile R_2O_3 forms. The remaining soil is treated alternately with 0.1 N H_2SO_4 and NaOH solutions 2–3 times. The alkaline filtrate is collected and the fraction II of humic acids is separated, more firmly bound to mineral phases. Then the soil is placed into a stainless steel water bath, mixed with 0.1 N NaOH solution, and heated to 80–90 °C for 2–3 hr. This hot treatment is repeated 2–3 times. The alkaline filtrate is siphoned, and the humin fraction is prepared by the same separation methods. Finally, the soil remnant is washed with acidified water, dried at 105 °C, and dated by ^{14}C.

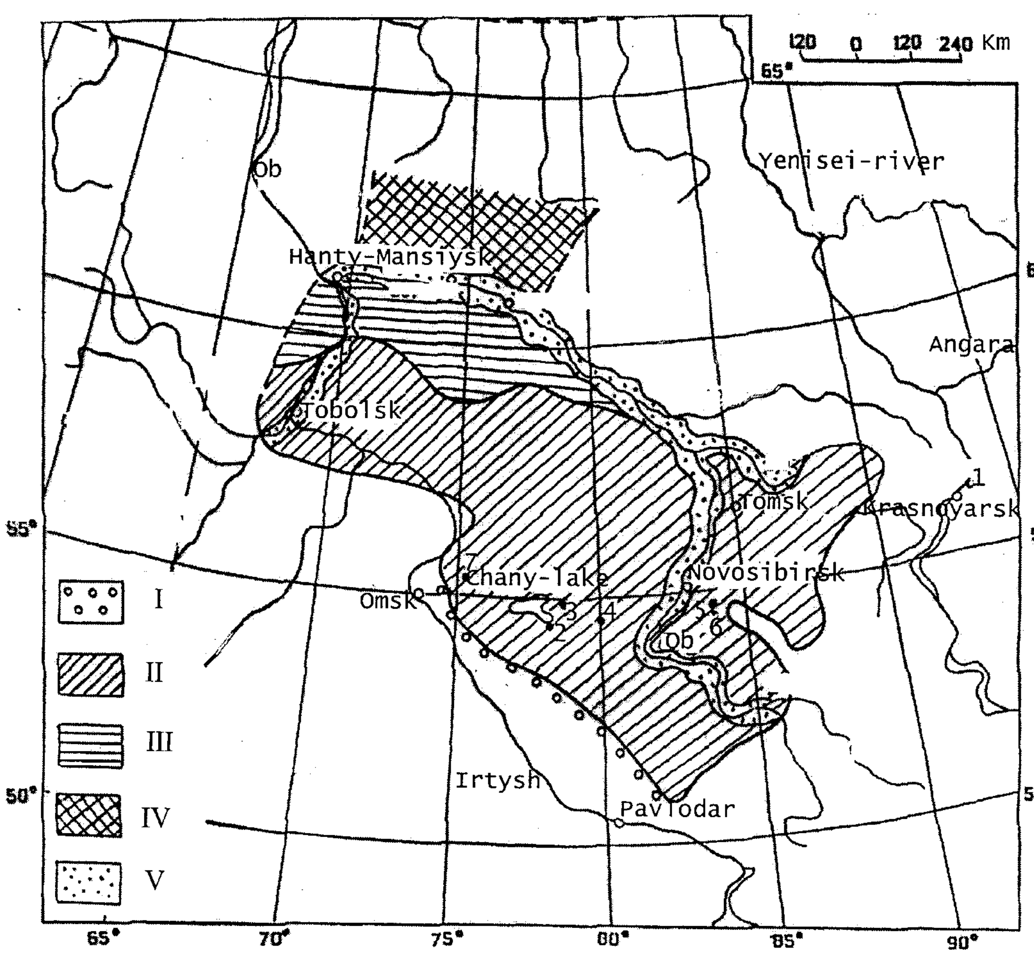

Figure 1 Holocene soils in western Siberia (Atlantic period): steppe (I), forested steppe (II), southern taiga subzone (III), middle-taiga subzone (IV), alluvial soils (V). Sections: 1 = Nyasha, Yenisei River, 2 = Shirokaya Kurya, Chany Lake, 3 = Zdvinsk, Chany Lake, 4 = Suma floodplain, Suma River, 5 = Mamonovo, Berd' River, 6 = Maslyanino, Berd' River, 7 = Malinino, Om' River.

RESULTS AND DISCUSSION

The dated material (Table 1) was sampled from buried peatbogs and paleosols in Holocene sections, located on the first and second lake and river terraces, on elevated floodplains, within lake basins, and in depressions between dunes.

A 5.8-m-thick Holocene section is exposed in a limnic broadening within the Om' River valley near the village of Malinino. The section contains two paleosols. Fraction I of humic acids, taken at the base of the upper 0.8-m-thick paleosol with well-developed genetic horizons, was dated to 1170 ± 85 BP (SOAN-1968A), and fraction II gave a ^{14}C value of 2240 ± 50 BP (SOAN-1968B). The upper 5 cm of the humus horizon revealed three ^{14}C ages: 570 ± 100 BP (SOAN-1969A) for fraction I; 790 ± 60 BP (SOAN-1969B) for fraction II, and 680 ± 85 BP (SOAN-1969C) for the humin fraction. The age of total I + II fraction from the 0.10-m-thick humus horizon of the lower paleosol, composed of black loamy sand, is 4240 ± 160 BP (SOAN-1967).

Subaerial deposits, widely distributed in the Om' River valley, are overlain with fluvial and lacustrine facies. The presence of humus horizons in the section is evidence of repeated regressions. One occurred at around 4240 BP, corresponding to the Subboreal period. The age of another regression coincides with the beginning of the Subatlantic, spanning from around 2240 to 570 BP. The soil formed during that time is of chernozem type, and is overlain by lacustrine deposits formed under the wetter climate, which may correspond to the cooling of the Little Ice Age, as evidenced by ^{14}C data (Orlova 1990).

Table 1 ^{14}C ages of Holocene buried soil horizons of Siberia

Location	Depth (m)	Soil organic matter fractions				Charcoal	Peat
		I	II	Total I + II	Humin		
Malinino	1–1.05	570 ± 100	790 ± 60		680 ± 85		
	1.3–1.4	1170 ± 85	2240 ± 50				
	2.8–2.9			4240 ± 160			
Mamonovo	2.9						4400 ± 340
	4.0						5930 ± 100
Maslyanino	0.5–0.6			4720 ± 50			
	1.9–2.0			1670 ± 40		1640 ± 40	
Nyasha							
	2.1–2.2			1900 ± 40		1770 ± 55	
	2.2–2.3			2480 ± 45		2500 ± 60	
	2.8–2.9					5445 ± 75	
Suma-1	1.2–1.3	6020 ± 90	6345 ± 140				
	1.2–1.3	6320 ± 120	6030 ± 150				
Suma-2	1.1–1.2			3480 ± 55			
	2.0–2.1			4555 ± 120			
	2.9–3.0			6355 ± 240			
Chany	0.3			1740 ± 30	1620 ± 20		
Zdvinsk	0.4–0.5			3170 ± 30			
Malye	0.4					820 ± 120	
Chany	1.6–1.7						
Shirokaya	2.35						
Kurya	2.8–2.9						
	1.6–1.7	1070 ± 50	1180 ± 50		1035 ± 40		
	2.35	2385 ± 35	2410 ± 50		2265 ± 40		
	2.8–2.9			5530 ± 210			

A 1.2–1.9-m-thick buried peatbog, located on the first terrace of the Berd' River, was studied near the village of Mamonovo (Firsov and Panychev 1973). The upper portion of the peat layer contains abundant wood fragments, and was ^{14}C dated to 4400 ± 340 BP (SOAN-114). The lower part of the layer, composed of dark-brown and more consolidated peat, yielded an age of 5930 ± 100 BP (SOAN-113). According to the spore and pollen record, the peatbog appeared to be in the second part of humid Preboreal time in a birch forest steppe environment. The younger pollen spectra, corresponding to the second part of Atlantic time period, show the bog evolution in birch-pine forest steppe environment when the landscapes were similar to modern ones (Zykina et al. 1981).

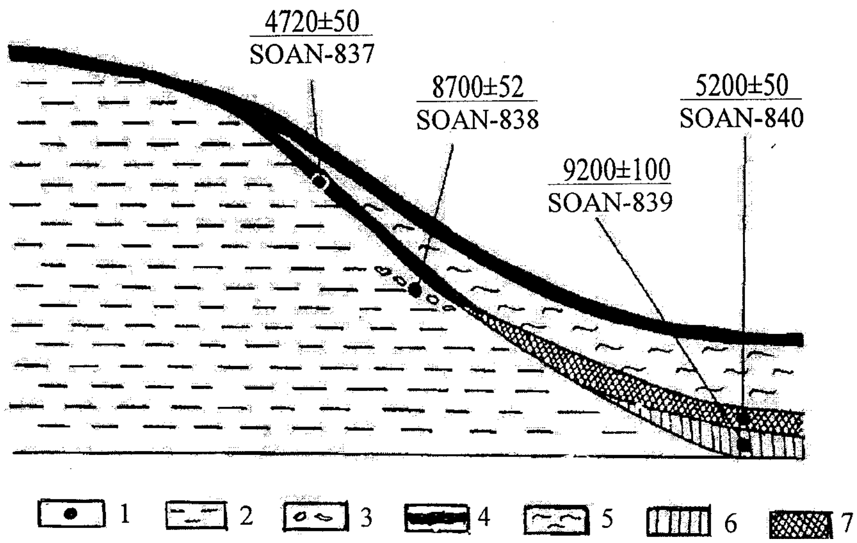

Figure 2 Stratigraphy of Holocene deposits near the village of Maslyanino, Berd' River. 1 = location of ^{14}C samples, 2 = silt, 3 = calcareous concretion, 4 = soil, 5 = loam, 6 = sapropel, 7 = peat.

We studied another Holocene paleosol in a section of a terrace-like surface, going down to the first Berd' River terrace, in the vicinity of the Maslyanino village (Figure 2). The paleosol consists of a 0.4-m dark-grey humus horizon, and of an illuvial carbonate horizon 0.5 m below the humus base. Panychev (1979) traced the paleosol for a few hundred meters and noted a transition downslope from chernozem to grassland-chernozem with a well-presented carbonate concretion horizon, and finally to peat-boggy soil in low-lying areas. The total I + II fraction from the humus horizon was dated to 4720 ± 50 BP (SOAN-837); the humus-bearing layer in the depression was dated to 5200 ± 50 BP (SOAN-840). The age of the carbonate concretions was estimated to be 8700 ± 50 BP (SOAN-838), and sapropel at the base of the section was dated to 9200 ± 100 BP (SOAN-839). Thus, we deal with a catenary succession of soils corresponds to the Atlantic time: chernozem–grassland-chernozem–peat-gleysol. The peat-gleysol soil was formed after the sedimentation interruption, on the surface of the Preboreal time sapropel.

The multilayered archaeological site Nyasha occurs near the edge of the 8–10-m first terrace of the Yenisei River (Drozdov et al. 1998) in a depression between dunes (Figure 3). The section under study contains four paleosols. The uppermost section (paleosol I) consists of dark-grey fine-grained loamy sand. The age of the total I + II fraction from this horizon is 1670 ± 40 BP (SOAN-3657), and the charcoal sample gave an age of 1640 ± 40 BP (SOAN-3653). The second paleosol (II) is made up of 25-cm-thick black fine-grained loamy sand. The age of a charcoal sample from its top is

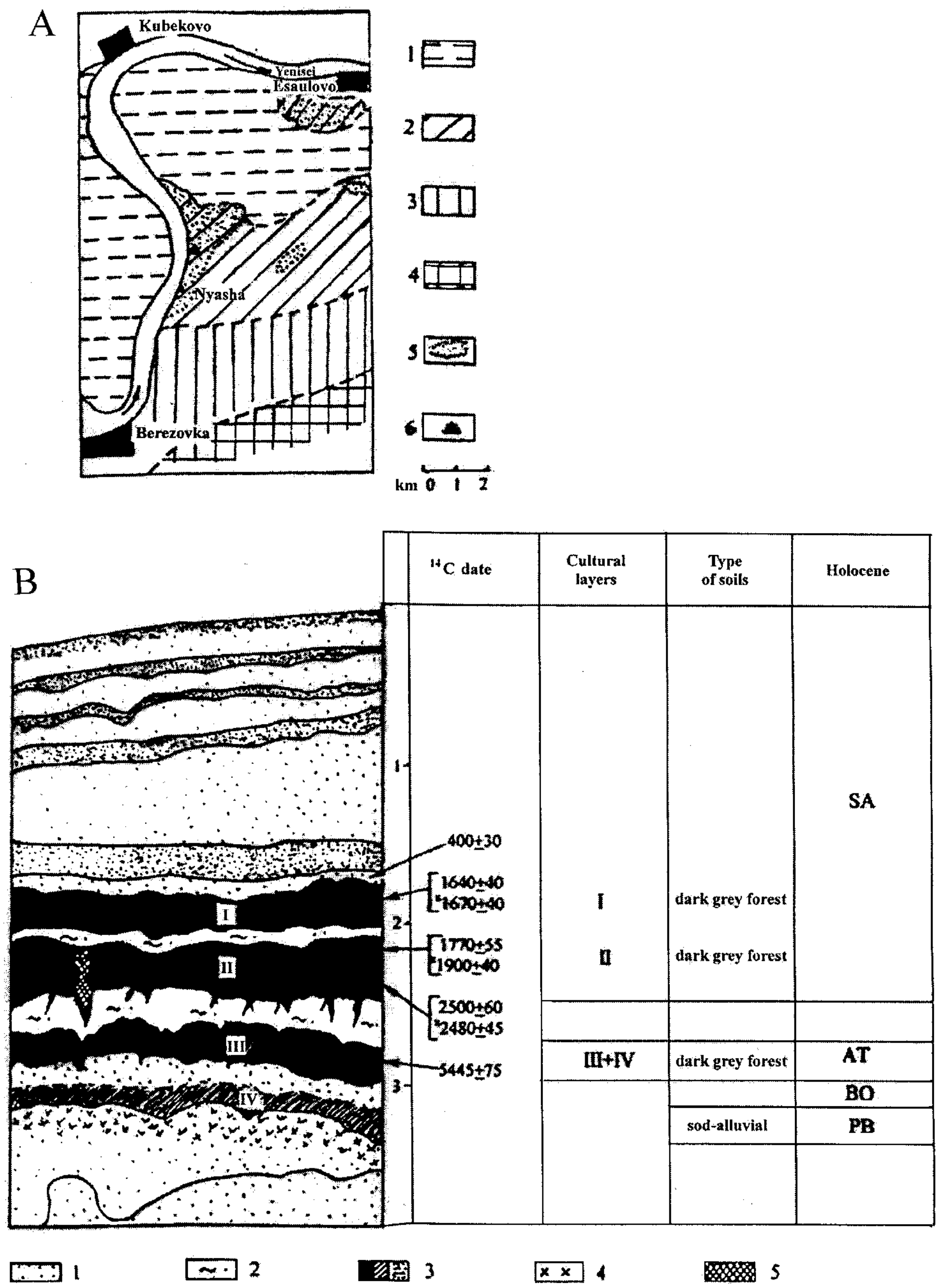

Figure 3 Geomorphic position and stratigraphy of Holocene deposits exposed in the region of the Neolithic site Nyasha, culture, region of Yenisei River (section 1 in Figure 1). A = Generalized geomorphology. 1 = floodplain, 2 = first terrace (8–12 m), 3 = second terrace (15–20 m), 4 = third terrace (30–40 m), 5 = areas of hilly (aeolian) topography, 6 = location of the Nyasha site. B = Geological cross-section of the trench (eastern wall). 1 = sand, 2 = loamy sand, 3 = humus content: high (a), medium (b), low (c); 4 = carbonate concretions, 5 = burrows of soil-dwelling animals, 6 = ^{14}C ages of total I + II fraction; other ages are on charcoal.

1770 ± 55 BP (SOAN-3654), and a sample from the lower part of the horizon gave a value of 2500 ± 60 BP (SOAN-3655). The age of total I + II fraction from the upper 10 cm of the second paleosol is 1900 ± 40 BP (SOAN-3658), and that for the lower 10 cm is 2480 ± 45 BP (SOAN-3659). The third paleosol (III) is represented by black fine-grained loamy sand, varying in thickness from 10 to 30 cm, and small charcoal fragments were dated to 5454 ± 75 BP (SOAN-3756). The 20-cm-thick lowermost paleosol (IV) consists of brownish to dark-grey loamy sands, much more consolidated than the overlying paleosols. Thus, three of the four paleosols in the Nyasha section yielded ^{14}C ages from approximately 5445 to 1640 BP. The Holocene Climatic Optimum soil and the two Subatlantic soils are the dark-grey forest type. During the Subboreal time, the intensification of eolian processes is observed, and this caused the activation of denudation.

Palynological evidence from the alluvial floodplain and dune deposits near the Nyasha site (Chekha and Kol'tsova 1990) shows forest-type spectra for the paleosol III. By the time when the Atlantic soil formation was finished, the vegetation was presented by birch forests with admixture of pine, and with poorly developed grass and moss cover. The paleosol II also reveals forest-type pollen spectra. The spectra of the paleosol I are characterized by predominance of forest species pollen (pine, larch, and birch), and the lower part of this horizon contains pollen of larch and fir. At present, the territory is covered by grey forest soils, with absolute dominance of forest-type pollen spectra contain 89–99% of forest species. The modern pollen spectra reflect the vegetation of pine forests with admixture of birch and larch grow on dunes of the first terrace of Yenisei River, and the vegetation of dark-conifer forests in swampy depressions between dunes. The modern grass and moss cover is poorly developed, but shows a wide diversity of species.

We also studied several sections in the territory of the Suma floodplain, an extended lake-like basin in the Bagan River valley, western Barabinskaya Plain. The eroded layer of the lacustrine sediments is accrued against the deposits of the surrounding ridge-like hills, and thus it is younger than the ridge ones (Orlova 1990). One section was investigated on the periphery of the floodplain where 0.8-m-thick steppe-type paleosol is exposed, with a well-differentiated profile and burrows from soil-dwelling animals. Fraction I from this paleosol was dated to 6020 ± 90 BP (SOAN-2324A) and 6320 ± 120 BP (SOAN-2325A), and fraction II gave ages of 6345 ± 140 BP (SOAN-2324B) and 6030 ± 150 BP (SOAN-2325B).

Another section of lacustrine deposits of the Suma floodplain was examined in the central part of the basin where their thickness is much greater (3.8 m compared to 1.5 m in the basin periphery). Here three paleosols were distinguished. The first paleosol (from top to bottom) was dated to 3480 ± 55 BP (SOAN-2132), using total I + II fraction. The 0.96-m-thick second paleosol, which is the saline type, was developed on sands with well-presented genetic horizons. The age of the total I + II fraction is 4555 ± 120 BP (SOAN-2131). The third paleosol found in the region is 0.35-m-thick and the age of the total I + II fraction is 6355 ± 240 BP (SOAN-2130). The ^{14}C data, along with the presence of paleosols among near-shore lacustrine sands, attest that the limnic basin persisted to as late as the Subatlantic time period, and the lake underwent repeated transgressions and regressions.

A section with paleosol containing a well-developed illuvial horizon of the Holocene Climatic Optimum (Figure 4A) was investigated beneath a defense rampart in the vicinity of the Late Bronze Age site on the Chany Lake near the town of Zdvinsk (Zykina et al. 1983). Rampart semi-circles surround the ancient settlement, which consists of three dwellings along the an abrasion-shaped bluff of the Chany Lake young terrace. The total I + II fraction (SOAN-2010A) and humin (SOAN-2010B) from the 0.4-m-thick modern soil on the lake terrace surface were dated to 1740 ± 30 BP and 1620 ± 20 BP, respectively. The age of the 1.1-m-thick paleosol below the rampart is 3170 ± 30 BP

(SOAN-2011). Comparison of the soil morphology allows one to assign the paleosols to different sub-types of chernozem series. The soil, which has been forming on the rampart top since the beginning of Subatlantic time, has a morphology proximal to ordinary chernozem species, and the paleosol below the rampart corresponds to leached chernozem.

In the second part of the Holocene, soils of peat-gley and peat-boggy types, varying in age from around 5530 to 820 BP, were developed upon lacustrine deposits on the shore of the ChanyLake

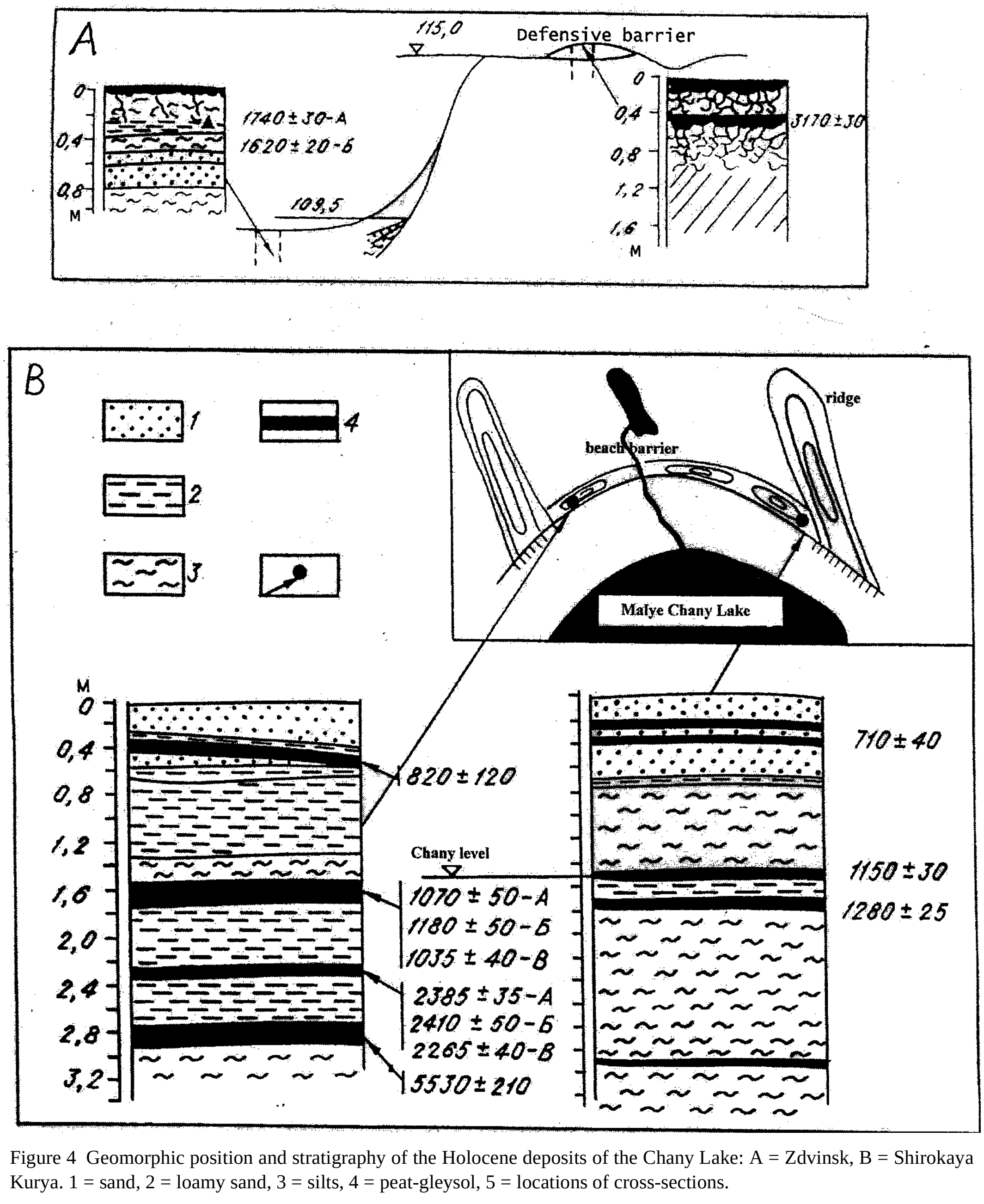

Figure 4 Geomorphic position and stratigraphy of the Holocene deposits of the Chany Lake: A = Zdvinsk, B = Shirokaya Kurya. 1 = sand, 2 = loamy sand, 3 = silts, 4 = peat-gleysol, 5 = locations of cross-sections.

(Orlova 1990). The section near the Shirokaya Kurya village on the shore of Malye Chany Lake is of particular interest (Figure 4B). The lake is surrounded from the northeast by an extensive lowland, superposed with a system of elongated hills and valleys between them. There is an ancient coastal ridge 500–800 m away from the present-day shoreline, its floor 1 m above the modern lake level, and with a weakly developed soil profile on the top. We studied a section of valley fill that contains four paleosols. The uppermost paleosol is immature and consists of loamy sand, with a thin humus horizon. At the base of the paleosol profile, large *Anodonta* sp. shells were found, and they yielded an age of 820 ± 120 BP (SOAN-2099). Below there is a peat-boggy paleosol with two genetic horizons. The ages of its three fractions are: 1070 ± 50 BP (SOAN-2092A) for fraction I; 1180 ± 50 BP (SOAN-2092B) for fraction II; and 1035 ± 40 BP (SOAN-2092C) for the humin fraction. The third paleosol consists of humus-bearing loamy sand, and humic acid fractions gave ^{14}C values of 2385 ± 35 BP (SOAN-2091A, fraction I), 2410 ± 50 BP (SOAN-2091B, fraction II), and 2265 ± 40 BP (humin). The fourth paleosol of peat-gleysol type is 0.15 m thick, and was dated to 5530 ± 210 BP. The lacustrine deposits alternate with the remains of mollusk shells and organic soil layers, which indicates repeated fluctuations of the lake level. The deposition during the highest stand of the lake level involved outwashed sands, loamy sands, and silts. When the lake was dried out, peat-gleysol formed.

In general, the lake underwent four regressions in the second part of the Holocene. As evidenced by ^{14}C ages, the first regression corresponds to the Atlantic time, around 5530 BP; the second one occurred in the early Subatlantic period, around 2265–2410 BP. The third regression coincided with the so-called "Small Climatic Optimum", around 1035–1180 BP; the fourth one was dated to around 820 BP. Palynological data show that at around 5530 BP the territory was covered by ferny marshes with shrub birch, xerophyte wormwood-cereal assemblages, and scarce pine-birch groves, and the climate was cold and wet. In the early Subatlantic time, during the second regression at around 2410 BP, vegetation was represented by light pine-birch forests with shrub birch, and the climate was also cold and wet. The third regression at around 1730–1950 BP was accompanied by broad development of pine forest steppe with admixture of elm and lime, and the climate was warm and humid. At around 820 BP, during the fourth regression, the climate was again cold and wet and vegetation was represented by light birch and pine forest with shrub birch (Levina and Orlova 1993).

Thus, the studies of paleosols and ^{14}C dating allow us to distinguish several stages of soil formation in the second part of the Holocene. The most intensive and the longest stage coincided with the Climatic Optimum, dated from around 6300 to 5200 BP. Soil formation stages in Subboreal (from around 5200 to 2500 BP) and Subatlantic (from around 2500 BP until the present) times were weaker and shorter.

The climate of Holocene Optimum, characterized by a number of ^{14}C ages (around 5930 BP, 6020 BP, 6355 BP, etc.), was warmer and wetter than now. At that time in the Siberian forest steppe zone, dark-grey soils were formed under birch forest environment, with admixture of pine and spruce. The birch forest steppe conditions were favorable for formation of grassland-chernozem and grassland soil types. The landscapes were similar to those of the present day. On the shores of Chany and Malye Chany lakes, peat-gley soils and peatbogs developed upon lacustrine sediments, which is evidence of the beginning of a regression. Large territories were covered by ferny marshes. Soil formation and humification occurred at higher rates, and the podzolization process was weak. According to paleopedologic evidence, the first part of Atlantic period was more humid than the second part. Subboreal time was characterized by a colder climate and more intensive erosion and sedimentation, which facilitated deflation of the Atlantic soils (Zykin et al. 2000). However, the Subboreal period includes two stages of soil formation as shown by SOM ^{14}C ages of around 3170 BP, 3480 BP and 4240 BP, and 4555 BP. However, they were less intensive than those of the Holocene Optimum.

Both Subboreal stages bear signatures of a short water-basin-level fluctuation, which is evident in the interbedding of chernozem-like, meadow-chernozem, and saline paleosols corresponding to regressions, and thin peat layers also corresponding to transgressions. The climate during the Subatlantic period was likewise cooler and wetter than the climate of the Atlantic period. During the time span from around 2500 to 400 BP, as recorded in the Nyasha section, two paleosols were formed but they did not reach the mature profile of the Holocene Optimum. The processes of humification and podzolization at that time were weaker and of shorter duration. The earlier paleosol was developed for about 1000 years, and the formation of the later paleosol took about 700 years. The earlier paleosol was formed under birch forest with shrub species and a weakly developed grass and moss cover. The later paleosol was formed under a pine-larch forest with scarce birches, and grass and moss cover that was also poorly developed. The Subatlantic paleosols in the sections of western Siberia correspond to two stages of soil formation that coincided with lake regressions. In the beginning of the Subatlantic period, ^{14}C dated to around 2240 BP, 2265 BP, 2385 BP, and 2410 BP, the hydromorphic soils formed around lakes and rivers in an environment of light pine-birch forest with shrub birch, and the chernozem soils formed in automorphic environments. From around 1950 to 1130 BP, the soil formation was of chernozem, dark-grey forest, and peat-gleysol types in the environment of pine forest steppe, with admixture of elm, lime, and xerophyte wormwood associations.

CONCLUSION

Original data on ^{14}C ages, palynology, and pedology of the Holocene paleosols of the forest steppe of western and central Siberia allow us to distinguish three climatic periods with five stages of soil formation, differing in intensity and duration. The climate changes show a clearly evident trend: the first part of the Atlantic period was warmer and more humid than at present, and the second part was warmer and drier. The climate was cool and humid during the Subboreal and Subatlantic periods.

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