IOP Conference Series: Earth and Environmental Science

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To cite this article: S N Timireva *et al* 2020 *IOP Conf. Ser.: Earth Environ. Sci.* **438** 012027

Landscapes, paleosols and climate in the north of Mongolia during the Holocene

S N Timireva[1,*], O Batkhishig[2], S A Sycheva [1], Yu M Kononov[1], A N Simakova[3], G Byambaa[2], T Telmen[2], M Samdandorj[2], K G Filippova[1] and E A Konsnantinov[1]

[1] Institute of Geography, Russian Academy of Sciences, 29 Staromonetny lane, Moscow 119017, Russia
[2] Institute of Geography and Geoecology, Mongolian Academy of Sciences, 15 Baruun selbiin, 4th khoroo, Chingeltei duureg, Ulaanbaatar-15170, Mongolia
[3] Geological Institute, Russian Academy of Sciences, 7 Pyzhevsky Lane, Moscow 119017, Russia

[*] Email: stimireva@mail.ru

Abstract. Integrated paleogeographic studies have been performed on the loess and soil sequence in the lower reaches of the Orkhon R., northern Mongolia. The samples were taken continuously through the sequence and studied using a broad assortment of field and laboratory analyses. There are five paleosols exposed in the section under study crowned with the present-day soil and separated from each other by loess horizons or proluvial-deluvial deposits. The dating by radiocarbon proved the soil development beginning from the early Holocene. The two lower soils (PS4 and PS5) formed at that interval are noted for the minimum salinity and a considerable content of carbonates. The soils dated to the middle Holocene (PS3 and PS2) contain the least proportion of organic matter and increased salinity, which may be attributed to a dryer climate (even at optimum intervals) than in the early and late Holocene. In common with the present-day soil, the PS1 buried soil is characterized by negligible (or absent) salinity, and a noticeable accumulation of organic matter and carbonates indicative of favorable warm and relatively wet conditions. All the pollen assemblages indicate the dominance of grass vegetation; it may be safely suggested that open meadow and steppe landscapes, occasionally replaced by semi-deserts, prevailed in the considered region during the Holocene.

1. Introduction

Mongolia is one of the key regions in the paleoclimatic and paleoenvironmental studies aimed at getting better insight into the climate changes during the Holocene. The studied region lies in the center of the Eurasian continent; it mostly belongs to a plateau dominated by arid and semiarid landscapes. The climate in Mongolia is under control of the central Asian anticyclone, which interacts with westerlies and monsoon circulation. Northern Mongolia forms a climatic barrier between relatively humid Siberia and arid Central Asia. So the geographical position of the studied region accounts for its high sensitivity to changes of climate.

At present most of the studies dealing with the environmental changes in Mongolia during the Holocene concentrate on the lacustrine sedimentary records [1 – 6 and many others].

In Mongolia loesses and loess-like deposits are rather common [7]; their sequences often include paleosols and form loess-paleosol formations together. In fact, the loess series of steppe regions present the most complete subaerial records as has been long noted by many specialists [8 – 11]. However, only a few recent works gave them a thorough consideration [12 – 17].

Recently Klinge and Sauer [18] made an attempt at differentiated synthesis of the available information on paleoenvironments of Mongolia with the aim of revealing the existing discrepancies and gaps in our knowledge. It has been shown that the present-day state of knowledge about the environmental history is based on a rather limited amount of natural records distributed irregularly over the territory in question. In conclusion of the synthesis, the authors proclaimed a necessity of further investigations at a higher time resolution to be carried out in new areas and involving some additional natural records. Our present work is in complete agreement with those recommendations. The paleogeographic works have been performed on the loess-soil section first introduced in the paper by Frank Lehmkuhl and his colleagues [13]. The work was done at a high time resolution: the sediments were sampled continuously at every 6 cm. In this way we obtained more detailed stratigraphic sequence and therefore could trace more closely the history of regional environments through the Holocene.

2. The region of the studies

The studies were carried out in northern Mongolia, within the Baikal–Ulaanbaatar Corridor (48–53° N, 104–108° E), mostly bearing a cover of thick eolian (loess) deposits [19 – 20].

The main object studied in the field was the loess and soil sequence exposed in the 1st terrace scarp on the left bank of the Orkhon River, ~150 km south of its falling into the Selenge R. The section is at the elevation of ~730 m a.s.l. The region is essentially a plain mantled with proluvial and alluvial sediments and surrounded with medium-high Burengiyn – Nuruu Mountains (up to 1025 m a.s.l.) composed mostly of granites and crystalline shists (figure 1).

The climate is extremely continental, marked by a dominance of sunny days, particularly in winter, by a considerable dryness of the air, a small amount of yearly rainfall, and sharp fluctuations of temperatures, both yearly and daily. The temperature may occasionally change within 20–30°C during a day. The coldest month is January. Mean values of daily winter temperatures are about –25°C, those of summer +19°C. Mean annual precipitation varies from 300 to 350 mm, 80 to 90% of them falling within a period of 5 months, from May to September [21].

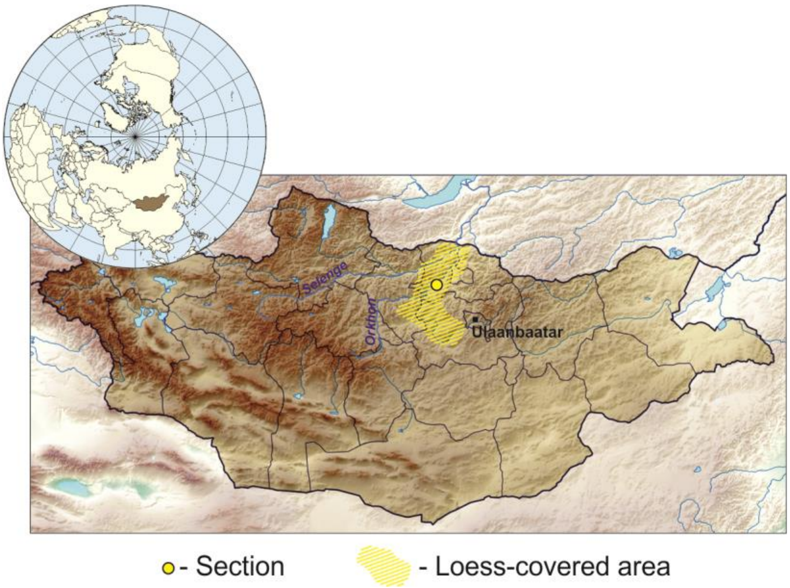

Figure 1. Study area.

The modern soils are mostly kastanozems north-facing mountain slopes under larch forest feature sod-taiga soils and, in the lower parts of the slopes, – chernozem soils [22]. Alluvial soils with silt loam texture develop on river floodplains. Locally on floodplains, for instance at the confluence of the Orkhon and Kharaa rivers, there are areas of loose sands occur indicative of active wind erosion. The soils of the Orkhon-Selenge river basin are the main agriculture resource of Mongolia. The Orkhon river valley is dominated by steppe landscape with *Stipa krylovii, Agropyron cristatum, Cleistogenes squarrosa, Leymus chinensis, Artemisia frigida* and *Caragana microphilla, C.pigmaea* [23]. In mountains north-facing slopes are mostly forested with larch (*Larix sibirica*) and pine (*Pinus sylvestris*).

3. Material and methods

3.1. Fieldwork and sampling strategy

The studies performed on the section in June 2018 included the description of its morphology, magnetic susceptibility measurements, and a detailed sampling for a number of analyses. The soil profiles were described and textural horizons identified as recommended by the international pedological standard [24]. Colors of the sediments and soils were determined in accordance with the ‘Munsell Soil Color Charts’. The sequence was sampled continuously at 6 cm intervals. Besides, samples were taken from every genetic horizon for palynological analysis and radiocarbon dating. Also during the field works the magnetic susceptibility was measured directly on the section three times in every 6 cm with the usage of pocket-size magnetic susceptibility meter ZHinstruments SM-30.

3.2. Laboratory analyses

The sediment granulometry measurements were performed using the Mastersizer 3000 laser diffractometer for the particle size analysis. Only silicate component of the sediments (most tolerant to diagenesis) was analyzed, both organic matter and carbonates being removed beforehand. The preparation of samples included a sequential treatment of the material with 20% solution of hydrogen dioxide (in order to remove organic matter), then with 10% solution of hydrochloric acid (to remove carbonates), and with 4% solution of sodium pyrophosphate (to disperse the clay aggregates). After the treatment the material was transferred by pipette to a liquid tray in the material dispersion unit. In the tray the material was subjected to ultrasonic at a power of 40 W for 100 seconds and intensely stirred with a special rotator at a rate of 2400 revolutions per minute. After the ultrasonics having been shut down, the measurements have been taken ten times, the results were averaged using Mastersizer v.3.62 application. The particle distribution over size fraction was found on the basis of the Fraunhofer diffraction model.

The loss on ignition (LOI) analysis was used to determine the content of organic matter and carbonates in the sample, which is of considerable importance in the paleosol diagnostics. According to specialists [25, 26], the LOI values obtained at 550°C show the organic matter content, and the difference between the values obtained at 950°C and those at 550°C indicated the loss of CO_2 carbonates. The samples, each of 10 cm^3 volume, were dryed up for 12 h at 105°C for the purpose of water (including hygroscopic) removal. Then they were incinerated in a muffle furnace at two temperature regimes (4 hours at 550°C and 2 hours at 950°C). The loss in weight was determined as the difference in weight before and after ignition using the electronic balance to the accuracy of 0.01 g. The resulting values were calculated as follows:

$$LOI550 = \frac{DW105 - DW550}{DW105} \times 100;$$

$$LOI950 = \frac{DW550 - DW950}{DW105} \times 100,$$

where *DW* is dry weight.

The sediment acidity (pH) and electrical conductivity (EC) have been obtained with the use of MULTIMETER, W/ISE 5STR W/PROBE Benchtop pH/DO device, the «Orion 5 Star Series» modification. The electrical conductivity is indicative of salinity; the unit of conductivity in the International System of Units (SI) is dS/m (decisiemens per meter). According to the classification published in [27], soils may be ranked by their EC as follows: 1) <2 – the soil is free of salts, 2) 2 to < 4 – extremely low salt content, 3) 4 to < 8 – soil of low salin ity, 4) 8 to < 16 – moderately saline soil, and 5) >16 – heavily saline soil.

The samples were dated by radiocarbon (AMS dating) practically from every layer in the Center for the Collective Use of the Institute of Geography RAS (Laboratory of Radiocarbon Dating and Electron Microscopy) and in the Center for Applied Isotope Study, University of Georgia. Nine AMS dates have been obtained altogether.

The spore and pollen analysis was done using the method practiced in the Institute of Geography, Russian Academy of Sciences. Pollen diagrams were compiled using Tilia 1.5.12 software; the latter makes possible calculations of the general pollen and spore proportions (arboreal pollen + nonarboreal pollen + spores = 100%), as well as individual constituents in proportion of the total grain number. The pollen specimens were analyzed under an optical microscope Motic BA400 supplied with a Moticam 2300 camera at ×400 magnification.

4. Results

Nine AMS dates have been obtained altogether (see table 1). The radiocarbon age of layer 16 overlaying paleosol PS5 appeared to be 9330±30 yr BP (IGAN-6795), the mean calibrated age being 10543 yr BP. Radiocarbon age of paleosol PS4 is 7975±25 yr BP (IGAN-6465), mean calibrated age is 8870 yr BP. PS-3 is dated at 7110±25 yr BP (IGAN-6794), mean calibrated age is 7947 yr BP. The age of PS2 is 5865±25 yr BP (IGAN-6793), mean calibrated age – 6691 yr BP. The age of PS-1 paleosol amounts to 3530±20 yr BP (IGAN-6790), and its mean calibrated age is 3793 yr BP. The modern soil age (sampled from the depth of 12 cm) is determined at 340±20 yr BP, or 1284 yr BP (calibrated age).

Table 1. Results of the radiocarbon dating (AMS dates were measured at Laboratory of Radiocarbon Dating & Electronic Microscopy of the Institute of Geography RAS and Center for Applied Isotope Studies at University of Georgia, USA)

Sample No.	Lab.No. IG RAS	Depth (cm)	Material	Method	Date (^{14}C yr BP)	Age (cal yr BP)
2	6462	12	Sediment	AMS	1340±20	1284
20	6790	120	Sediment	AMS	2880±20	3003
24	6791	144	Sediment	AMS	3530±20	3793
28	6792	168	Sediment	AMS	4870±25	5606
34	6793	204	Sediment	AMS	5865±25	6691
36	7069	216	Sediment	AMS	6600±25	7493
47	6794	282	Sediment	AMS	7110±25	7947
77	6465	462	Sediment	AMS	7975±25	8870
105	6795	630	Sediment	AMS	9330±30	10543

The least values of magnetic susceptibility are confined to the deepest part of the section – to the gleyed horizon (layer 18) (figure 2). The averaged values do not exceed 1×10^{-3}; more precise, they amount to 0.831×10^{-3}; 0.929×10^{-3}; 0.849×10^{-3}. The maximum value is recorded in the sample taken from the humified interlayer within layer 15, it amounts to 5.35×10^{-3}. The higher values (~2 to 3×10^{-3}) are typically confined to paleosol horizons.

The granulometric composition is noted for a considerable proportion of sand (25-60%), represented mostly by fine and medium-size fractions. The higher sand proportion is typical of layer 1, the lowest one recorded in layer 17. The silt content varies over the section from 30 to 70%, that of clay – from 5 to 20%.

The LOI at 550°C values indicative of the amount of organic matter in the deposits vary between 2 and 4.5%. They are higher in the modern soil and in all the paleosols, their maximum being recorded at the base of PS1 and in PS5.

The LOI at 950°C values depending of the carbonate content vary from 2 to 9.5%. The peak values correspond to BC horizon in PS1 (layer 5) and PS5 (layer 17), which may be attributed to the abundance of pedogenic carbonates.

The pH value changes only slightly over the sequence and shows a slightly alkaline reaction (7.7-8.8).

The electrical conductivity values (EC) mostly do not exceed 1 and only at the level of humus horizons PS1 and PS3 increase by factor of 2.5 and more. According to [27], the indicated layers may be considered as lightly saline (figure 2).

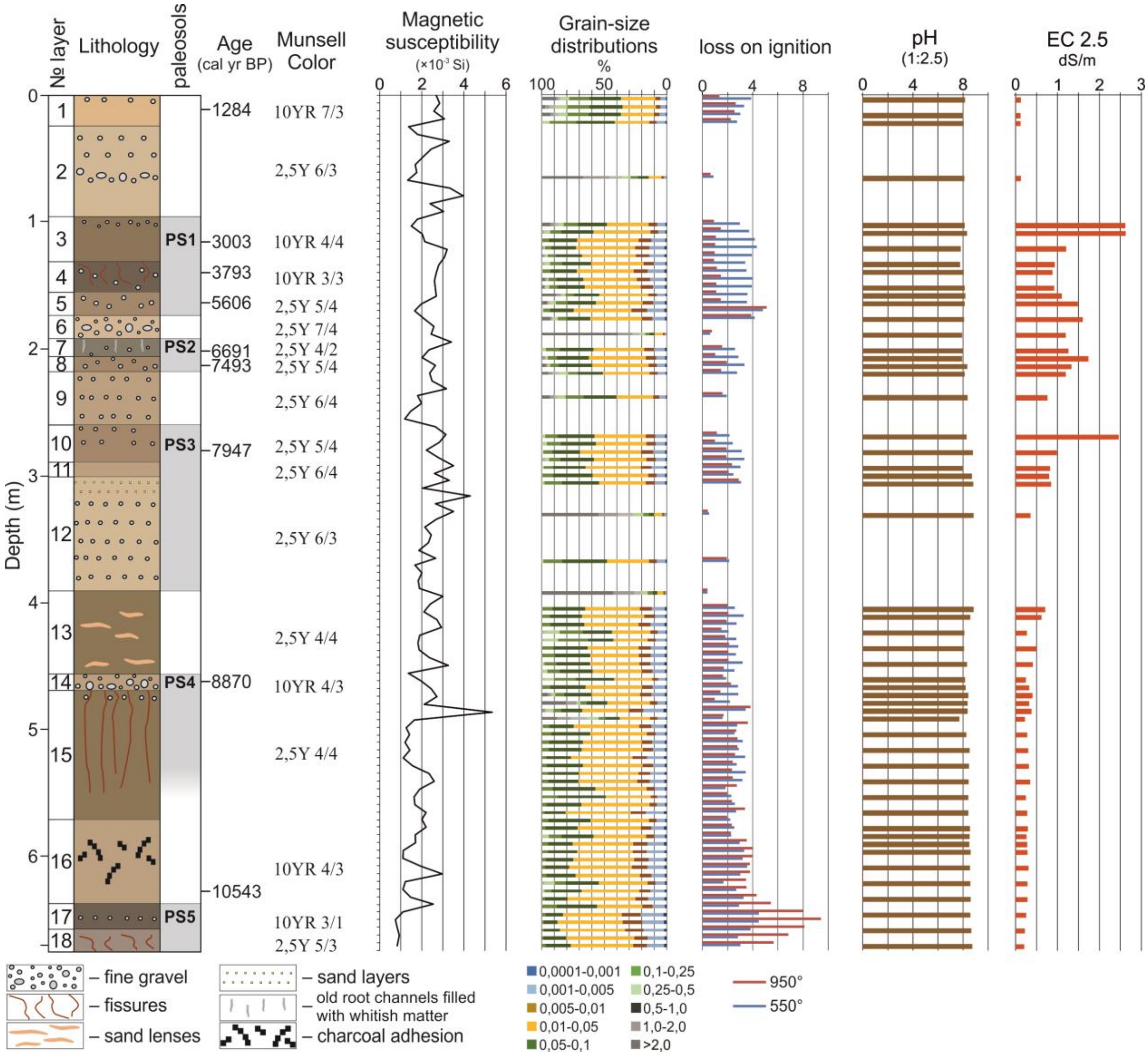

Figure 2. Litho- and pedostratigraphy and chronology of the Orkhon section.

The pollen spectra were divided into seven pollen zones (PZ) dominated by grass vegetation (figure 3). The pollen assemblage recovered from the lowermost paleosol PS5 (PZ-I) is dominated by pollen grains of Cichoriaceae, Chenopodiaceae. Grains of *Picea*, *Pinus*, *Ulmus*, Poaceae, Polypodiaceae, *Selaginella sanguinolenta* are found occasionally (figure 3). The assemblage composition indicates the presence of meadow and steppe vegetation. An increasing proportion of *Artemisia*, Chenopodiaceae, *Ephedra* pollen in the transition horizon from PS4 to PS5 (PZ-II) suggests a growing climate aridity and a wide occurrence of steppe and semi-desert coenoses.

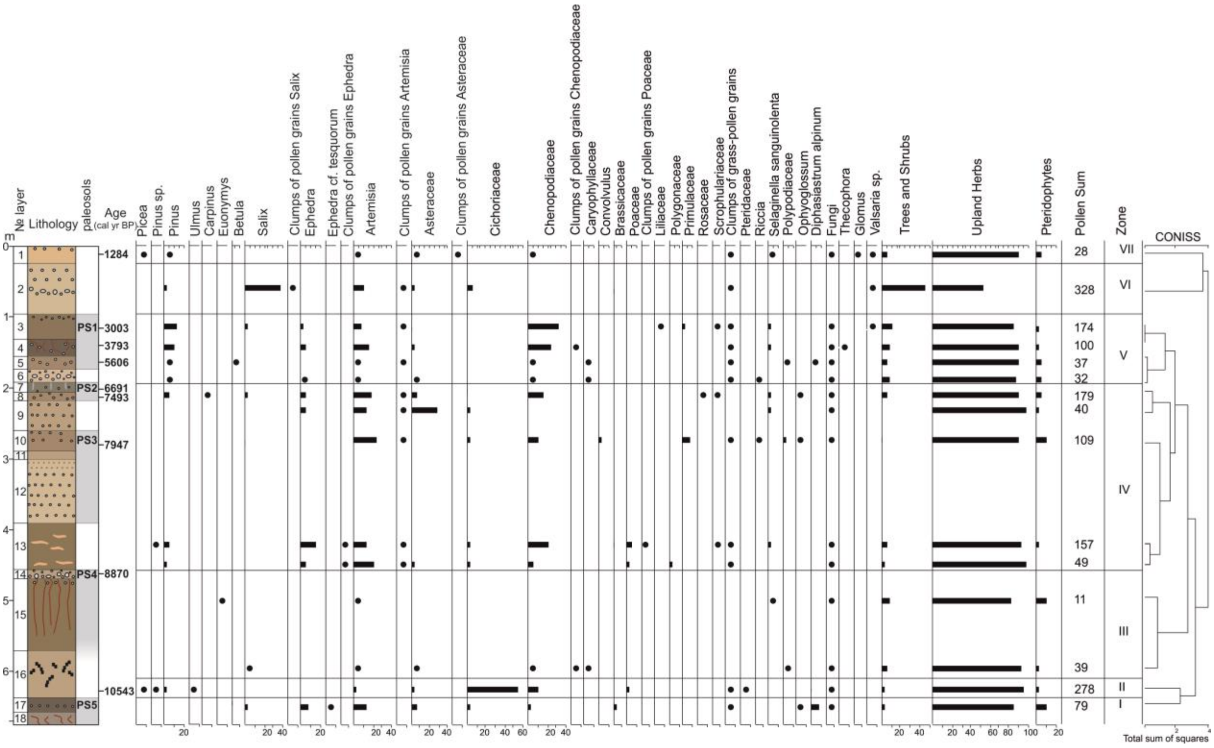

Figure 3. Spore-pollen diagram of samples from paleosols and sediments.

Pollen assemblage recovered from PS4 (PZ-III) is noted for a dominance of *Artemisia* and Chenopodiaceae and the absence of *Pinus*, *Picea*, and *Ephedra* grains, so steppe coenoses seem to be dominant. Occasionally found are spores of Polypodiaceae, *Diphasiastrum alpinum*, *Ophyoglossum*, *Riccia*, which suggests the presence of disturbed grounds. Pollen assemblages obtained from paleosols PS2 and PS3 (PZ-IV) are dominated by *Artemisia*. In parallel, *Pinus* pollen grows in proportion, and Caryophyllaceae and *Ephedra* pollen make their appearance. There are also grains of Polypodiaceae, *Diphasiastrum alpinum*, Riccia. The pollen spectra reflect the wide occurrence of the steppe coenoses and the presence of areas with disturbed soil cover. In the pollen complex PZ-V recovered from the upper buried soil PS1 Chenopodiaceae appears and comes to dominance. There are also *Pinus*, *Ephedra*, *Artemisia* present, along with occasional *Salix*, *Selaginella sanguinolenta*. The assemblage composition suggests an expansion of the steppe plant communities. The territory was dominated by steppe and semi-desert plant communities. At the same time, coniferous forests may be growing at higher altitudes.

In PZ-VI the amount of *Pinus* pollen decreases the willow pollen dominates, and *Artemisia*, Asteraceae, Brassicaceae are present. Meadow-steppes prevailed in the landscapes. Willow thickets grew along the banks of the rivers and on the floodplain. In the pollen spectrum of PZ-VII, the quantity of Asteraceae increases along with single grains of *Pinus, Picea, Selaginella sanguinolenta* are present, which indicates the dominance of steppe and semi-desert vegetation.

Open meadow-steppe and semi-desert landscapes dominated during the formation of the Orkhon section sediments. The expansion of forest vegetation in the mountains is noted during the paleosoil PS1 formation.

5. Discussion

The Orkhon section exposes a complete continuous and rather detailed succession of the Holocene paleosols and deposits. The obtained radiocarbon data provided evidence of several soils developed here since the beginning of the Holocene (and, probably, since the end of the late glacial time) – five of the soils are now buried and one functioning at present. They developed under most favorable conditions at the phases of increasing humidity and warming (stages of soil formation). Subsequently, under conditions of drier and colder climate (unfavorable phases marked by droughts and cooling), the soils were buried under eolian deposits (loess or sands) and/or deposits of temporary streams (deposition stages). Judging from the radiocarbon dates available, the soil formation stages fall on the beginning of the Holocene (the lowermost soil PS5), Boreal period (PS4), and Atlantic period – its beginning (PS3) and end (PS2). The uppermost paleosol (PS1) is distinguished by the maximum thickness and a complex profile; its development took the longest interval – from the end of Atlantic period throughout the entire Subboreal. All the soils display an increased amount of organic and carbonate matter indicative of the chernozem type of the soil formation. The lower soil PS5 is gleyed, most probably in the process of the chernozem-meadow soil formation. Two lower soils (PS4 and PS5) are the least saline, though the carbonate presence is considerable. The middle Holocene soils (PS3 and PS2) contain the least proportion of organic matter, while the salinity is increased due to dryer (even at its optimum) climate in comparison with the early and late Holocene. The modern soil is noted for a low salinity and for a notable accumulation of organics and carbonates, which suggests favorable, warm and relatively wet, environments.

As follows from the results of pollen analysis, the studied region was dominated by meadow and steppe plant communities. It may be safely suggested that pine and birch forests expanded their range. The most favorable conditions for the organic matter accumulation seemingly existed at the time of the uppermost paleosol PS1. The pollen complex (PZ-V) recovered from the soil is dominated by Chenopodiaceae. There are also present *Pinus*, *Ephedra*, *Artemisia*, occasionally *Salix* and *Selaginella sanguinolenta*. The assemblage composition suggests an expansion of steppe plant communities. At the same time coniferous forests could grow at higher levels, while the steppe vegetation occupied hypsometrically lower surfaces. The pine pollen proportion is reduced in the lower part of the present-day soil (PZ-VI). The pollen assemblage is dominated by willow (*Salix*) pollen, with *Artemisia*, Asteraceae, Brassicaceae being also present. Meadow vegetation dominated in landscapes, giving way to willow thickets at the river banks and locally on the floodplain. In the uppermost part of the present-day soil the pollen complex (PZ-VII) displays an increase in Asteraceae proportion indicative of the dominance of meadow vegetation. Grains of *Pinus*, *Picea*, *Selaginella sanguinolenta* pollen are found occasionally. Herb and grass pollen prevails in all the pollen spectra, so it may be safely concluded that open meadow-steppe, steppe and, probably, semi-deserts dominated the studied area throughout the Holocene.

Steppe and semi-desert plant communities were widely spread at the time of pollen complexes PZ-I (the lowermost part of the sequence – PS5), and also PZ-VI and PZ-VII at present (the uppermost part of the sequence – the recent soil). The forest landscapes in mountains gained in importance at the time of pollen zone PZ-IV (PS2,) and PZ-V (PS1).

There are spores of soil fungi present in the spectra, incuding *Glomus*, *Valsaria* (parasitic fungus), *Alternaria* (mold fungus), and Conidiophores. The fungi are concentrated in the sod horizon of the modern soil and in paleosols PS1 and PS3.

6. Conclusion

The data obtained in the field works and in laboratory make it clear that all the five paleosols developed in the Holocene following the chernozem type of the soil formation. The PS1, PS5 paleosols and the modern soil display typically zero or negligible salinity, along with notable accumulation of organic matter and carbonates, which suggests favorable, warm and relatively humid, environments. During phases unfavorable to soil formation the soils were buried under eolian sands and slope deposits. In all probability, the phases corresponded to dry climate.

All the spectra contain a high proportion of non-arboreal (herb and grass) pollen indicative of open spaces with meadow and steppe, possibly also semi-desert, landscapes dominant in the region during the Holocene.

The data on the paleosols are in reasonably good correlation with those on paleo-vegetation and supply additional information on the climate fluctuations in that region of Mongolia throughout the Holocene. They provide evidence of a high variability of climates and landscapes expressed in kind of rhythmicity – alternation of soil formation and lithogenesis stages.

At the same time, there is a well pronounced trend in the soil formation and climate changes traceable through the Holocene. The middle Holocene soils (PS3 and PS2) contain the least proportion of organics and are rich in salts, which may be due to somewhat greater climate aridity (even at its optimum) as compared with the early and late Holocene. That is to say, the beginning and the end of the Holocene were marked by a wetter climate than its middle part.

Acknowledgment

The reported study was funded by Russian Foundation for Basic Research (project number 18-55-91010) and by the Russian Academy of Sciences Fundamental Research Program (State Task 0148-2019-0005). We are grateful to our colleague P.G. Panin for help during the field work and detailed description of the morphological features of the section.

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