ISSN 1064-2293, Eurasian Soil Science, 2010, Vol. 43, No. 8, pp. 876–892. © Pleiades Publishing, Ltd., 2010.
Original Russian Text © S.N. Sedov, O.S. Khokhlova, A.A. Sinitsyn, M.A. Korkka, A.V. Rusakov, B. Ortega, E. Solleiro, M.S. Rozanova, A.M. Kuznetsova, A.A. Kazdym, 2010, published in Pochvovedenie, 2010, No. 8, pp. 938–955.

Late Pleistocene Paleosol Sequences as an Instrument for the Local Paleographic Reconstruction of the Kostenki 14 Key Section (Voronezh Oblast) as an Example

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Received October 19, 2009

Abstract—A sequence of five paleosol units (with seven individual paleosol profiles) buried in the Late Pleistocene (20–40 ka) deposits was studied at the Kostenki 14 (K14) key section in Voronezh oblast with the use of a set of morphological, physicochemical, and instrumental methods. The upper-lying paleosols differed from the lower-lying paleosols in the less pronounced gley features, stronger aggregation of the soil material, more significant accumulation of carbonates, and higher percentage of calcium humates and fulvates. These features attested to the higher aridity of the paleoclimate and the development of the upper-lying paleosols under grassy vegetation. Within the studied paleosol sequence, the most developed profiles were typical of the soils that formed 27–32 ka ago during the Bryansk interstadial. The good aggregation, the presence of features left by the soil fauna activity, the high magnetic susceptibility, and the morphology of the secondary carbonates in the studied paleosols suggest that they were formed under meadow-steppe vegetation in well-drained positions and resembled modern cryoarid soils.

DOI: 10.1134/S1064229310080053

INTRODUCTION

The problem of the reconstruction of the paleoenvironmental conditions of the latest glacial epoch (the Valdai, Würm, Wisla, or Wisconsin glaciation) has been studied for many decades. Great progress in our understanding of the sharp changes in the climatic conditions has been achieved in recent years owing to the analysis and correlation of geological records with high temporal resolution, including ice cores from Greenland and Antarctica [44, 45] and marine sediments [43]. In comparison with these valuable information sources, the role of paleosol information on the global paleoenvironmental conditions during the latest glacial epoch is relatively small. The major reason for this consists of the fact that the development of mature full-profile deep soils under the conditions of the strong cooling of the climate and climatic aridization in many regions was suppressed. The Valdai paleosols in the modern temperate regions of Europe are thin, poorly developed, and disturbed by cryogenesis, solifluction, or other slope processes. Often, these are synlithogenic soils. Such objects have been described by Quaternary geologists in many regional chronostratigraphic schemes of the deposits of glacial epochs; as a rule, they are used as certain stratigraphic labels [5, 25, 46].

As for the paleoclimatic interpretation of paleosol information, it is generally believed that the paleosols of the Valdai epoch were formed during relatively warm intervals, whereas the sediments of various geneses (eolian, colluvial, etc.) separating these paleosols were deposited in the cold intervals. However, the experience gained in the pedogenetic analysis and paleoenvironmental interpretation of the particular paleosols of that period is relatively small; it is incomparable with the huge amount of studies of the more ancient interglacial paleosols with better-developed profiles, particularly in the loess–paleosol sequences.

For the Valdai glacial epoch, the major attention was paid to the paleosols that developed during marine isotope stage (MIS) 3, which included several interstadials of the Middle Würm epoch with relatively mild climatic conditions [42]. In Russia, the Bryansk paleosol of the Middle Valdai age (corresponding to the second half of MIS 3) was examined in various places [8, 14, 19, 21, 30, 53].

Data on the Early Würm humic paleosols that often form pedocomplexes with the Eemian interglacial paleosol were obtained in Germany and France [42, 56]. Similar Early Valdai paleosols, together with the Mezinsk interglacial paleosol, were studied in Russia [33]. Recently, individual paleosol profiles of that period have been described in the Upper Pleistocene gully deposits in the center of European Russia [37].

Much less is known about the character of the pedogenesis in the weakly developed paleosols dating back to the coldest Late Valdai glacial maximum (MIS 2). Some paleosol horizons in the sediments of that period are known in western Europe [42, 47] and in Russia (e.g., the Gmelinsk and Trubchevsk paleosols) [9, 14, 34, 37]. However, the information on the paleoenvironmental conditions and processes that shaped these paleosols is insufficient.

The definite pedogenetic characterization of the paleosols of particular periods is usually attributed to some "central image" derived from the description of a few key sections (as a rule, these are loess–paleosol sequences on watersheds). The spatial diversity of the paleosols, paleosol catenas, and paleosol cover patterns remain poorly studied; the first works devoted to paleosol studies on slopes and in gullies appeared in the last decade [36, 37].

It seems that the attention paid to the paleosols of glacial epochs is inadequate considering the great potential of the use of data on these soils for paleoenvironmental reconstructions. The specific nature of the "soil memory" consists of its high spatial resolution; paleosol studies provide information not only on the regional but also on the local conditions of pedogenesis [55]. This is particularly important for the paleoenvironmental reconstructions performed within the framework of archaeological projects. Archaeologists should know not only the regional characteristics of the environment but also the particular local characteristics of the sites of ancient human settlements.

The experience in pedoarchaeological investigations in Russia is very extensive, but it is mainly related to Holocene objects [1, 12, 15, 22, 23, 29, 38, 40]. Similar works performed for the Paleolithic cultures of the Pleistocene age are few in number [17, 18, 20, 34, 35], though the role of the paleosol studies for this particular period may be very important.

The latest glacial epoch was a period during which some major archaeological and anthropological events took place: Neanderthals were replaced by modern humans with the corresponding change in the material cultures of the Late Paleolithic period. These processes took place under environmental conditions that radically differed from the modern environmental conditions. Surely, the study of paleosols that formed in that period should help us to understand the local regularities in the evolution of the landscapes and in the history of the interaction between the Paleolithic human communities and the environment. Our work is aimed at the study and interpretation of the paleopedological records of the latest glacial epoch at the Kostenki archaeological monument, one of the richest and best-studied archaeological monuments of the Late Paleolithic period in Eastern Europe.

The village of Kostenki in Voronezh oblast is an area of high concentration of Late Paleolithic archaeological sites in Russia. Systematic archaeological excavations with the participation of natural scientists have been performed in this area since 1923. In the 1950s–1970s, the chronostratigraphic sequence of the cultural layers was thoroughly described [6, 7, 16, 27]. The new stage of archaeological investigations in this area is associated with the names of Anikovich [2, 3], Sinitsyn [32], and Lisitsyn [28]. It is characterized by the more active application of the methods of various natural sciences. In recent years, the work of international and interdisciplinary teams has made it possible to develop a detailed chronological scale for key sections, including the Kostenki 14 (K14) section [41, 48, 54]. However, the characteristics of the paleosols found in many sections are not considered in these works. An exception is the recent study by Holliday with coauthors [49], in which data on the buried paleosols and sediments are used for the paleoenvironmental reconstruction, though the suggested interpretation is only based on the morphological characteristics of these objects.

In relation to this, the aim of our work was to study the polygenetic complex of paleosols at the K14 key site (Markina Mount) with the use of a set of morphological, analytical, and instrumental methods in order to develop the paleoclimatic and paleoenvironmental reconstruction on the basis of the paleopedological analysis.

MATERIALS AND METHODS

The authors took part in the work of the archaeological expedition of the Institute of the History of Material Culture of the Russian Academy of Sciences under the supervision of Candidate of Historical Sciences A.A. Sinitsyn in 2004–2008. Our studies were performed together with the team of paleogeographers headed by A.A. Velichko. A collective paper devoted to the paleogeography of the K14 key site was published earlier [10]. In the present paper, we focus our atten-

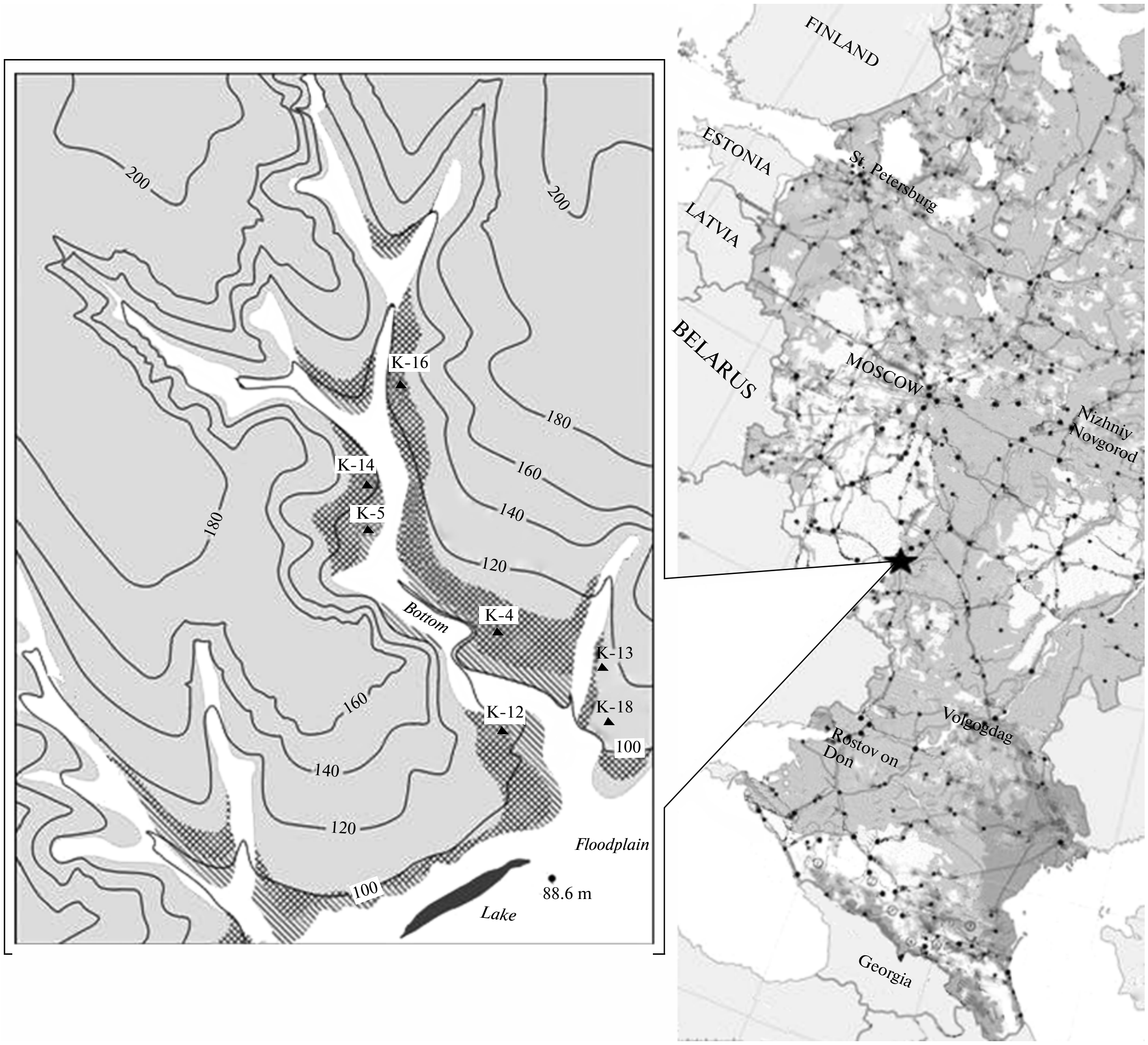

Fig. 1. Location of the studied area.

tion on the paleosols of this key site dating back to several chronointervals of the Late Pleistocene (20–40 ka ago).

The relief and sediment stratigraphy at the K14 key site. The studied key site is found on the right slope of the Pokrovskii Gully on a local watershed known as Markina Mount between two flat-bottomed gullies (balkas) dissecting the slope of the main gully (Figs. 1 and 2). The soil pits and archaeological excavations cut the deposits of the colluvial fan overlying the alluvial deposits of the second terrace of the Don River [6, 27].

As a result of our studies, the deposits were subdivided into four major stratigraphic units. Their detailed characterization is given in [10]. In the context of our study, it is important that each unit includes several paleosols, which are shown in Fig. 3.

Methodological aspects of the paleosol studies. The Pleistocene paleosols studied in section K14 belong to the category of not fully developed paleosols on slopes [30]; they are relatively thin and strongly disturbed by the slope and cryogenic processes. This made it necessary to examine all four of the walls of the excavation in order to find the places with the minimum disturbance of the paleosol profiles. Thus, the sampling of the different paleosol layers was performed in different parts of the excavation (with the minimum soil disturbance) instead of sampling from the same column, which is usually done upon sedimentologic and paleobotanic studies [10]. For all the sampled paleosols, the analysis of their correspondence to the general stratigraphy of the key section was performed in the field together with the morphological description of the paleosols and their sampling from separate genetic horizons for laboratory analyses. Undisturbed soil samples (soil monoliths) for preparing thin sections were also taken. For the magnetic susceptibility analysis, additional samples from the modern (surface) chernozem and from the oldest paleosol (section K14/V) with clear features of its burning under some ancient fire were taken. Electron microscopy analyses were mainly preformed for the samples containing secondary carbonate minerals; they were taken from the sediment layer of unit 3. This layer did not contain clear paleosol features, but it was enriched in secondary calcite of presumably hydrogenic origin.

The micromorphological observations were performed under an Olympus polarizing microscope with a digital camera. A raster electron microscope (CamScan S-2) was used for the submicromorphological analysis after the sputtering of the samples with an Au–Pd alloy at the accelerating voltage of 20 kV.

The humus content in the samples was determined by the Tyurin method; the content of carbonates, by the acidimetric method; and the particle-size distribution, by the pipette method with the soil pretreatment with pyrophosphate. The magnetic susceptibility was measured under laboratory conditions with an MS2B magnetic susceptibility meter (Bartington Instruments). The group and fractional composition of the humus in the samples from the humus horizons of the paleosols was performed by the method of Tyurin in the modification of Ponomareva and Plotnikova with the direct determination of the carbon content in the insoluble residue (the humin fraction) [31].

The radiocarbon scale developed for the cultural layers of section K14 on the basis of numerous radiocarbon dates was used by us for the determination of the chronological intervals of the separate paleosols. Often, these cultural layers in the studied part of the section were found together with paleosols within the same stratigraphic levels [47, 54]. It should be noted that, at present, a series of dates obtained by the method of luminescent dating is available for these levels. According to them, their age is more ancient than the radiocarbon age. Moreover, the luminescent dates are in better agreement with the tephrochronological and paleomagnetic data [54; Sinitsyn, 2007 (personal communication)].

RESULTS

Chronostratigraphy and Macromorphology of the Paleosols

Poorly developed paleosols with different morphologies and different degrees of preservation were identified in the thickness of the colluvial loams within section K14. The thickness of the separate paleosol layers did not exceed 20 cm and was generally much lower than the thickness of the sediment layers separating them. With respect to their stratigraphic position, morphology, and degree of preservation, the buried paleosols were grouped by us into five paleosol units indexed as K14/I, II, III, IV, and V (from the top to the bottom) (Fig. 3). These paleosol units were in certain relationships with the lithostratigraphic units

Fig. 2. Landscape position of the K14 key section.

distinguished in section K14 [10]: paleosol unit K14/I belonged to lithostratigraphic unit I, paleosol unit K14/II belonged to lithostratigraphic unit II, paleosol units K14/III and K14/IV belonged to lithostratigraphic unit III, and paleosol unit K14/V belonged to lithostratigraphic unit IV. The overlying layer of colluvial deposits served as the parent material for the surface soil (a typical aggraded chernozem developed in the Holocene). The surface soil had a deep humus layer (Ap + A + AB = 110 cm), distinct effervescence from HCl in the humus horizon, and mycelial forms of secondary carbonates in the BCk horizon.

Paleosols K14/I are weakly developed and strongly deformed soils. They belong to the first stratigraphic unit [1], in which the first cultural layer with the age of 22–23 ka is found. Two fragmentary paleosol profiles (K14/Ia and K14/Ib) consisting of the AB–BC–C horizons are separated by a layer of sediments without pedogenetic features. The average thickness of the AB–BC horizons in both paleosols is about 5–7 cm. These are brown and grayish brown horizons; in the lower paleosol, the color is more intense. The lower paleosol is also characterized by more developed pedogenic features. It is probable that it corresponds to the Gmelinsk paleosol.

Paleosols K14/II are found within the second stratigraphic unit. They are also represented by two paleosol profiles (K14/IIa and K14/IIb). The lower of them is found in the same stratigraphic position as cultural layer III (30–31 ka ago), and the upper of them corresponds to cultural layer II (28–29 ka ago) [10]. These paleosol profiles are clearly distinguished in the section by their color and distinct pedogenetic features. Both paleosols consist of the A–BCk–C horizons and are overlain by the gleyed Bg horizon. On the northern wall of the excavation, the overlying BCk horizon is also preserved above the Bg horizon.

Within the larger part of the walls of the excavation, this sequence of pedogenetic horizons is not clearly

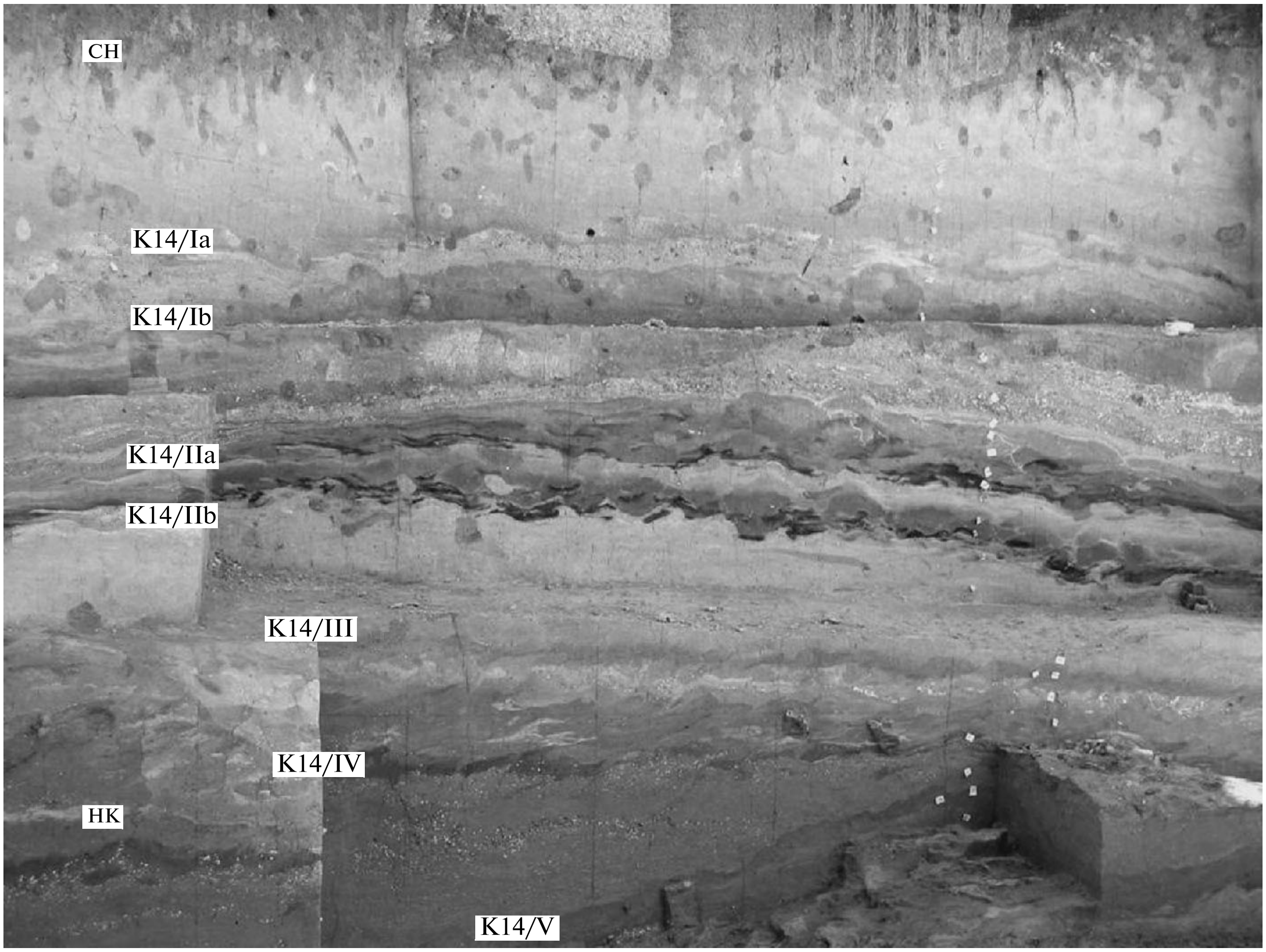

Fig. 3. Pedostratigraphy of the K14 key section. Designations: CH—lower part of the Holocene chernozem; HK—accumulations of hydrogenic carbonates.

expressed because of various disturbances and shifts; a complete sequence can be seen in the northwestern corner of the excavation. The thickness of the humus (A) horizons in both paleosols is up to 15 cm; these horizons have a dark gray-brown color, and their material is rich in smeary dispersed organic matter; the fine crumb structure of the humus horizons is quite distinct.

The thickness of the BCk horizon is about 20 cm in the lower paleosol and 7 cm in the upper paleosol. These horizons have a whitish color because of the abundance of dispersed (farinaceous) calcite. The traces of biogenic activity in the form of pore-canals penetrating into them from the A horizons and filled with dark humus material are clearly seen in the BCk horizons.

The Bg horizon has a light brown color with an olive tint; in some places, it has a mottled color pattern with numerous rusty mottles. The maximum thickness of this horizon on the southern wall of the excavation is about 8 cm.

A characteristic feature of the K14/II paleosols is the abundance of krotovinas in the A and BCk horizons. Their upper parts are "cut" by the overlying Bg horizon. In turn, the Bg horizon also contains krotovinas "cut" by the C horizon of the overlying paleosol.

Paleosol K14/III is developed in the upper part of stratigraphic unit III containing an intermittent interlayer of volcanic ash. This paleosol corresponds to the cultural layer with the ash interlayer dating back to 32.5 ka. It is underlain by cultural layer IVa with a date of about 33 ka. The paleosol's profile is thin and strongly deformed. It consists of the yellow-brown AB horizon and the underlying whitish B and whitish yellow BC horizons. It should be noted that the lenses of volcanic ash at the same level are in direct contact with the AB horizon and have very clear boundaries. However, no traces of pedogenesis can be identified in these lenses.

Paleosol K14/IV in the lower part of stratigraphic unit III correlates with the cultural layer dating back to 34 ka. This paleosol is preserved fairly well on the eastern wall of the excavation, though its horizons are

Table 1. Distribution of micromorphological indications of pedogenesis in the paleosols of the K14 section

Paleosol, horizon		Pedogenic carbonates	Iron–manganic segregations	Dispersed humus	Humified plant residues	Pedogenic microstructure	Charcoal particles
Ia		++	±	–	–	++	+
Ib		++	±	–	–	++	–
IIa	Bg	+	++	–	–	++	–
	A	+++	–	++	+++	+++	+
	BCk	+++	–	–	–	++	–
IIb	Bg	+	++	–	–	+	–
	A	++	+	++	+++	+++	+
	BCk	+++	–	–	–	++	±
III		++	+	±	–	++	–
IV		+	++	±	–	+	+
V		+	+++	–	–	±	+

Note: The frequency of the occurrence of the paleosol features is indicated as follows: (+++) high, (++) moderate, (+) low, (±) solitary, weakly developed, and (–) not detected.

strongly disturbed by cryoturbation. Paleosol K14/IV consists of the A and AC horizons. The A horizon is a thin (5 cm) horizon with a homogeneous gray-brown color and with inclusions of charcoal.

Paleosol K14/V is the lowermost paleosol within stratigraphic unit IV. A rich cultural layer (IVb) dating back to 34–37 ka is confined to this stratigraphic unit. The paleosol horizons are only seen on the northern and, partly, on the southern walls of the excavation. In contrast to the overlying paleosols subparallel to the surface, paleosol K14/V was formed under different geomorphic conditions; its surface is inclined (relative to the current slope surface) at about 20°. The paleosol profile consists of the Ag–Bg–CG horizons with a total thickness of about 20 cm. In some places, the thickness of this paleosol is reduced to 1–3 cm. The entire paleosol profile has distinct gley features in the form of rusty mottles and a bluish tint against the background of the brown color of the upper horizon. In 2004, the remains of two large hearths were found at the level corresponding to this paleosol.

Micromorphology of the Paleosol Horizons

The study of thin sections demonstrated that silty and plasmic material predominates in the studied paleosols; their microfabrics are sandy–plasmic or, in some cases, sandy–silty–plasmic. Microcrystalline calcite (micrite) predominates in the plasmic material (the clayey–carbonate plasma). The sandy and coarse silty skeletal grains are represented by the derivatives of local rocks, including the Cretaceous limestone (limestone debris, including those with microfossils) and sands (rounded grains of quartz and glauconite).

The micromorphological features of the pedogenetic processes are represented by pedogenic microaggregates (mostly, of zoogenic origin related to the mesofauna activity; some of the microaggregates could have been formed due to the cryogenic structuring of the material), calcitic and iron–manganic concentrations, and various organic components (dispersed humus, humified plant debris, and charcoal particles). Table 1 presents semiquantitative data on the abundance of these features in the studied paleosols. It can be concluded that the lowermost paleosols (K14/V and K14/IV) are specified by a lower degree of microaggregation and a smaller number of carbonate concentrations in comparison with the upper paleosols; at the same time, they are richer in iron–manganic concentrations. The number of the latter decreases in paleosols K14/III and K14/II and has a minimum in the weakly developed brown paleosols (K14/I), in which the pedogenetic features are mainly represented by the secondary calcite and by the local microaggregation.

Some specific micromorphological features of the studied paleosols should be specially described because of their value for the paleopedogenetic and paleogeographic interpretation.

The lowermost paleosol (K14/V) is specified by the abundant and diverse indications of redoximorphic processes. Ferruginous films on the walls of pores, which attest to long-term water stagnation, are only observed in this paleosol (Fig. 4a). The sandy grains are irregularly distributed in the soil mass and tend to form clusters (Fig. 4b). Similar phenomena are known for the soils affected by cryogenesis with frost sorting of the skeletal particles. Finally, this paleosol contains some components that were presumably left by humans, such as microfragments of burnt bones (Fig. 4c) and coarse charcoal fragments (Fig. 4d).

In paleosol K14/IV, the morphology of the iron–manganic concentrations is very specific; they are represented by composite dark-colored dendritic pedofeatures (Fig. 4e). The cellular fabric of these pedofeatures resembles decomposing charcoal particles; their iron–manganic nature is seen from their yellow-brown color in reflected light.

The micromorphological study of paleosol K14/III from the layer containing volcanic ash demonstrated that a larger part of the soil mass consists of the local material transformed by the pedogenesis with clear microaggregation and with redistribution of secondary carbonates in the form of micrite concentrations around the pores. Pyroclastic material—fragments of light-colored volcanic glass of the fine sand and coarse silt sizes—is only present in small amounts in the uppermost paleosol horizon. The pyroclastic material is present in the large pores and contains no features attesting to its transformation by pedogenesis. The contact of the lenses of the pyroclastic material with the main soil mass is very sharp (Fig. 4f).

The humus horizons of the K14/II paleosols are specified by the great diversity of the forms of organic matter. The colloidal humus particles (particulate organic matter) specify the uneven pigmentation of the soil mass; also, there are abundant fragments of semidecomposed plant tissues of two kinds: isotropic black-colored tissues and brown tissues of lighter color with local anisotropy owing to the admixture of calcite (Fig. 4g). These horizons also contain diverse forms of pedogenic carbonates, including microcrystalline calcite dispersed in the soil mass (carbonate impregnation of the soil mass), small clusters of large isometric crystals of sparite, pseudomorphic substitution of calcite grains for plant tissues (Fig. 4h), and lublinite crystals. The zoogenic granular structure of the soil mass is well developed. In some places, coprolites fill the biogenic pores (Fig. 4i). The plant tissues in the horizon are comminuted under the impact of mesofauna (Fig. 4j).

The material in the carbonate BCk horizons of the K14/II paleosols is generally more compact, though it contains some loci with ooidal pedogenic aggregates having high porosity. The abundance of pedogenic carbonates in this horizon is not accompanied by the diversity of their forms; the soil mass is evenly saturated with microcrystalline calcite (micrite) (Fig. 4k).

The pedogenic microaggregation of the soil mass and the high interaggregate porosity were described in the gleyed Bg horizon within the K14/II pedostratigraphic level. The micromorphological indications of gleyzation are manifested by the mottled color pattern and by the iron–manganic concentrations. The pedogenic carbonates are represented by micrite, though its amount is smaller than that in the BCk horizon, and its distribution in the soil mass is rather uneven.

In the brown-colored paleosols of the upper level (K14/I), the soil mass is enriched in coarse-grained and micrograined calcite; the clayey–carbonate plasma has a weakly pronounced pigmentation with iron hydroxides. In the thin sections from the lower paleosol of this level, we identified the presence of coarse-grained calcite (sparite) in the pores. The soil mass around such pores is depleted of carbonates, which is well seen from the lack of components with high birefringence under crossed nicols (Fig. 4l). In these loci, the plasma is predominantly clayey and is enriched in iron hydroxides. It is reasonable to suppose that the synthesis of the coarse-grained calcite in the pores took place at the expense of the dissolution and local migration of calcium carbonates from the adjacent soil mass into the pores. This was accompanied by the relative enrichment of the plasma around the pores in the clay matter and iron pigment.

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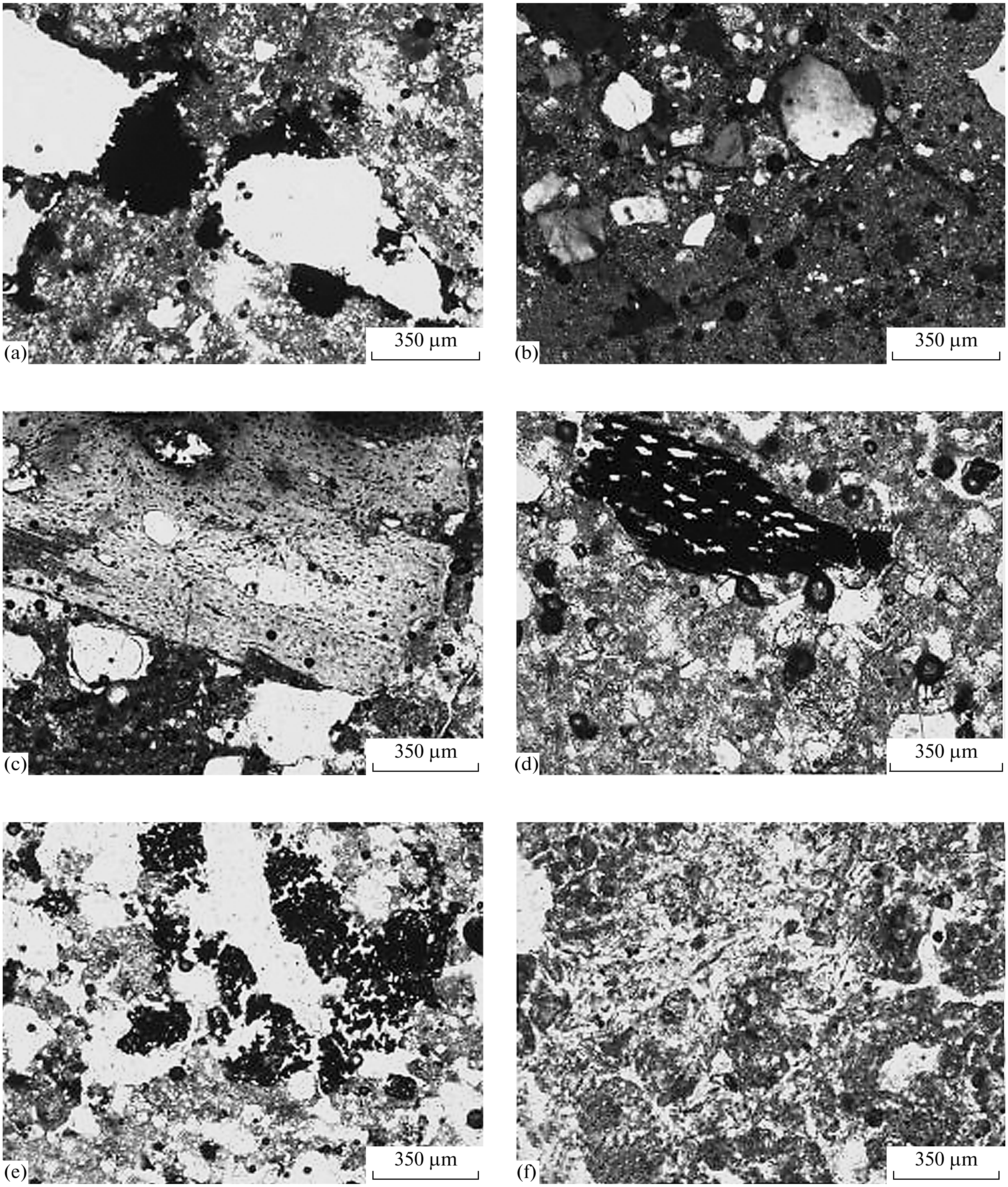
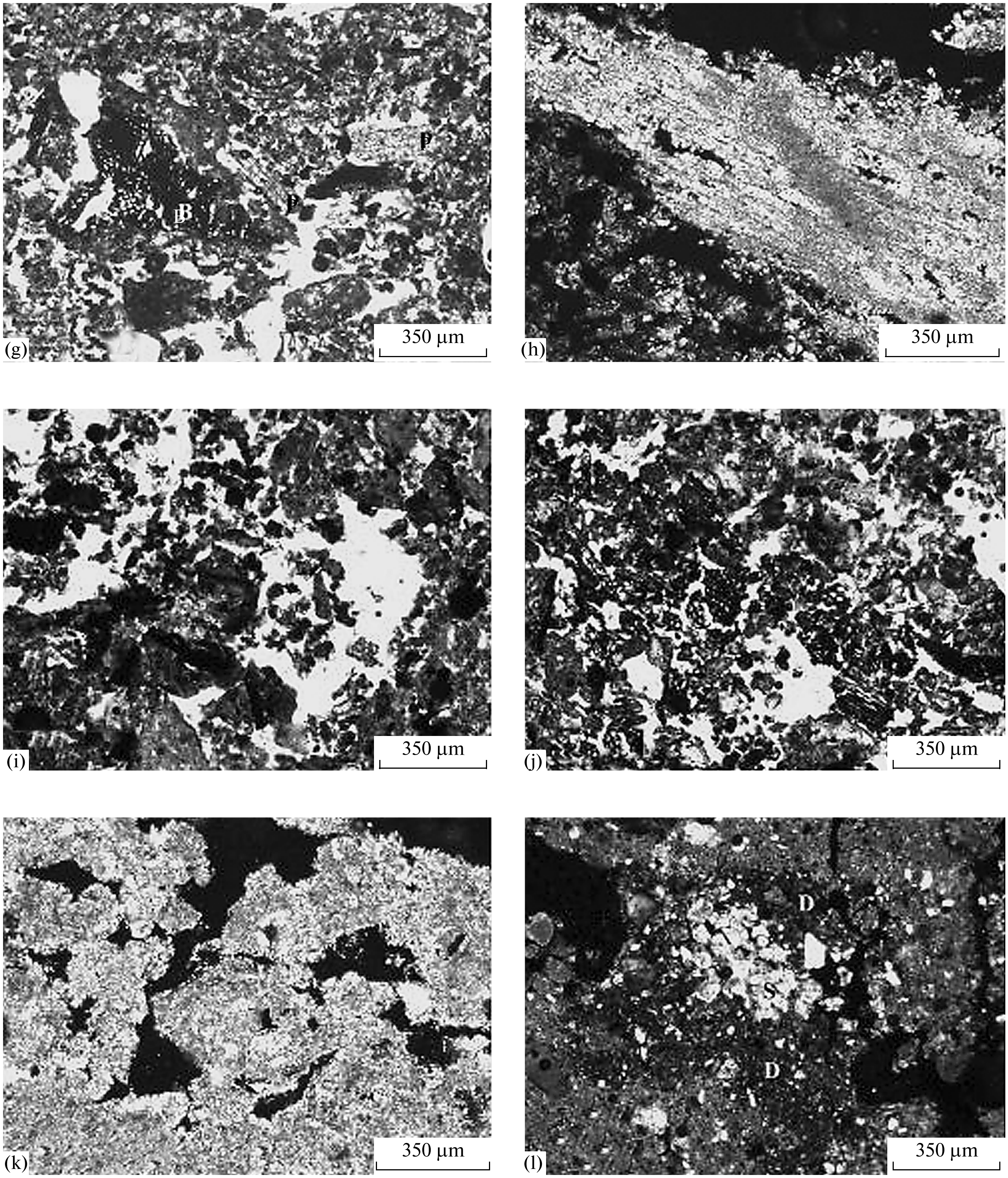
Fig. 4. Micromorphology of the paleosols from the K14 key section: (a) iron concentrations and films on pore walls (paleosol K14/V, Bg horizon, II N); (b) irregular distribution of skeletal grains with a concentration of sandy particles in the upper left corner of the visual field (paleosol K14/V, Bg horizon, II N); (c) fragment of burnt bone (paleosol K14/V, Ag horizon, II N); (d) charcoal particle (paleosol K14/V, Ag horizon, II N); (e) complex iron nodule with a dendritic structure (paleosol K14/IV, AC horizon, II N); (f) ash particles in the pore and pedogenic microaggregates in the main mass (paleosol K14/III, AB horizon, II N); (g) black (B) and light brown (P) plant residues (paleosol K14/IIa, A horizon, II N); (h) pseudomorphic substitution of calcite for plant tissue (paleosol K14/IIa, A horizon, X N); (i) pores–chambers filled with loosely packed excrements of mesofauna (paleosol K14/IIa, A horizon, II N); (j) fragmented plant tissues partly preserving their cellular structure (paleosol K14/IIa, A horizon, II N); (k) pedogenic microstructure and abundant microcrystalline calcite (paleosol K14/IIa, BCk horizon, X N); and (l) accumulation of newly formed sparite in a pore and zone depleted of carbonates and with low birefringence around the pore (paleosol K14/Ib, BC horizon, X N).



Submicromorphological Study

In the layers of accumulation of the pedogenic carbonates, the collomorphic structure of the latter is well seen under the scanning electron microscope (Fig. 5a). According to our data [26], such a structure is typical of the contrasting conditions of the pedogenesis. The collomorphic calcareous film has a fragmentary character with dissolution features in the Bg horizon (Fig. 5b).

Lithogenic carbonates in the form of small shells are present in almost all the layers of the studied



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pedocomplex. According to the study by P. Kabanov from the Paleontological Institute of the Russian Academy of Sciences, these are coccoliths from the Cretaceous deposits (the *Watznaueria barnesae* and *Biscutum* sp. species). Within the proper paleosol layers, these shells are few in number and often contain

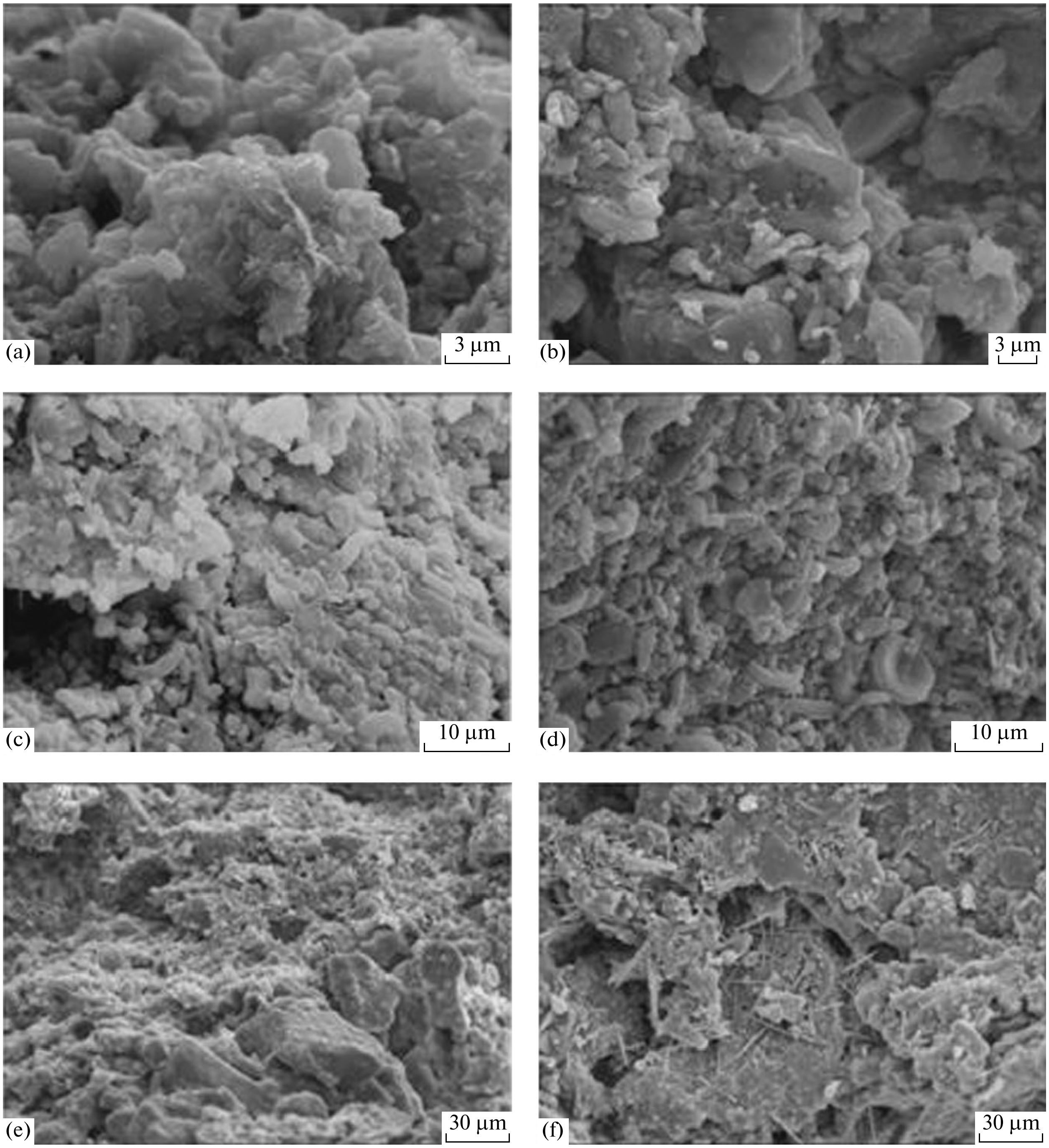

Fig. 5. Submicromorphology of the paleosols from the K14 key section. Collomorphic calcite forming (a) a continuous film on silicate skeletal grains with several growth planes (paleosol K14/IIb, Bk horizon) and (b) a fragmentary film with dissolution caverns on silicate skeletal grains (paleosol K14/IIb, Bg horizon). Coccoliths (shells) from the Cretaceous deposits: (c) with dissolution and recrystallization features and with rare shell detritus (paleosol K14/IIa, A horizon) and (d) abundant slightly transformed entire shells and their fragments (the layer between the C horizon of the K14/III paleosol and the A horizon of the K14/IV paleosol); (e) thin collomorphic calcitic film and sparse segregations of crystallomorphic calcite (paleosol K14/IIb, A horizon); and (f) acicular calcite crystals of perfect form (paleosol K14/IIa, Bg horizon).

features attesting to their recrystallization (Fig. 5c), whereas, in the layers of sediments separating the paleosols (e.g., in the layer of sediments between the C horizon of paleosol K14/III and the A horizon of paleosol K14/IV), the shells are abundant and preserve their morphological shape intact. This particular layer was named in the field the layer with hydrogenic carbonates. It consists of the mechanical mixture of

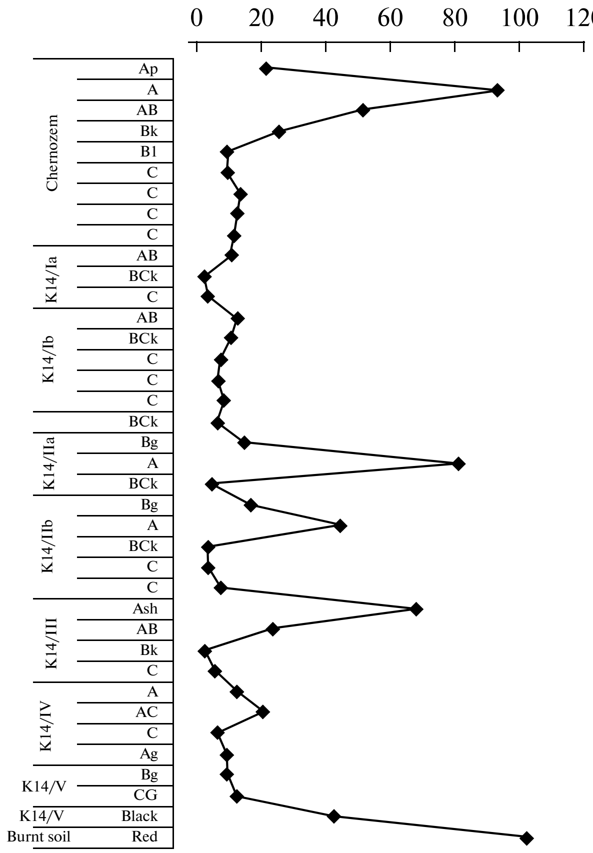

Fig. 6. Magnetic susceptibility of the paleosols in the K14 section.

shell detritus of various configurations without any features attesting to their dissolution or recrystallization (Fig. 5d).

The different paleosol horizons have their own specificity as seen at the submicromorphological level. Thus, the A horizon with the highest humus content is characterized by the presence of a thin and fragmentary collomorphic calcite film on silicate skeletal grains. In the microloci of the carbonate concentrations, the collomorphic film has a cellular structure. Granular or crystallomorphic carbonates are present on silicate grains in the form of fragmentary agglomerations (Fig. 5e).

In the BCk horizon, the collomorphic calcite film on skeletal grains becomes thicker and contains numerous growth planes (Fig. 5a). Such a structure of the film is formed when the accumulation of carbonates predominates over their dissolution and removal; in particular, it is formed upon the ascending migration of colloidal solutions with calcium carbonates from the deep soil horizons [39]. Microloci with concentrations of calcite grains are abundant in the soil mass. This horizon is also characterized by the features of recrystallization of the ancient (Cretaceous) lithogenic carbonates (coccoliths).

The Bh horizon is specified by the maximum diversity of carbonate concentrations. Fragmentary collomorphic films on skeletal grains contain separate imperfect calcite crystals growing from them. There are also acicular calcite crystals (Fig. 5f) that may have a diagenetic origin, because they do not have definite relationships with other forms of carbonate concentrations.

Magnetic Susceptibility

Against the background of the low magnetic susceptibility values in the sediment layers, well-pronounced maximums of this index are typical of the A and AB paleosol horizons (Fig. 6). The highest magnetic susceptibility is typical of the Holocene chernozem and of the dark-colored A horizons from paleosol K14/II. In the lower paleosols (K14/III–V), the peaks of the magnetic susceptibility are low; the interlayer of volcanic ash (correlated with paleosol K14/III) is specified by the strong maximum of the magnetic susceptibility. A high value of this index is also observed in the burnt material of the ancient hearth at the level of paleosol K14/V.

Physicochemical Properties

The changes in the soil texture (Fig. 7) are characterized by a general tendency toward an increase in the portion of sandy particles down the studied section; in the upper part, the portion of silty particles increases at the expense of the rise in the content of the coarse silt (0.05–0.01) fraction, which points to the admixture of the eolian loess-like material.

The distribution of the organic carbon has a maximum in the A horizons of paleosols K14/II (0.8–1.0%); in the other paleosols, it does not exceed 0.2–0.3% (Fig. 7). In paleosols K14/II, the difference between the contents of carbonates (CO_2) in the A horizon (8–16%) and in the BCk horizon (20–26%) is higher than that in the other paleosols. The distribution patterns of the humus and carbonates in these soils correspond to those in the cryoarid soils with the maximum accumulation of humus in the A horizon and the maximum accumulation of carbonates in the BCk horizon.

In general, key section K14 is characterized by the high content of carbonates in the paleosols and sediment layers (10–15% CO_2^{carb}), which may be related to the abundance of the debris of calcareous Cretaceous rocks in the parent material. It can be supposed that the secondary carbonates in the paleosol horizons appeared due to the in situ recrystallization of the lithogenic carbonates in the course of the proper pedogenic and diagenetic processes.

The high content of carbonates (22%) has been determined in the horizon of "hydrogenic carbonates" (the layer between the C horizon of paleosol K14/III and the A horizon of paleosol K14/IV). At the same

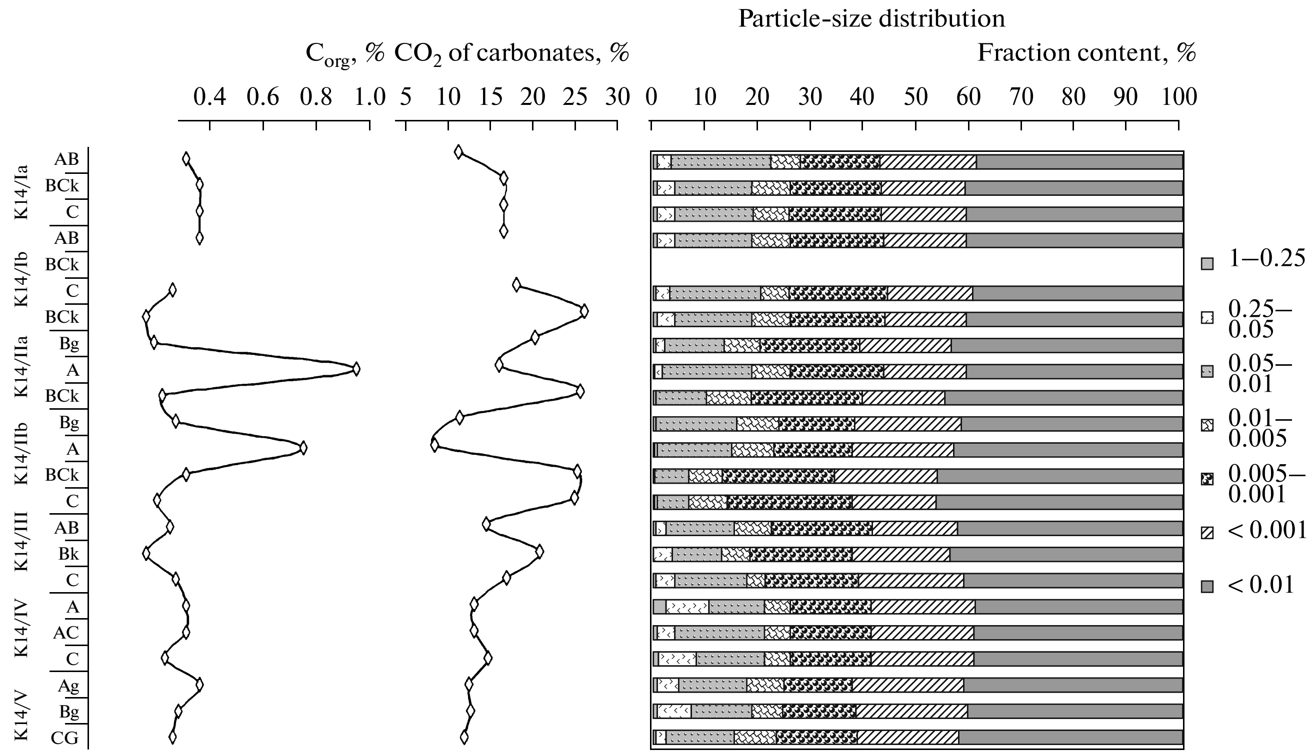

Fig. 7. The contents of C_{org} and CO_2^{carb} and the particle-size distribution in the paleosols from the K14 section.

time, there is a significant difference between the morphology of the carbonate concentrations in the horizons of their pedogenic and hydrogenic accumulation; therefore, the percentage of carbonate minerals per se cannot be indicative of their lithogenic or pedogenic origin.

Group and Fractional Composition of the Humus

The ratios of the humic acids (HAs) to fulvic acids (FAs) in the surface chernozem of the Holocene age and in the buried paleosols are sharply different (Table 2). In the paleosols, these ratios remain relatively stable. At the same time, the fractional composition of the HAs and FAs in the paleosol sequence displays quite definite changes. In the lower paleosols (K14/III–V), the third fraction of HAs and FAs (acids firmly bound with sesquioxides) predominates; the portion of the first fraction of FAs (free FAs and FAs bound with mobile sesquioxides) is also high. In the upper paleosols (K14/I–II), the second fraction of FAs and HAs (the fraction bound with calcium) predominates.

Table 2. The group and fractional composition of the humus in the modern chernozem and in the buried paleosols from the K14 section ($C_{fraction}$, % of the sum of the fractions)

Soil, horizon	C, %	Sum of the fractions	HA-1	HA-2	HA-3	FA-1	FA-2	FA-3	Humin
Modern chernozem, A	3.97	3.759	13.87	34.27	5.04	6.89	14.09	0.86	24.98
Ib, AB	0.28	0.278	0.00	20.52	7.56	8.14	14.40	6.16	43.21
IIa, A	0.9	0.896	0.53	44.63	3.35	7.97	21.20	0.00	22.32
IIb, A	0.38	0.346	1.37	29.85	16.17	0.58	17.78	8.27	25.98
III, AB	0.23	0.200	0.00	4.50	36.00	22.00	0.50	16.00	21.00
IV, A	0.52	0.492	4.07	0.00	30.49	12.40	0.00	10.37	42.68
V, Ag	0.43	0.423	0.00	20.34	17.94	21.52	0.00	16.55	23.65

Note: The analysis was performed by the Tyurin method in the modification of Ponomareva and Plotnikova. The content of C_{org} in the humin fraction was determined by the Tyurin method. Therefore, the total C_{org} content (%) differs from the C_{org} content calculated as the sum of the fractions. The latter value was taken equal to 100%.

Though the authors do not fully agree with the idea of the pedohumus method suggested by Dergacheva [24] for the paleoenvironmental reconstruction; we suppose that, in the case of a good degree of preservation of the organic-accumulative horizons in situ and their quick burying under new portions of sediments (when the admixture of allochthonous organic components into these horizons is minimal), the composition of the humus may serve as an important element of paleosol records. The paleosols studied in section K14 meet these requirements.

DISCUSSION

The memory of the Late Pleistocene paleosols is limited by a number of factors controlling the development and preservation of the paleosol profiles. First, as seen from the results of the radiocarbon dating, the intervals of the soil formation in the considered section were relatively short (up to the first thousands of years). The short period of the soil formation limited the realization of the pedogenetic processes with moderate and long characteristic response times (such as weathering, the synthesis of secondary minerals, and illuviation), which can shape the most informative and stable paleosol features. Second, the severe climatic conditions of the Valdai glacial epoch retarded the rates of the pedogenetic processes and enhanced the development of the slope and cryogenic processes, which disturbed the soil profiles. These destructive processes were favored by the position of the studied key section on a slope. The relatively weak manifestation of the Late Pleistocene pedogenesis is clearly seen if we compare the paleosols with the Holocene chernozem: the thickness of the latter is larger by an order of magnitude.

Despite these limitations, the paleosols represent an important part of the geological record. The value of this part is determined by two factors. First, the information about the paleoenvironment stored in the paleosols is independent of the other information sources (paleobotanic, sedimentologic, etc.) in the geological section because of the specific information carriers and the specific means for their interpretation, which is important for the verification of the scenario of the environmental evolution. Second, the paleosol information has a complementary character with respect to the sedimentologic information, because the soil formation manifests itself and contributes to the paleoenvironmental record during the periods of the attenuation of the sedimentation processes; in other words, it fills the gaps in the sedimentation record.

The stratigraphic position of the paleosols and the character of their bedding are the most important elements of the paleosol memory. The mere fact of the existence of the paleosol horizons attests to the stabilization of the surface, the development of vegetation, and the attenuation of various slope processes. In the context of the paleoenvironmental history of the Valdai glacial epoch, these phenomena are associated with the periods of relatively mild climatic conditions. The appearance of well-developed paleosols corresponds to the interstadial periods of the glaciation. The paleosols mark ancient surfaces, and the character of their bedding in the section makes it possible to judge the paleotopographic conditions at the site and their changes with time. In this relation, the sharp difference in the character of the bedding between paleosols K14/I–IV and K14/V is of great importance. The upper paleosols form layers subparallel to the modern earth's surface, whereas the lowermost paleosol layer has an eastward dip (which is seen on the southern wall of the excavation). It can be supposed that this paleosol was developed on the slope of a local stream that crossed this place in the past. Afterwards, its valley was filled with sediments, so paleosol K14/IV and the subsequently developed paleosols were formed on a slope having a configuration close to that of the modern slope's surface.

The main volume of the paleopedological information is recorded in the set of morphological and physicochemical properties of the buried paleosols. The short duration of the intervals of active pedogenesis in the Late Pleistocene predetermined the formation of the paleosol features created by the soil processes with relatively short characteristic times, such as the aggregation of the soil mass, the organic matter accumulation, the gleyzation, the redistribution of carbonates with the formation of secondary calcite, the bioturbation, and various cryogenic processes.

Though the number of soil processes that can be diagnosed in the paleosol profiles is limited, the relationships between them in the different paleosols bear valuable information about the paleoenvironmental conditions during the entire period of the formation of the studied section and during the particular intervals of pedogenesis.

If we consider the entire thickness of the paleosols, we can see that the lower paleosols (K14/III–V) are characterized by more pronounced gleyzation, whereas the upper paleosols (K14/I–II) have better developed pedogenic aggregation and clear features of the redistribution of the humus and carbonates. This tendency is evidenced by the macro- and micromorphological observations (Table 1). The data on the magnetic susceptibility are also in agreement with it: the low values of the magnetic susceptibility in paleosols III–V may be due to the predominance of reducing conditions favoring the destruction of magnetic minerals; the minimum values of the magnetic susceptibility are known in the gleyed horizons of both the modern [4] and buried [52] soils. The development of reducing conditions and gleyzation takes place upon the excessive soil moistening. Thus, we may suppose that the lower paleosols formed under conditions of higher moistening. In turn, this conclusion is in agreement with the observed changes in the fractional composition of the humus: the first and the third fractions of the humic and fulvic acids typical of the humid (forest) pedogenesis predominate in the lower paleosols, whereas the second fraction of humic and fulvic acids typical of the steppe pedogenesis predominates in the upper paleosols. Our conclusion about a general trend toward an increase in the aridity of the climate during the period of the formation of the upper part of the studied section is confirmed by the palynological data [10]. The spore–pollen spectra from the lowermost stratigraphic unit (unit 4) are indicative of the predominance of spruce forests; forest-steppe communities are identified by this method in the second and third units, and periglacial steppe communities are identified in the upper (first) stratigraphic unit.

A question about the absence of carbonate leaching in the lower paleosols (K14/III–V) arises. It can be supposed that the leaching of carbonates could not be realized in these paleosols because of the short periods of their development and because of the specificity of the climatic conditions. The macro- and micromorphological indications of cryogenic processes (cryogenic cracking, frost heaving, and sorting of sandy grains) point to the presence of permafrost. In turn, the presence of permafrost in the profile retards the leaching of carbonates.

The Late Valdai Paleosols (K14/I) are the most developed paleosol profiles in the studied section. They are distinguished by the brown color of the soil mass clearly seen against the background of the pale color of the enclosing sediments. The micromorphological observations point to a probable mechanism of the development of this brown color. In these soils, calcite grains tend to concentrate in the large pores, where they form relatively coarse crystals. At the same time, the surrounding mass is depleted of the microcrystalline calcite with its relative enrichment in the clayey and ferruginous components, which condition the intense brown color of the soil plasma and of the entire soil mass. This interpretation of the micromorphological data makes it possible to explain the development of the intense brown color without the participation of weathering processes (resulting in the release of iron compounds from silicate lattices and the formation of newly synthesized iron hydroxides) and iron illuviation, which could hardly be active in these poorly developed paleosols.

Paleosols K14/II are the most developed paleosols in the studied section. Their chronostratigraphic position allows us to correlate them with the Bryansk interstadial. At the same time, the morphology of these paleosols differs from the "central image" of the Bryansk paleosol that was shaped during the studies of loess–paleosol sequences on watershed positions. According to Morozova [30, p. 41], the Bryansk interstadial in the central part of the Russian Plain was the time of the development of soddy suprapermafrost gleyed soils disturbed by cryogenic processes. In section K14, the complex and multiphase nature of the considered paleosol unit should be noted. In fact, two full paleosol levels (cycles) and one reduced (eroded?) level can be distinguished. They reflect the alternation of the periods of active pedogenesis and active erosion and sedimentation processes. At the same time, the sequence of genetic soil horizons within each of these levels—the Bg–A–BCk horizons—does not make it possible to interpret the paleosol profiles as monogenetic profiles. It is more logical to subdivide this sequence of horizons into two monogenetic soil bodies: the Bg horizon corresponding to the phase of the gley pedogenesis and the A–BCk horizons reflecting the accumulation of humus in combination with the accumulation of carbonates. These pedogenetic phases could have been separated by episodes of the weak accumulation of sediments on the slope surface; these newly deposited sediments served as the parent material for the Bg horizon. An additional argument in favor of the hypothesis about the activation of the slope and sedimentation processes between the separate pedogenetic cycles and phases is the cutting of krotovinas at the boundaries between the corresponding paleosol horizons (see above).

The origin of the most developed A and BCk horizons in the paleosol profiles was a matter of a discussion among soil scientists studying section K14. M.I. Skripnikova from the Dokuchaev Soil Science Institute (personal communication, 2003) and V.T. Holliday [49] supposed that these horizons belong to a hydromorphic soil or pedosediment that formed under waterlogging conditions in the zone of the groundwater discharge. Within the framework of this hypothesis, the A horizon could have been a peaty or mucky horizon in the past, and the BCk horizon could have represented the zone of hydrogenic accumulation of carbonates. We argue that certain characteristics of the considered paleosols do not agree with the "hydromorphic" hypothesis of their origin.

(1) The accumulation of organic matter in the A horizon is clearly seen from its dark color, thought the absolute content of the organic matter is relatively small (1%). This horizon contains numerous features attesting to the activity of soil mesofauna; it has a well-developed granular structure and high interaggregate porosity. These features are typical of the automorphic humus-accumulative horizons rather than the hydromorphic horizons.

(2) The abundance of krotovinas points to the presence of small mammals in the soil; it is hardly probable that they dwelled in the water-saturated soils.

(3) The values of the magnetic susceptibility in these horizons are high and close to the values typical of the modern chernozem. High values of the magnetic susceptibility are typical of the automorphic soils, whereas the hydromorphic soils are characterized by their low magnetic susceptibility because of the destruction of magnetic minerals under the impact of reducing conditions.

(5) The comparison of the morphologies of the carbonates in the BCk horizon and in the layer of "hydrogenic carbonates" according to the electron microscopy data shows that they are different despite the similar contents of carbonates in both horizons. The collomorphic film of calcite on silicate grains in the BCk horizon is rather thick and contains several growth planes, and the lithogenic shell debris are few in number and display clear features of dissolution and recrystallization. The layer of "hydrogenic carbonates" consists of a mixture of entire shells and shell debris with sharp edges from the Cretaceous bedrock. The morphology of the calcite crystals in the BCk horizon attests to their formation under a contrasting water regime with seasonal alternation of moistening and drying cycles [50].

We cannot exclude some additional moistening of the paleosol profiles and the input of allochthonous substances (including calcium carbonates) into them with lateral water flows along the slope. However, in general, the development of the considered paleosols took place under automorphic conditions. We suppose that the modern steppe cryoarid soils of Eastern Siberia [11] are close analogues of the Late Valdai paleosols. Indeed, these soils have relatively shallow profiles with humus and carbonate-accumulative horizons; both particulate colloidal humus and plant detritus are present in the humus horizon, and dispersed calcium carbonates predominate in the carbonate horizon.

It can be supposed that the transition from a cryoarid soil (A–BCk) to a gleyzem (Bg) within each of the pedogenic cycles was indicative of some humidization of the climate. In general, the complex morphology of the paleosol–sediment sequence corresponding to the Bryansk interglacial attests to the cyclic dynamics of the paleoenvironmental conditions.

The morphology of paleosol K14/III is of great importance for revealing the relationship between the periods of pedogenesis and deposition of the ash layer. Though lenses of volcanic ash are found at the same stratigraphic level as the paleosol, they have abrupt boundaries with the soil material and are not affected by the pedogenesis. It is known that volcanic ash is a substrate highly susceptible to transformation by supergene processes. We suppose that the ashfall took place at the very end of the development of paleosol K14/III, and the pyroclastic material was partly mixed up with the soil material under the impact of relatively rapid slope processes. However, it was not transformed by the pedogenesis, because it was buried under the younger sediments. Thus, the ashfall marked the end of the pedogenesis on a relatively stable surface and the beginning of the new stage of active geomorphological processes. The activation of the latter could be caused by the climatic factor. This interpretation is in agreement with the magnetic susceptibility data: the magnetic susceptibility in the lenses of ash is much higher than that in the K14/III paleosol. It should be noted that the slightly weathered pyroclastic materials are characterized by high maximums of the magnetic susceptibility [52], and this fact may serve as an additional characteristic for the identification of the ash layers in the sediment columns.

The paleopedogenic investigations of key section K14 give us little evidence about the anthropogenic impact on the paleosols. In some of the thin sections, we identified charcoal particles that could have been produced by fires related to anthropogenic activity. In the thin section from paleosol K14/V, microfragments of burnt bone were identified. These findings are in agreement with artifacts found in the cultural layer in the same stratigraphic position; in particular, the remains of a large hearth (fire) were found in this cultural layer. It is interesting that the magnetic susceptibility of the burnt material from the hearth was very high and close to that in the surface chernozem and in paleosol K14/II; it was much higher than that in the gleyed material of paleosol K14/V. This fact points to the high potential of magnetic methods for the diagnostics of materials transformed by fire, which is of great importance for geoarchaeological investigations [51]. As seen from our data, the diagnostics of such materials is especially easy and reliable when the pyrogenic substrate is found in the gleyed soil horizon with a low magnetic susceptibility. In this case, it is easy to distinguish between the pedogenic and pyrogenic maximums of the magnetic susceptibility.

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