Landscape change and occupation history in the Central Russian Upland from Upper Palaeolithic to medieval: Paleopedological record from Zaraysk Kremlin

Tatiana Romanis, Sergey Sedov, Sergey Lev, Marina Lebedeva, Kirill Kondratev, Anna Yudina, Konstantin Abrosimov, Alexandra Golyeva, Dmitry Volkov

A V.V. Dokuchaev Soil Science Institute, Pyzhevsky per., 7/2, Moscow 119017, Russia
B Instituto de Geología, Universidad Nacional Autonoma de Mexico, Ciudad Universitaria, Del. Coyoacán, CDMX C.P.04510, Mexico
C Earth Cryosphere Institute, SB RAS, Malygina Str. 86, Tyumen 625026, Russia
D Institute of Archaeology RAS, Dm. Ulianova St., 19, Moscow 117292, Russia
E Zaraysk Kremlin State Museum-Reserve, Dzerzhinskogo St. 38, Zaraysk, Moscow Region 140600, Russia
F Institute of Geography RAS, Moscow 119017, Russia
G Chemistry Department of M.V. Lomonosov Moscow State University, Leninskie Gory, 1-3, GSP-1, Moscow 119991, Russia

ABSTRACT
Paleosol-sedimentary sequences encountered in the settlements with long occupation history could provide a unique insight into the trends of landscape development and human-environment interaction over long time scales. We studied paleosols exposed by the excavations in the Kremlin of Zaraysk (Central European Russia) which were formed during the late Pleistocene and the Holocene and contain archaeological materials spanning from Upper Palaeolithic till late Medieval. Archaeological findings and numerous radiocarbon dates provide a reliable time frame for paleopedological record which we extracted from paleosols using macro- and micro-morphological observations as well as physical and chemical properties and paleobotanical indicators (phytolith assemblages). The basal layer without archaeological materials presents signs of soil formation which resemble Bryansk fossil soil developed in the second half of Marine Isotope Stage (MIS) 3. The overlying archaeological stratum - one of the Gravettian cultural layers is linked to the paleosol level known as Zaraysk soil. Its age is estimated at 16 ka BP. Macro- and micromorphological features point to moderate dark humus accumulation, anthropogenic compaction and cryogenic processes at the final stages of paleopedogenesis. Poorly sorted heterogeneous composition of the mineral material with a large proportion of sand grains indicates colluvial origin of the paleosol parent material. The overlying sorted silty deposit supposes contribution of windblown material to its formation. We associate cryogenic and eolian processes at the end and after Zaraysk soil development with the cold intervals at the end MIS 2, presumably with the Oldest and Younger Dryas. The complete profile of Luvisol/Grey Forest Soil with eluvial and illuvial horizons and relict dark humus morphons is developed within the silty unit. This soil indicates long-term natural pedogenesis under first steppe and then deciduous forest vegetation during major part of the Holocene. The topsoil however is formed by clear plough horizon which points to cultivation started in the Middle Ages. Sharp boundary separates the buried Luvisol from the overlying cultural layer-Technosol developed after building of Zaraysk Kremlin in the 16th century. Technosol presents a mixture of natural soil with construction materials, especially limestone fragments. Soil units, both natural and affected by humans, are not separated one from another by an unaltered C horizon, so soil-forming processes from the upper soils penetrate into the underlying ones forming a multistory pedocomplex.

ARTICLE INFO
Keywords:
- Paleosol
- Upper Palaeolithic
- Late Glacial
- Luvisol
- Pedocomplex

1. Introduction

The societies depend to a great extent upon their interaction with their environment that is variable in time and space. Tracing this interaction through the past could reveal long-term trends of direct and feedback processes of human adaptations linked to ecosystem
transformation valuable for strategic forecast and planning. This is a task for interdisciplinary research bringing together historians and archaeologists with geoscientists. The latter are expected to provide “paleoecological proxies” - the datasets from the geological archives documenting the climatic and environmental changes. Among them more attention is usually given to those which provide the highest chronological resolution (preferably at the yearly to decadal scale): i.e. to the records from the lacustrine and peat cores, speleothems etc.

Paleosols – soils formed under the environmental conditions of the past (Catt, 1990) – also provide a paleoecological proxies which have special significance for historical and archaeological research. Although they rarely reach the temporal resolution of the above-mentioned sedimentary records, they have another unique advantage – high spatial resolution (Targulian and Goryachkin, 2004). Being controlled by the local soil forming factors paleosols provide site-specific paleoecological information whereas most of other proxies could be interpreted as a regional approximation. Especially important are findings of paleosols and even paleosol sequences at the archaeological and historical sites with long occupation history, in the direct relation with ancient constructions and artefacts. In these cases, paleosol-sedimentary profiles

---

Fig. 1. Location of the site: 1 - Location of Palaeolithic sites in the historical part of Zaraysk; 2 - Zaraysk town plan with test pit of 2018; 3 - Zaraysk on the map of the Eastern Europe.

Legend
- trench with Palaeolithic cultural layer (2016)
- excavations and test pits
- expected boundaries of different loci on Zaraysk site
- titles of different loci on Zaraysk site

- trench with Palaeolithic cultural layer (2016)
- excavations and test pits
- expected boundaries of different loci on Zaraysk site
- titles of different loci on Zaraysk site
could be integrated with the local historical record and thus could be presented in a modern museography as an object of public interest. There are several successful case studies in the major Russian historical centres: Moscow Kremlin (Golyeva et al., 2018), Yaroslavl (Engovatova and Golyeva, 2012), southern ancient cities (Alekseandrovskii et al., 2015) however, in general, this potential of paleosol research is still under-exploited.

With these ideas in mind we studied the section of Zaraysk site within the Kremlin of Zaraysk – a famous historical and archaeological site in the centre of European Russia, 165 km to the south-east from Moscow (Amirkhanov, 2000; Amirkhanov et al., 2009; Amirkhanov and Lev, 2008, 2009). The site has a major significance for the occupation history of the Eastern Europe, integrating evidences of human presence spanning from Palaeolithic till Medieval although with major hiatuses (see Section 2.1.2). It is located in the northern part of the East European forest-steppe – a major continental ecotone between forest and steppe biomes where large-scale environmental changes occurred since the spread of Homo Sapiens 30–40 ka BP. Major information about the ecosystem response to the climatic change is derived from the palaeological records (Khotinsky, 1984; Klimanov and Serebyannaya, 1986; Novenko, 2006; Spiridonova, 1991). Evolution of pedogenesis is documented for the Late Pleistocene by the works on buried loessic soils (Morozova, 1981; Velichko, 1990; Velichko et al., 2006), and for the Holocene – by the study of polygenetic surface soils (Alekseandrovskii, 1983), floodplain and colluvial paleosol-sedimentary sequences (Alexandrovskiy and Chichagova, 1998; Alexandrovskiy et al., 2004) and soils buried at the archaeological sites (Chendev, 2008; Rusakov et al., 2019). The proposed paleoenvironmental scenarios are still not free from contradictions, in particular concerning the position of the forest/grassland boundary throughout the Holocene. Some pedogenetic stages are poorly documented, especially the Late Glacial soil formation. In the scheme of Velichko et al. (2006) it is represented by Trubchevsk paleosol level; also lateglacial paleosols were encountered and dated in several natural sections as well as archaeological sites, receiving the local denominations (e.g. Gugalinskaya et al., 2015; Kovaleva et al., 2013; Velichko et al., 1977, 1997). However, their pedogenesis has not been studied in detail.

The earlier geoarchaeological research in Zaraysk (Gribchenko et al., 1997) was focused on the Palaeolithic archaeological strata and did not involve detailed pedogenetic analysis. Recently the paleosols of the section Zaraysk B were investigated by two independent groups; one study was based on the micromorphological observations (Lev et al., 2018), the other - on the micropaleontological (biomorph) and geochemical results (Naugolnykh, 2019). This paper presents the new research of the complete paleosol-sedimentary sequence exposed in the section of the archaeological excavations of Zaraysk F site in the Kremlin of Zaraysk (Lev, 2018, 2019). A set of morphological and physico-chemical methods was applied to detect the main phases of pedogenesis (both natural and human-induced) during the whole period preceding and coinciding with the human occupation. The pedogenetic succession is further linked to the local historical and archaeological contexts and on the other hand correlated with the regional paleopedological and paleoecological records. We finally intend to develop a comprehensive scenario of the human-landscape interaction at the local scale and its imprint in the “soil memory” of the site section. This scenario will further contribute to the regional model of environmental change in the centre of the Russian Plain since MIS3.

2. Materials and methods

2.1. Study site

2.1.1. Geographical setting

The Upper Palaeolithic site of Zaraysk F is located in the center of Zaraysk town (54°45′27.12″N 38°52′14.98″E), Moscow Region, Russia, at the north-eastern margin of the Central Russian Upland (Fig. 1). Due to its position on the high promontory of the right bank of Osetr river, it is characterized by strongly dissected topography and a network of gullies. The valley of Osetr belongs to the Oka river basin which is situated at the northern limit of the Quaternary loess deposition and quite close but still outside the margins of the last Pleistocene glaciations: Valday (MIS4-MIS2) and Moscow (MIS6) (Velichko et al., 2006).

The study area is characterized by moderately continental climate with mean annual temperatures from +3.5 °C to +4.3 °C. The warmest and the coldest months are July and January with respective mean temperatures of +21 °C and −11 °C. A mean annual precipitation of 500 mm includes summer precipitation of up to 200 mm (Annenskaya et al., 1997). Natural vegetation consists of meadows dominated by silver cinquefoil (Potentilla argentea), common chicory (Cichorium intybus), common wormwood ( Artemisia absinthium) and hoary alyssum (Berteroa incana) combined with broad-leaved and mixed forests with oak, lime, maple and ash with admixture of birch, aspen and spruce (Map of vegetation, 1996). Large part of the natural plant cover is replaced by cropland.

According to the Russian soil-bioclimatic regionalization (Map of Soil Ecological Regionalization, 2007), the study area belongs to the region of deciduous forests, forest-steppe and steppe and the subzone of Grey Forest Soils under deciduous forests. Loess-like (silty) mantle loams served as parent materials of predominant soils, which were defined according to the Russian classification as Grey Forest (National Atlas, 2011) or Agrogrey (Shishov et al., 2004) Soils; their WRB (2014) analogues are Luvisols.

2.1.2. Archaeological and historical context

There are more than 3.500 archaeological sites discovered by the present time within the Moscow Region. Their historical ages embrace all archaeological epochs (Stone Age, Bronze Age and Iron Age) and range from the Upper Palaeolithic period (40-10 thousand BP) to the Modern Era.

The present study is focused on the archaeological site in Zaraysk Kremlin. In 2018, a pit 2 m wide and 2 m deep was excavated with the aim of verifying the boundaries and stratigraphy of Zaraysk F locus of the Upper Palaeolithic Zaraysk site (Fig. 2A).

The upper part of the profile consisted of urban deposits of the 16th–19th centuries (Cultural Layers from 2 to 6, see Fig. 2). Below, there was the Kremlin foundation level marked by a layer of crushed limestone and brick, i.e., Cultural Layer 7 (Fig. 2), which was confidently dated to 1528–1531 on the basis of written sources. It is documented that Zaraysk Kremlin was built following the order by Vasily III to fortify the southern border of Medieval Russia and defend from Crimean tatars.

The Kremlin foundation layer was underlain by the plough layer of ancient paleosol, which contained pottery of the 12th-14th centuries (Cultural Layer 8) and had a clear lower boundary corresponding to plough line. There were no artifacts found in the underlying layers 8a, 9 and 10, i.e., there was no record of human activity at the Zaraysk F site in the middle/early Holocene and the latest terminal Pleistocene. Archaeological Layer 11 was characterized by a strong dark pigmentation and inclusions of charcoal particles (Fig. 2B). Similar observation is repeated on the previous excavation sites of Zaraysk A and B, with particularly detailed study on the site of Zaraysk B (Lev et al., 2018).

In the studied pit of Zaraysk F, Layer 11 was underlain by Cultural Layer 12, which also contained artifacts of the Kostenki-Avdeevko (Eastern Gravettian) culture (Fig. 3A,B). Age of Layer 11 was estimated at 16 ka BP (16,520 ± 760 GIN-4458a) and 18 ka BP (17,900 ± 200 GIN-8865) by radiocarbon dating of charred bone and humus, respectively, from the nearby locus of Zaraysk B placed just outside of Zaraysk Kremlin, at a distance of about 100 m from Zaraysk F test pit (see locations of excavation pits in Fig. 1A).

There were more than 1300 flint artifacts recovered from Cultural Layer 12 (a small cash pit with selected blades, zones of primary debitage and blade production) as well as large pieces of ocher (mixture of
red ferric oxide and varying amounts of clay and sand) and mammoth bones (Fig. 3B). A deepen mammoth scull with down-facing alveoli (root sockets of tusks), which was exposed in Cultural Layer 12 (Fig. 3B), was believed to be a marker of an earth-dwelling or big pit – typical features of Kostenki type living structure with the central raw of hearths surrounded by pit houses (Amirkhanov, 2000; Amirkhanov et al., 2009; Efimenko, 1958).

Despite a lack of record of human activity for a certain period in the studied pit (i.e., Layers 8a, 9, and 10), it is known that the area of Zaraysk Kremlin was populated by humans all along the historical timeline including different climatic phases. Cultural layers of a rural non-fortified settlement of Medieval period including pre-Mongolian time (12th–14th centuries AD) were exposed during a previous archaeological excavation just outside of Kremlin wall, at a distance of 100 m to the south of the Zaraysk F profile; we encountered the fragments of pottery of this period in the buried Ap horizon (layer 8) of the studied pit. The first Slavonic occupation in the study area corresponds to the 8th–10th century CE. The Early Iron Age hillfort of the Dyakovo (Finno-Ugric) culture (the 7th century BCE – the 7th century CE) was discovered at a distance of 50 m to the north the Zaraysk F locus. Unfortified settlements with artifacts of the Romensko-Borshevo (the 8th-10th century CE) and the Ienevsky archaeological cultures of the Mesolithic period (9–8 thousand years BP) were found at a distance of 1 km to the north of Zaraysk Kremlin. Sites of the Neolithic and Bronze Age are known within the Zaraysk town borders and the Upper Palaeolithic sites are reported within the Zaraysk region, e.g., the Tregubovo settlement located 9 km to the southwest of the Zaraysk site (Trusov, 2011).
2.2. Paleopedological methods

2.2.1. Sampling strategies
We described soil-sedimentary sequence exposed in one of the archaeological excavations on Zaraysk site – locus Zaraysk F (Fig. 2B). The soil profiles and their diagnostic horizons were described following the guidelines of IUSS Working Group WRB (2014). Soil color was determined in the field using Munsell Soil Color Charts (2013). Bulk samples for laboratory analyses, undisturbed oriented monoliths (4 × 5 × 1.5 cm) for micromorphological analysis and undisturbed monoliths in hermetically sealed cylindrical plastic containers (d = 0.8 cm, h = 0.5 cm) for X-ray computed tomography (CT) were taken from each buried soil horizon and cultural layer. Additionally, we took undisturbed monoliths from contact zones of soil horizons and cultural layers. Samples for phytolith analysis were taken from buried A horizons, i.e., surface horizons of paleosols, which were expected to contain silica microfossils produced by ancient vegetation in this location.

2.2.2. Soil micromorphological analysis
The samples for thin section preparation were impregnated with polyester resin–acetone mixture (with the refractive index of 1.536). A week later the hardened monoliths were cut into small blocks with a diamond-edge saw. One side of each block was smoothened with a diamond grinding and mounted on a thin section glass. Then the thickness of the block was reduced down to 50 μm using the Brotlab system and further down to about 30 μm using a grinding machine and finishing with manual grinding with boron carbide powder.

The thin section analysis was conducted using an Olympus BX51 polarizing microscope (Tokyo, Japan) with an Olympus DP26 digital camera (Tokyo, Japan) in plane-polarized light (PPL), crossed-polarized light (XPL) and oblique incident light (OIL). Computer software supplied with the Olympus BX51 microscope was used for visualization of the features observed. For better detection and differentiation of illuvial coatings in the studied soil profiles image processing of all microphotographs was done by using Image analysis system «Thixomet». International terminology was used for describing the soil microstructure (Stoops, 2003). Process interpretation of micromorphological features were based on the Stoops et al. (2010).

2.2.3. The 3D structure of undisturbed samples (monoliths)
of paleosols and cultural layers was studied by the use of X-ray Micro-CT SkyScan1172, with settings recommended by producers for certain measurements. Series of 2D-images obtained by the CT Scan were processed on computer to create 3D-images of the internal structure of the monoliths studied and to calculate different morphometric parameters using the Bruker software (NRecon; CTan 1.18.4.0; Data Viewer; CTvox).

2.2.4. Particle size distribution
Was estimated using a Microtrac Bluewave laser diffraction analyzer (Microtrac, USA). Irregular shape and absorption index equal to 1 were used for solid phase. Soil water suspensions were dispersed by a Sonifier S-250D ultrasonic horn-type digital disruptor (Branson Ultrasonics, USA) with the standard horn tip. Energy of dispersion was equal to 500 J·ml⁻¹. Particle size fractions were determined according to the Russian system (clay < 1 μm, silt 1–50 μm and sand 50–1000 μm). Soil texture classes were defined using the USDA terminology.

2.2.5. Portable X-ray fluorescence
Spectrometry was used for in-field nondestructive investigation of pedogenesis. In-field soil profile scanning utilizing pXRF shows good results in the absence of the possibility of destruction of the sample for subsequent laboratory analysis. The Vanta-M Portable EDXRF Analyzer (Olympus) features an Rh anode X-ray tube of 8–50 eV at < 200 mA (Silicon Drift Detector/ Resolution < 135 eV) and operates based on an internal factory-installed calibration procedure, which uses the Fundamental parameter method to estimate the elemental concentration of the soil directly in mg kg⁻¹ (PPM). In-field measurements were taken using the Geochem operational mode, which operated in a two-beam configuration at 50 and 10 kV. Samples were scanned for a duration of 60 s per beam, with the size of the analyzed area of 216 mm². Concentrations of Cu, Zn, P, Ca, S, Ti, Fe, Al, Mg were measured in each soil horizon and cultural layer.

Element mapping for thin sections was done by micro-X-ray fluoroscopy (µ-XRF) spectrometer Tornado M4 Plus (Bruker Nano GmbH, Germany). Rh-anode X-ray tube with 500 μm collimator aperture (50 kV, 600 μA) and polycapillary lens was used for X-ray generation, at this conditions X-ray spot size was 20 μm. Two identical energy dispersive detectors (at 90 keV maximum pulse throughput; 40 keV maximum energy, temperature ~35 °C) were used for the detection of fluorescence radiation. For mapping spectra (0–40 keV range) were collected at each point after 8 μm with 10 ms measurement time at the point. Kα lines were used for distribution maps of all elements. Measurements were done in a vacuum (approx. 2 mbar). An optical camera was used for a sufficient overview of the sample and an optical mosaic generation.

2.2.6. Microbiomorphic analysis
The main method of microbiomorphic analysis was the consecutive study of separate kinds of biomorphs under the microscope (detritus, phytoliths, sponge spicules and other remains of the biota). The amount of 50 g of samples were treated with a hot 30% solution of H₂O₂, separated from sand and clay, and subjected to flotation in a heavy liquid (cadmium iodide and potassium iodide with a specific gravity of about 2.3 g/cm³). After 10-minute centrifugation, the floating siliceous and other biomorphs were collected into a tube and washed with distilled water several times, then immersed in oils (silica oil or glycerine), and studied under the optical microscope at magnifications varying from 200 to 900 times. The quantitative content of silica microbiomorphs was assessed. We counted all morphotypes we found per the whole slide. Analyzing the entire complex of soil microbiomorphs enables one to determine the entire spectrum of particles from one sample. Ecological and environmental interpretation of the phytolith assemblages was given according to Golyeva (2007) who characterized phytolith assemblages from different ecological zones of the Russian Plain.

3. Results

3.1. Field morphological characteristics of the section
A sequence of two paleosols was described under set cultural layers accumulated since 16th century CE in the archaeological excavation test pit at Zaraysk F locus (Fig. 2). Cultural layers that consisted of organo-mineral soil materials mixed with construction wastes were underlain by a discontinuous seam of fine calcareous debris (archaeological layer 7).

The profile of the first paleosol buried under the calcareous layer has the Ap-AE-AB-Bt set of horizons and corresponds to the archaeological layers 8–10. The plough layer Ap (archaeological layer 8) was grey (10YR 5/1), compact, well-structured, with abrupt lower boundary that corresponded to the plough line. The lower humic horizon (AE) had bleached zones, subangular blocky structure and diffuse lower boundary. The transitional horizon (AB) was darker, compact, with subangular blocky to platy structure, with a sharp lower boundary. The underlying illuvial Bt horizon had a Munsell color of 10YR 5/2 and fine angular blocky structure with clay coatings on ped.

The second paleosol is developed in the archaeological layers 11–14. It begins with the 2AB horizon (the uppermost A horizon was supposedly lost due to erosion and/or mixed with sediment). The 2AB horizon is rather compact, 7.5 YR 4/4, with fine granular structure.
Below lies the 2BA horizon formed within the Cultural Layer 12; it had a Munsell color of 7.5 YR 6/4, with laminated structure and uneven humus pigmentation. The 3B horizon/archaeological layer 14 was characterized by 2.5YR 4/6 color and the presence of zones enriched in coprolites. The texture of the 2BA and especially 3B horizons was coarser (sandy loam) than that of the overlying horizons of paleosols (silty loam).

3.2. Micromorphology of paleosols

At a microscale, Cultural Layer 3a consisted of angular blocky pedds that were formed of sandy-silty-clayey material (Fig. 4A) and incorporate small fragments of laminated clay coatings and diverse pedofeatures of calcium phosphate. Below lies thin calcareous layer 7, which consists of sand-size limestone fragments with numerous marine Paleozoic microfossils (Fig. 4B). The underlying ancient plough Ap horizon is made up of compacted well-structured sandy-silty-clayey material strongly impregnated with humus (in form of punctuations...
and clods). It contained abundant concentrations of calcium phosphate that were round-shaped, almost isotropic under crossed polarizers and yellowish in transmitted light (Fig. 4C) and few concentrations of mica in some peds (Fig. 4D). Other micromorphological features of the plough layer included dark humus mottles, fungal hyphae, small charcoal particles and charred residues of plant tissues within peds.

The AE horizon is characterized by a well-developed subangular blocky, fine angular blocky and platy structure. Locally we observed bleached silt microzones indicative of eluviation process neighbouring fine clay-humic intrapedal material (Fig. 4E). There were also occasional small Fe concentrations and Mn-clay-Fe nodules that were formed as a result of redoximorphic processes within this horizon. The AB horizon has clayey-silty groundmass impregnated with humus, subangular blocky structure produced by a system of planar voids sometimes crossed by channel pores. There were humus pedofeatures in form of fine clods and streaks along pore walls. Some larger channels are loosely filled with coprogenic granular aggregates (Fig. 4F). Below, in the Bt horizon the clayey-silty material was better structured than that in the above horizon, with the predominance of large angular blocky peds. They contain coatings that differed in thickness, composition and, presumably, time of formation. There were abundant clay coatings inside peds with strong interference colours combined with ferruginous coatings and mottles (Fig. 4G,H). There were also thick laminated coatings of complex composition, i.e., consisting of clay, humus-clay and occasionally silt laminae; many of such coatings were fragmented.

The 2AB horizon of buried soil of the Palaeolithic age at a micro scale consisted of sandy-silty-clayey material of heterogeneous structure. There were predominant large angular blocky peds and occasional small subangular blocky peds, which were characterized by the presence of micro clods of humus or humic pigmentation (Fig. 5A). Bleached quartz and feldspar grains free from coatings were arranged in either clustered (Fig. 5B) or, less frequently, circular patterns due to cryogenic separation processes.

There were two types of coatings within the 2AB horizon that had different composition, structure and localization within soil fabric. The predominant Type 1 was represented by thin coatings that were formed within small intrapedal pores and consisted of oriented clay (Fig. 5B). Type 2 included compound coatings that consisted of a thick laminated clay layer associated with ferruginous films and mottles (Fig. 5C). These pedofeatures are quite similar to those observed in the Bt horizon.

Further down the profile, Cultural Layer 12 – 2BA horizon consisted of very compact sandy-clayey material similar to that of the lower horizon, but with an admixture of silt. There were alternating sandy and sandy-clayey microzones with humus-clay intercalations of subparallel orientation (Fig. 5D). The groundmass contained inclusions of bones, which were covered with fragmentary Fe-clay-humus films (Fig. 5E,F), as well as phosphate pedofeatures and small particles of charcoal.

At the bottom of the studied profile, 3B horizon had a compact consistency, isolated peds, abundant sand grains and close porphyric c/t related distribution with ganostratiated b-fabric of clayey fine material (Fig. 5H). Sand fraction consisted of quartz, feldspars and isotropic grains of glauconite. There were microzones with compact rounded microaggregates (probably coprogenic) and few sparitic granules – calcified earthworm casts (Fig. 5G).

### 3.3. Particle size distribution

As shown in Fig. 6, there was a change in the type of deposits at a depth of 140 cm, i.e., from coarser-textured 2BA and 2B horizons of second paleosol (cultural layers 13 and 14) (loamy sand and sandy loam, respectively) to finer-textured deposits above (silt loam). The 2BA and 2B horizons were enriched with fine and medium sand (50–250 and 250–500 µm, respectively). The overlying sequence, including the 2AB horizon and the profile of the first paleosol - Grey Forest Soil was dominated by silt fractions (1–50 µm), among which coarse silt (10–50 µm) prevailed. However, sand (50–1000 µm) was present at all depths, with the minimum of 11.1% in the Bt horizon. Contents of clay fraction (< 1 µm) were low throughout the studied section; however within the profile of Grey Forest Soil it shows clear eluvial/illuvial differentiation with minimum in Ap and AE of just 4.8% and maximal values close to 10% % in the Bt and 2AB horizons (Fig. 6).

### 3.4. X-Ray computed tomography

Results of X-ray computed tomography included quantitative measurements (Table 1) and 3D-diagrams of pore distribution (Fig. 7).

The plough layer Ap was characterized by the highest total porosity (32.73% of soil volume) with high proportion of open pores which accounted for 31.86%. The 3D diagram of pore distribution showed that the plough layer had a whole range of pore sizes, with abundant small pores (15.7–47.1 µm) and occasional large channel pores (100–600 µm). Below Ap horizon the pore space gradually decreased with depth within the sequence AE-AB-Bt horizons, also the proportion of open pores was lower in AE and AB.

The underlying 2AB horizon - cultural layer 11 had the highest degree of compaction and the lowest percentage of open pores (9.65% of the total porosity). However, there was an increased percentage (1.85%) of closed pores. The 3D diagram of pore size distribution showed a predominance of pores of up to 100 µm in size. 2BA horizon of the second paleosol had the highest compaction and the lowest number of closed pores (409.68 1/mm³). However, percent of closed pores per volume of sample was relatively high (1.83%). The closed porosity probably developed as a result of human-induced compaction of soil material.

The 3B horizon (150–155 cm) had the highest closed porosity (2.67%) and the highest number of closed pores (1468.85 1/mm³) as well as a relatively high open porosity (14.44%).

### 3.5. Results of the microbiomorphic analysis

The microbiomorphic analysis of five samples of paleosols from the Zaraysk site showed that all horizons had low contents of plant detritus (Table 2). Detritus was represented by large fragments within the AE horizon and by very small fragments within the Bt horizon. Amorphous organic material was generally frequent and even abundant within the 2AB horizon. Diatom shells and sponge spicules were rare and only occurred in upper horizons, i.e., Ap and AE. Diatom shells were fragmented and sponge spicules were corroded (Fig. 8A). Phytoliths were abundant in the AB horizon and rare in the underlying Bt horizon, with intermediate frequencies of occurrence in other horizons (Table 2). All phytoliths found within the Bt horizon were strongly corroded.

The distribution of phytolith forms is shown in the Table 3. The Ap, AB and 2AB horizons were characterized by the prevalence of phytoliths of mixed meadow communities (Fig. 8B, C) and the AE horizon was dominated by woodland phytoliths (8D). The AB horizon was also distinguished by the maximal diversity of phytolith forms with the presence of steppe and xerophytic grass species (4% and 1% of all phytoliths, respectively) as well as phytoliths of conifers and other woodland species. The latter were strongly corroded and often charred. Phytoliths of dicots (including meadow grasses) were less corroded and only partly charred. Steppe and arid forms were well preserved and not charred.

### 3.6. The results of the XRF elemental analysis and high-precision XRF mapping

The portable X-ray fluorescence (XRF) elemental analysis of different paleosol horizons and cultural layers of the Zaraysk F pit allowed us to distinguish two groups of chemical elements depending on their distribution within the studied profile. Elements of Group 1 (P, Ca and
K) were concentrated within the layers, which contained artifacts such as bones and charcoal and/or had evidences of cultivation (Fig. 9A, B).

Highest concentrations of Ca and P were registered in the urban deposits of the 16th–19th centuries (Cultural Layers 3a, 5 and 6). Potassium was accumulated within the ancient plough horizon (Ap, which corresponded to Cultural Layer 8) and its content sharply decreased with depth. The Ap layer was also characterized by increased contents of P and Ca (1.23 and 4.52%, respectively). A high-precision XRF element map of a thin section from the Ap horizon showed that P and Ca were concentrated within round-shaped pedofeatures (Fig. 10), which were distinguished during the micromorphological analysis of thin sections. The second maximum of both P and Ca concentrations was observed lower down the profile – within the artifact-rich Cultural Layer 12, which corresponded to the 2BA horizon of the second paleosol (Fig. 9A).

Elements of Group 2 (Fe, Al, and Ti) had higher concentrations in the paleosol horizons having no evidence of human impact (Fig. 9B). The eluvial-illuvial pattern of distribution of Fe, Al, Mg was observed in AE-AB-Bt horizons of the first paleosol, where their concentrations increased with depth and reached maximum levels within the Bt horizon.

Fig. 5. Micromorphology of the Late Pleistocene buried soils and Upper Palaeolithic cultural layer. PPL – Plain polarized light, N+ - crossed polarizers. A. Heterogeneous distribution of dark organic pigment in the blocky aggregates. 2AB horizon, PPL; B. Assimilated clay coatings within thin intrapedal pores, concentration of sand and coarse silt grains. 2AB horizon, N+; C. Dark Fe-Mn coating and nodule. 2AB horizon, PPL; D. Humus intercalation. 2BA horizon, PPL; E. Clay and ferruginous coating in the porous bone fragment. 2BA horizon, PPL; F. Same as E, N+; note high birefringence of clay coatings and low grey interference colours of bone. G. Sparitic granule – calcified earthworm cast. 3B horizon, N+. H. Porphyric c/f related distribution, granostriated b-fabric. 3B horizon, N+.
Fig. 9B. The observed trend correlated with the eluvial-illuvial distribution of clay within this paleosol, which was established from micromorphological and particle-size composition data. At the same time high concentration of Ti was registered within the eluvial AE horizon.

4. Discussion

4.1. Pedogenetic and sedimentary processes in the section: inferences for the landscape evolution since the initial human occupation in Zaraysk

It should be highlighted that in the studied profile different buried soil units are never separated one from another by a “sterile” sediment stratum/C horizon, unchanged by pedogenesis. Moreover, in most cases the soil-forming processes from the upper soil unit penetrate into the underlying one, producing a puzzling combination of pedogenetic features and generating obstacles for correct identification of paleopedogenesis, as shown below. Detailed macro- and micromorphological observations combined with a set of analytical data were necessary to document the main stages of soil development and sediment deposition in the studied section. They also help to discriminate between natural and human induced processes which participated in the formation of the sequence since the earliest occupation of the site in the Upper Palaeolithic.

Two major sedimentary units were identified within the profile below the Kremlin cultural layer. The lower unit is the basal sandy deposit with admixture of clay in which the 3B paleosol horizon is developed. It consists mainly of the components derived from the underlying local Cretaceous shallow marine sands (their principle marker is glauconite, common in 3B horizon), thus we suppose that this deposit was produced by the short-distance colluvial transport.

The upper sedimentary unit hosts 2AB horizon and the profile of the younger paleosol – Grey Forest Soil (Ap-AE-AB-Bt set). Coarse material of these horizons is dominated by silt fractions (predominantly coarse silt) detected both in the thin sections and by the particle size analysis. In such an elevated geomorphological position one could hardly imagine other mechanisms of silt accumulation than eolian deposition. The stage of windblow sediment deposition was clearly detected in the nearby section Zaraysk B where the Palaeolithic layer and associated paleosol are overlain by sorted silty loess-like sediment (Lev et al., 2018). However presence of sand particles point to the mixing with the local materials through the slope redepotition.

The 2BA horizon comprises a transitional zone between the two units: it is still sandy however its coarse silt content is higher and medium sand – lower that in 3B.

The lower paleosol unit clearly presents a pedocomplex: the basal sandy-clayey 3B horizon corresponds to a different phase of sedimentation and pedogenesis that the overlying 2BA and 2AB horizons. Absence of human-induced materials and properties in the 3B implies that its formation took place before the Palaeolithic occupation. The specific set of micromorphological features of the 3B horizon: rounded blocky microstructure, dense clayey fine material with granosтратified b-fabric and spartic nodules – calcified earthworm casts resemble the micromorphological pattern of Bryansk paleosol recently described in detail in a toposequence near Kursk/Central Russian Upland (Sycheva et al., 2019). Relying on this similarity we hypothetically attribute the
3B horizon/layer 14 to the Bryansk paleosol level which in the Russian Quaternary chronostratigraphic scheme corresponding to the MIS3-Middle Valday interstadial (Velichko, 1990; Velichko et al., 2006). Its pedogenesis took place under continental boreal forest and forest-tundra ecosystems, the nearest recent analogues are Pale taiga soils (Cambic Cryosols) of Yakutia (Morozova, 1981). Similar morphological features were observed also in the other MIS3 paleosols of Europe e.g. in Stillfried B (Terhorst et al., 2015). The Bryansk paleosol was already encountered earlier within Zaraysk site in the section of Zaraysk B locus. Its stratigraphic position was quite similar: below the Palaeolithic cultural layer, separated from it by a thin loamy seam. We speculate that Bryansk paleosol comprises a prominent unit of the Zaraysk stratigraphy and could serve as a marker for archaeological excavations as a basal archaeologically sterile stratum.

The micromorphological pattern of the 2BA and 2AB horizons is quite different from that of 3B. Strong anthropogenic impact is observed in the archaeological layer 12 - 2BA horizon: structural changes, organic intercalations are accompanied by numerous microartifacts (bone, charcoal). Presence of human-induced materials produced definitive geochemical signals: high concentrations of P and Ca against the background of low content of other elements. Compaction due to trampling resulted in the reorganization of the pore space – formation of closed pores, shown by the tomographic investigation. The horizon 2AB shows signs of frost action – cryogenic separation of sand grains and blocky aggregation. At the same time there are frequent textural and ferruginous pedofeatures in the 2BA and 2AB horizons indicative of clay illuviation and redoximorphic processes. We, however, associate the latter phenomena not with the pedogenesis of this paleosol but with the posterior influence of the Holocene soil formation in the overlying Grey Forest Soil, as it will be discussed below. In the Zaraysk B profile the correlative paleosol associated with the Gravettian archaeological layer is much less affected by the Holocene processes; there it was possible to observe specific micromorphological features of intrinsic gleyzation (Lev et al., 2018). Another important additional observation from Zaraysk B are ice wedge pseudomorphs penetrating into buried humus horizon with artifacts (Lev et al., 2018); this confirms activation of cryogenesis at the end of paleosol formation.

We conclude that the landscape evolution during the formation of the 2AB-2BA paleosol level was complex. It included rather a mild period supposedly under meadow vegetation, as shown by the phytolith assemblage recovered in the studied profile and also in the correlative level of Zaraysk B section (Naugolnykh, 2019). Cryogenesis and eolian silt deposition infer climatic deterioration which took place at the final stages of paleosol development. Relying on the available 14C dates we associate the phase of milder climate with the warmer period of the Late Glacial between 18 and 16 ka BP (analogue of Lascaux interstadial (Sümegi and Krolopp, 2000)); the indicators of climate deterioration could correspond to one of posterior cold events – Late Glacial stadials.

Fig. 7. 3D-diagrams of pore size distribution at soil depths of 150 cm – 3B horizon, 130 cm – 2AB horizon, 95 cm - AB horizon and 73 - Ap horizon.

Table 2

<table>
<thead>
<tr>
<th>Level</th>
<th>Depth, cm</th>
<th>Non-siliceous vegetable indicators</th>
<th>Siliceous non-vegetable indicators</th>
<th>Plant silica</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Detritus*</td>
<td>Amorphic organic material*</td>
<td>Diatoms*</td>
</tr>
<tr>
<td>Ap</td>
<td>73–78</td>
<td>+</td>
<td>+</td>
<td>Single</td>
</tr>
<tr>
<td>AE</td>
<td>85</td>
<td>++</td>
<td>+</td>
<td>Single</td>
</tr>
<tr>
<td>AB</td>
<td>95</td>
<td>+</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>Bt</td>
<td>123</td>
<td>+</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>2AB</td>
<td>130</td>
<td>+</td>
<td>+</td>
<td>–</td>
</tr>
</tbody>
</table>

* +++ (many): over 100 units; ++ (middle): 40–100 units; + (little): 5–40 units; (single): 1–4 units; (absent): –.
The paleosol 2AB-2BA is known as Zaraysk soil, its development is supposed to coincide with the East Gravettian occupation (Naugolnykh, 2019). Taking into account the concentration of the Gravettian artifacts already at the bottom of the lower 2BA horizon (archaeological layer 12) the earliest occupation phases could initiate on the eroded surface of Bryansk paleosol even earlier than the onset of the Zaraysk soil pedogenesis. Climate deterioration at the last formation stages of this paleosol as well as further switching of the eolian sedimentation and geomorphic instability that resulted in the burial of Zaraysk paleosol under silty sediments could be important factors of the site abandonment.

The next stage of soil development in the eolian/colluvial silty loam occurred during the Holocene. The most notorious process developed in this unit is eluvial-illuvial clay redistribution. It is evidenced by eluvial features in the AE horizons: bleaching and concentration of pale silty material as well as by the residual accumulation of Ti. At the same time the underlying Bt horizon has abundant illuvial pedofeatures – clay coatings. The latter penetrate also into the lower paleosol unit (Zaraysk paleosol), as mentioned above. Illuviation is also indicated by clear maximum of clay content (as shown by grainsize analysis), as well as higher values of Al and Fe and decrease of pore space in the Bt and 2AB horizon. Clay redistribution was accompanied by the surface re-
doximorphic (Stagnic) processes which produced ferruginous pedo-features both in AE and Bt horizons. Basing on this set of pedogenetic characteristics we classified this buried soil as Grey Forest Soil (according to the traditional Russian classification – National Atlas, 2011) that corresponds to Stagnic Luvisol in WRB (2014).

**Table 3**
Silica microbiomorphs (unit/%) and distribution of phytoliths forms (%).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Depth, cm</th>
<th>Total</th>
<th>Diatoms/Spicules</th>
<th>Phytoliths total</th>
<th>Phytolith distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1(^a)</td>
</tr>
<tr>
<td>Ap</td>
<td>73–78</td>
<td>36/100</td>
<td>2/5/__</td>
<td>34/95</td>
<td>57</td>
</tr>
<tr>
<td>AE</td>
<td>85</td>
<td>76/100</td>
<td>2/3/1/1</td>
<td>73/94</td>
<td>53</td>
</tr>
<tr>
<td>AB</td>
<td>95</td>
<td>161/100</td>
<td>–</td>
<td>161/100</td>
<td>43</td>
</tr>
<tr>
<td>Bt</td>
<td>123</td>
<td>2/100</td>
<td>–</td>
<td>2/100</td>
<td>50</td>
</tr>
<tr>
<td>2AB</td>
<td>130</td>
<td>18/100</td>
<td>–</td>
<td>18/100</td>
<td>45</td>
</tr>
</tbody>
</table>

\(^a\) 1: herbs; 2: indicator types of coniferous species; 3: trichoms of grasses of forest habitats; 4: trichoms of grasses of meadow type habitats; 5: short sells of grasses of steppe type habitats; 6: indicator forms of grasses of arid type habitats; 7: reed; 8: mosses; 9: unknown and broken particles.
corresponds to the pedogenesis under deciduous forest ecosystems that form part of the vegetation of the forest-steppe zone, it is the dominant component of the present day soil mantle in the vicinities of Zaraysk. From the other hand there are evidences of dark humus accumulation in the AB horizon: it is observed in some micro-areas in the thin sections and provides its greyish pigmentation on the macroscopic level. This feature called “second humus horizon” is quite common in the Russian Grey Forest Soils. It is usually interpreted as indicator of an earlier period of soil development under the steppe-like plant community (Alexandrovskiy, 1983). We conclude that during the Holocene the plant community at site of Zaraysk evolved from the meadow-steppe (which extended in the region during the Atlantic optimum, as discussed below) to the forest type. Biomorphic analysis which shows a combination of the phytoliths typical for the forest ecosystem in the AE horizon with those of meadow and more xerophytic plants (especially in the AB horizon) supports this conclusion. No evidence of anthropogenic materials or processes was detected in the AE, AB and Bt horizons so the site was most probably not settled by humans during the major part of the Holocene.

Next phase of the human impact within the studied sequence is detected in the Ap horizon developed on top of the Luvisol profile and having abrupt even boundary with the underlying AE horizon. It contains small fragments of plant tissues and charcoal particles incorporated into the groundmass due to ploughing. It has micromorphological signs of compaction and transformation of pore space – formation of inter-pedal pores and planes – detected by the X-ray tomography. All this points to cultivation which we associated with the compaction and structure deterioration. The Ap horizon has some atypical pedofeatures: it contains neoformed phosphates and micritic carbonates. These components are not expected in a plough horizon formed on top of a leached Luvisol poor in P and Ca - it suppose some allochtonous input of P and Ca rich materials. We speculate that this cultivated plot was located very close (100 m) to the Medieval (12th–14th centuries AD) Russian non-fortified settlement from where fertilizers or waste materials could be introduced to the cultivated soil. Findings of the pottery corresponding to this period directly in the Ap horizon confirm this attribution. However the neoformed micritic carbonates in this horizon could also be washed in from the overlying cultural layer rich in calcareous anthropogenic materials discussed below.

The last phase of the anthropogenic soil development is recorded by the uppermost cultural layer/Technosol. It was formed since the foundation of Zaraysk fortress in 1528 till the present day. The layer consists mostly of the mixture of materials derived from the underlying soil and sediment horizons with numerous incorporated artifacts. The abrupt lower limit of the Technosol is marked by a thin white layer of fine carbonate material. In the field, we interpreted it as a layer of lime cement or a lime floor. However, in the thin sections, we have not observed a “lump” structure typical for carbonates derived from slacked lime. On the contrary, it consisted predominantly of the fragments of carbonate microfossils derived from the unprocessed calcareous rocks. We conclude that the white layer at the base of the urban Technosol is formed from the limestone dust – the product of stone sawing at the initial stages of Kremlin construction.

The main phases of the soil and sediment formation, natural environmental change and human activity in the Zaraysk Kremlin site are presented in the Fig. 11.
4.2. Correlation with the regional paleopedological and paleoecological records

4.2.1. Late Pleistocene and Palaeolithic occupation

The basal paleosol level of the studied profile hypothetically identified as Bryansk soil relying on micromorphological similarities with this unit represented in other sites of Central Russian upland. However in the key loess-paleosol section of Gololobovo (about 50 km to NW from Zaraysk) representative for Oka river basin, Bryansk soil shows some specific features not present in Zaraysk F (Velichko et al., 2006). Bryansk soil in Gololobovo has strong morphological features of gleyization, accompanied by a clear minimum of magnetic susceptibility, all this indicative of hydromorphic soil development. On the contrary in Zaraysk F the 3B horizon (which we associate with Bryansk soil) does not show gleyic features. We attribute these differences to the specific geological and geomorphic conditions of Bryansk pedogenesis in Zaraysk F: an elevated river bank close to escarpment together with sandy composition of colluvial parent material provided conditions for better soil drainage and hampered redoximorphic processes.

Another important difference between these two sections consists in the stratigraphic context of Bryansk paleosol. In Gololobovo it is overlain by the Desna loess that corresponds to the Last Glacial Maximum; this fits into the generalized loess-paleosol stratigraphy for Eastern Europe (Velichko, 1990). In the Zaraysk F Desna loess is absent and 3B/Bryansk soil is overlain by Late Glacial paleosol 2BA-2AB coinciding with Gravettian cultural layer. This implies hiatus of several thousand years corresponding to the first half of the MIS2 between the layers 3B and 2BA. Our results agree with the recent studies of MIS3/ MIS2 chronostratigraphy of the Central Russian Upland. Sycheva and Khokhlova (2016) summarized the results on stratigraphic position and radiocarbon dating of Bryansk soil in several locations. They concluded that this paleosol unit formed in the late MIS3 in many cases persisted on the surface during early MIS2 in the elevated interfluvies; its burial under eolian loessic sediments occurred only after 17 ka BP during Late Glacial stadials. Our observations in Zaraysk F fit very well into this scenario.

The 2AB-2BA paleosol (Zaraysk soil) has major importance as the marker of Late Palaeolithic occupation surface. This level could be correlated with the buried paleosols of terminal Pleistocene described in a number of localities within the central Russian Plane. Alexandrovskiy (1983) in his broad evolutionary study of the Holocene soils mentions thin deformed humus horizons belonging to the Late Glacial at the base of some studied profiles. More detailed characteristics is provided by Gugalinskaya et al. (2015) for the Puschino paleosol encountered below the recent Grey Forest Soil in the upper Oka basin; for this paleosol the radiocarbon date 14100 ± 370 yr BP was obtained. Kovaleva et al. (2013) describe two Late Glacial paleosols in the neighbouring Desna basin: the older has the radiocarbon date 16.5 ka BP and the younger ~ 13 ka BP. It is important that incipient paleosols corresponding to the terminal Pleistocene and associated with the cultural layers were encountered in several East European Late Palaeolithic archaeological sites, e.g. Yeliseyevichi (Velichko et al., 1997) and Timonovka (Velichko et al., 1977).

In the standard East European loess-paleosol chronostratigraphic scheme of Velichko (1990) the Trubchevsk gleyic paleosol level (dated back ~ 16 ka BP) is detected within the loessic unit corresponding to the Late Valday (MIS2) epoch. This level is registered in particular in the above mentioned Gololobovo section (Velichko et al., 2006). This thin weakly developed paleosol separates the Desna loess corresponding to the Last Glacial Maximum and Altynovo loess accumulated at the end of MIS2. We correlate the 2AB-2BA paleosol in Zaraysk F (Zaraysk soil) with the Trubchevsk paleosol wereas the overlying silty deposit (in which the Holocene Luvisol is developed) could be the analogue of the Altynovo Loess (Lev et al., 2018). This correlation also agrees with the regional scenario of dynamics of loess accumulation proposed by Sycheva and Khokhlova (2016), discussed above.

![Proposed model of the evolution of the pedosedimentary sequence and human influence on soil profile.](image)
Paleoenvironmental interpretation of the lower paleosol as a product of pedogenesis under meadow vegetation is congruent to the paleobotanical proxies for the terminal Pleistocene in the central Russian Plain. According to the paleovegetation zoning of Europe for Late Glacial Transition Zaraysk is located within the open forests with tundra and meadow associations (Markova et al., 2008). Spiridonova (1991) in her overview of the Late Quaternary vegetation history in the Don basin (to the south of the study site) states that during Late Valday interstadials together with the extension of forests, also mesophilic (meadow) grasses were abundant. The reconstruction of the Late Valday vegetation of the Desna river basin based on the pollen spectra from the Late Palaeolithic sites (Novenko, 2006) supposes the dominance of periglacial steppe and meadow-steppe communities on the interfluvies and gentle slopes – that could be also applicable for Zaraysk. Recent results on the molecular biomarkers and δ13C composition of organic matter in the Late Glacial paleosols of this region confirmed their development under grass vegetation (Stolnikova et al., 2020).

4.2.2. Holocene soil evolution and the impact of agricultural and urban land use

Central part of the section is occupied by the Grey Forest Soil/ Stagnic Luvisol that is considered to be a central image of the Holocene soil development in the East European forest-steppe under woodland ecosystems (Gerasimova et al., 1996; Bronger, 2003). However as mentioned above the combination of dark humus accumulation and strong leaching and clay illuviation within the profile of these soils gave rise to the polygenetic model of their evolution. Alexandrovskiy (1983) studied the relict dark humus features in the Luvisols of the central part of European Russia: second humus horizons, dark krotovinas, etc. and concluded that many of them passed through Chernozemic steppe stage of pedogenesis during the Atlantic optimum of the middle Holocene. After the Chernozemic stage the Luvisol development under forest took place in the second half of the Holocene – Subboreal and especially Subatlantic periods, resulting in partial degradation of the dark humus horizon. Chendev (2008) further supported this model with the study of the dated buried and surface soils of associated with the natural and artificial landforms of different age in the Russian forest-steppe. The buried middle Holocene Phaeozem with dark humus horizon was found in the floodplain sequences of Oka basin; the younger paleosols of these sequences are Luvisols. (Alexandrovskiy et al., 2004). Reconstructions of the Holocene vegetation change based on palynological proxies after decades of discussions also arrived to a similar conclusions: maximum extension of steppe/grassland communities in the Russian plain corresponds to the Atlantic period whereas the advance of forests took place in the late Holocene (Klimanov and Serebryannaya, 1986; Serebryannaya, 1992). Recently Shumilovskikh et al. (2017) calculated the south-western shift of the forest-steppe boundary after 4500 yr BP basing on statistical analysis of several pollen diagrams. All these works support our conclusion that at the Zaraysk site plant cover evolved from a meadow-steppe to forest during the Holocene.

The plow Ap horizon on top of Luvisol profile was formed during the period of cultivation and human disturbance which started in the East European forest-steppe since 2500–2000 yr BP according to the paleobotanical proxies (Novenko et al., 2014; Shumilovskikh et al., 2017). The anthropogenic soil and landscape change took place already after a period of forest expansion and Luvisol pedogenesis.

The final stage of Zaraysk profile development – formation of the Kremlin cultural layer/Technosol – coincides with the records of dramatic anthropogenic change of the Russian forest-steppe during the last 400 years. Palinological spectra point to dramatic drop of tree pollen that indicates nearly total forest clearance for agricultural land use (Shumilovskikh et al., 2017). Strongest acceleration of anthropogenic soil erosion took place in the same period (Alexandrovskiy and Chichagova, 1998).

4.2.3. Integration of Late Pleistocene and Holocene pedogenesis in a pedocomplex: A phenomenon of regional importance?

Soil horizonation of the Zaraysk section highlights an important feature of the soil mantle of the East European Plain still not taken into account sufficiently by the soil scientists. As described above the Late Glacial 2AB-2AB paleosol is “welded” to the Holocene Luvisol Bt horizon and affected by recent clay illuviation, thus producing a pedocomplex (in the sense of Smolikova (1967)). It seems that such organization of the soil profile is not uncommon for different zonal soils of Eastern Europe: various studies report Late Pleistocene relict horizons found at the base of the Holocene profiles forming a pedocomplex with them. As mentioned above Late Glacial humus horizons were encountered in the bottom of the forest-steppe Luvisols (Alexandrovskiy, 1983; Gugalinskaya et al., 2015). Even earlier paleosols formed during Middle Wolday – MIS3 interstadial are frequently incorporated into the “recent” zonal soil profiles. In particular gleyic MIS3 horizons were encountered in the forest Retisols of the Upper Volga (Rusakov and Sedov, 2012; Sedov et al., 2016) immediately below clay-illuvial horizons. Brown MIS3 horizons (Bryansk paleosol) are common in the steppe Chernozems (Sycheva et al., 2019) being located under dark humus A and AB horizons. These data should be considered not only for pedogenetic interpretation but also for soil classification, mapping and even applied soils science issues.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The reported study was funded by Russian Foundation for Basic Research, research project № 19-29-05267. Digital image processing studies were performed within the V.V. Dokuchaev Soil Science Institute Basic Scientific Research № 0591-2019-0031. Element mapping for thin sections was supported by M.V.Lomonosov Moscow State University Program of Development (X-ray fluorescence spectrometer Tornado M4 plus). Biomorph analysis was carried out by A.Golyeva within the framework of the state assignment № 0148-2019-0006. We acknowledge Vladimir Vermus (XRF/XRD Specialist Olympus Moscow LLC) for providing us with the results from the Vanta-M Portable EDXRF Analyzer. Authors are grateful to Mikhail Lebedev and Jaime Díaz for preparing thin sections. We also appreciate corrections and critical comments of two anonymous reviewers helpful for improving the manuscript.

References


