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Morphology and micromorphology of the loess-paleosol sequences in the south of the East European plain (MIS 1–MIS 17)

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ABSTRACT

The micro- and macromorphological studies performed on the loess-soil sequences in the south of the East European Plain permitted to identify and describe the type of soil-formation processes that took part in the development of interstadial and interglacial paleosols. Four paleosol complexes are distinctly identified within the limits of the studied region: Vorona (MIS 13/15), Inzhavino (MIS 8/9 or MIS 10/11), Kamenka (MIS 6/7 or MIS 8/9), Mezin (MIS 5); besides, there are the Bryansk interstadial paleosol (MIS 3) and Rzhaksa interglacial paleosol (MIS 17), both well identifiable in the region. The results obtained are in general agreement with the earlier conclusions by Velichko et al. (2012) about a general reduction of heat and moisture supply and an increase in aridity from the earlier towards later stages of the Pleistocene. The new data revealed, however, a few differences from the earlier concept. To mention but one example, we have found that the Kamenka interglacial (MIS 7 or MIS 9) paleosols formed in environments more humid than those of the Likhvin interglacial (MIS 9 or MIS 11).

1. Introduction

Loess occupies vast areas in the East European Plain, where loess-paleosol sequences (LPS) contain paleosol complexes (PC) datable to the Late, Middle, and Early Pleistocene. The loess-paleosol sequences demonstrate alternating series of loess and fossil soils that indicate changing environments and enable us to reconstruct climatic fluctuations from the beginning of the Pleistocene to the present days.

The paleosol complexes are represented in the region by interglacial and interstadial paleosols distinguished by differences in their profiles (Velichko et al., 2007; Velichko and Morozova, 2015). In the paper we apply the term 'profile' to a sequence of soil horizons typical for a certain type of soil. Soils dated to warm interglacials are noted for a fully developed profile with a set of genetic horizons (Little et al., 2002; Panin, 2007; Velichko et al., 2017a; and others). During interstadials, under conditions of insufficient heat and moisture supply, humus-accumulative soils formed, with horizons A and AB only. After the paleosol complex had been buried under loess material during the subsequent glacial time, the soil-forming processes stopped and initial soil characteristics were partially lost and replaced by others related to diagenesis processes. When studying LPS characteristics traditional techniques are mostly used, including: description of the sequence morphology; studies of the quartz sand grain morphoscopy; an assortment of physic-chemical analyses, such as grain size, bulk composition, mineralogical composition; determination of carbonate contents, humus, iron sesquioxides, pH, etc. (Velichko and Timireva, 1995; Nettleton et al., 2000; Muhs, 2007; Chizhikova et al., 2007; a.o.).

The wide experience in paleosol research gained by the present time has shown the studies of soil micromorphology in thin sections to be the most promising approach to the paleosol genetic identification. That approach makes it possible to recognize specific characteristics of the principal soil-forming processes in paleosols (Matviishina, 1982; Bronger and Heinkele, 1989; Bronger et al., 1998; Nettleton et al., 2000; Kühn et al., 2006; Stoops et al., 2010; Mason and Jacobs, 2013; Sprafke et al., 2014). The properties of the processes vary in their resistance to the time and diagenesis factors. The most resistant are the soil fabric, peds, voids, b-fabric, carbonate and gypsum pedofeatures, and some others. Here we consider in details the LPS structure at macro- and micro-levels, which forms the basis for correlating the paleosol levels and reconstructing specific features of the soil-forming processes, their intensity and stages in their development (Velichko et al., 2017c). The comparison between the results obtained on paleosols and characteristics of the modern soils makes possible the tracing of the changes in climate and environments within the Azov region.

2. Materials and methods

The works were performed in cooperation with specialists from the

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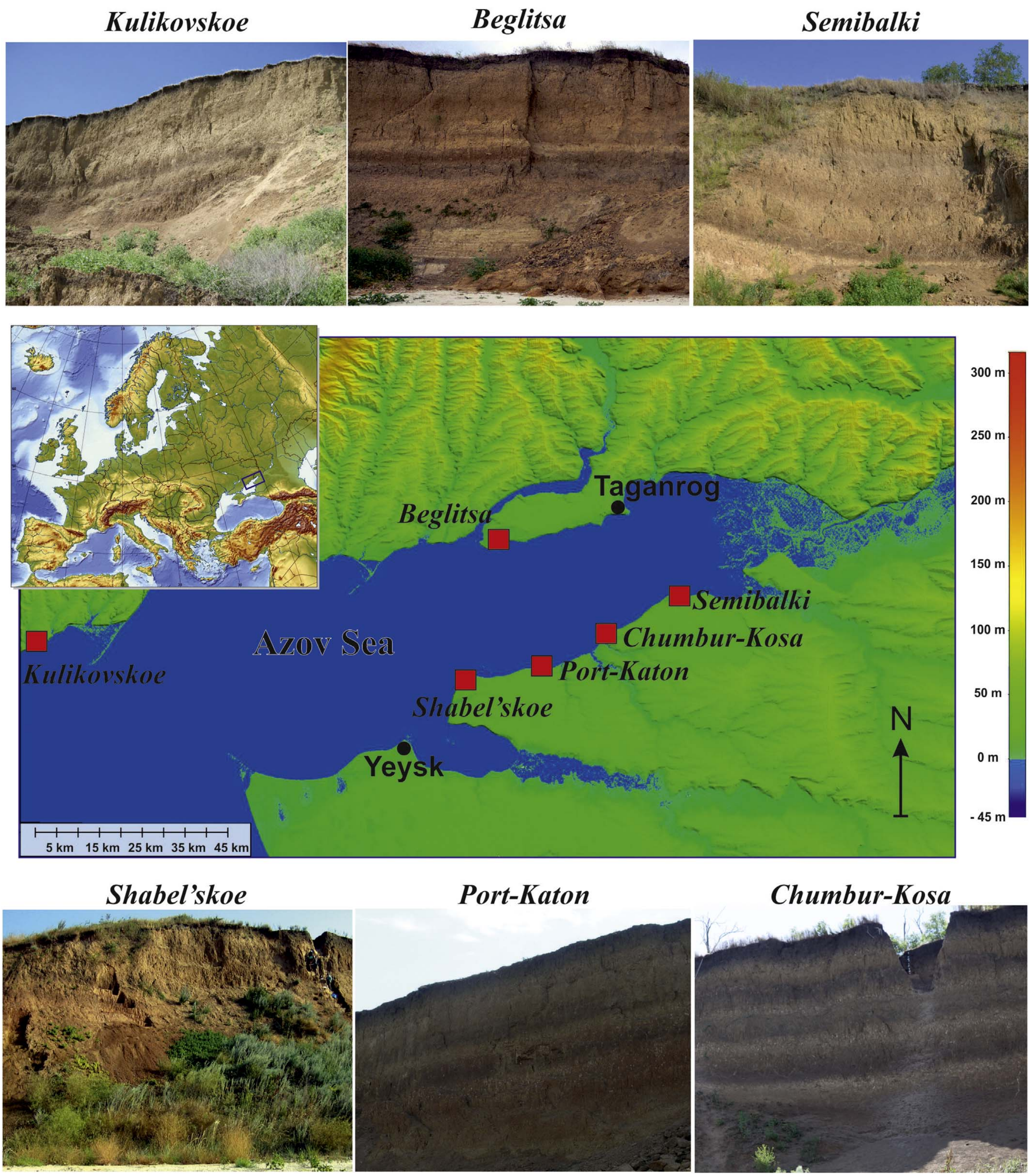

Fig. 1. The region under study with photographs of the main LPS sections (the topographic base taken from Shuttle Radar Topography Mission materials).

Southern Scientific Center (city of Rostov-on-Don) and the Geological Institute (Moscow) of the Russian Academy of Sciences. Since 2003 several main sections had been studied: Shabelskoye (N 46°51′34″; E 038°27′46″), Port-Katon-1 (N 46°52′39″; E 038°43′59″), Chumbur-Kosa (N 46°57′48″; E 038°56′47″), Semibalki-1 (N 47°00′35″; E 039°02′22″), Semibalki-2 (N 46°59′48″; E 039°00′53″), Beglitsa (N 47°07′38″; E 038°30′56″), and Kulikovskoye (N 46°52′58″; E 037°03′16,57″) (Fig. 1).

The loess-paleosol sequences are exposed in the coastal cliffs of the Azov Sea. The modern soils are Chernozems ordinary according to the Russian classification (Egorov et al., 1977; Shoba, 2011), or Chernozems Pachic according to the international classification WRB 2014 (2015); they are mostly ploughed at present. The climate is temperate continental. The temperature fluctuation range in a year amounts to ~28 °C on average, the maximum annual range is up to 70 °C. The temperature minimum falls on January–February, the highest temperatures are recorded in July–August. The mean annual temperature is +9 to 10 °C. Winter is mild; with average January temperatures −2 to −4 °C, permanent snow cover is not formed. The warm season with mean daily temperatures over 10 °C begins in April and lasts until October. The mean temperature of the warmest month (July) is +24 °C. Yearly amount of rainfall (~580 mm) is unevenly distributed over the year. Instrumental observations show two maximums – in winter (December, January), with up to 110 mm of precipitation falling as snow and rain, and in late spring–early summer (May, June) with 120 mm falling. In other months the total monthly precipitation varies from 30 to 50 mm.

Here we use the latest variant of the chronostratigraphic scheme as suggested by A.A. Velichko and his colleagues (Velichko and Morozova, 2015) based on many years of LPS investigations on the East European Plain (Velichko et al., 2011). Every unit (glaciation, interglacial) in the scheme by Velichko corresponds to a certain interval MIS. It is this stratigraphy that we use in our work.

There exists, however, another variant of correlation between stratigraphic horizons and the marine isotope stages, also in wide use (Velichko and Morozova, 2010; Zastrozhnov et al., 2017) according to it, the Romny paleosol is correlated with MIS 7, and paleosols of Kamenka and Likhvin interglacials – with MIS 9 and MIS 11 respectively.

According to the chronostratigraphic scheme developed for the East European Plain (Table 1), there are the following buried paleosol complexes (PC) known in the Azov region formed from Lower

Table 1
Chronostratigraphic scheme of the East European Plain (Velichko and Morozova, 2010, 2015; Velichko et al., 2011).

<table>
<tr><th rowspan="2">Ice ages</th><th rowspan="2" colspan="2">East European loess region</th><th colspan="2">MIS</th></tr>
<tr><th>Var. 1</th><th>Var. 2</th></tr>
<tr><td colspan="3">Holocene</td><td>1</td><td>1</td></tr>
<tr><td rowspan="7">Valday Glaciation</td><td colspan="2">Altynovo loess</td><td rowspan="3">2</td><td rowspan="3">2</td></tr>
<tr><td colspan="2">Trubchevsk soil</td></tr>
<tr><td colspan="2">Desna loess</td></tr>
<tr><td colspan="2">Bryansk paleosol</td><td>3</td><td>3</td></tr>
<tr><td colspan="2">Khotylevo loess</td><td>4</td><td>4</td></tr>
<tr><td rowspan="3">Mezin paleosol complex</td><td>Krutitsa interstadial paleosol</td><td>5c</td><td rowspan="2">5</td></tr>
<tr><td>Sevsk loess</td><td>5d</td></tr>
<tr><td>Mikulino Interglacial</td><td>Salyn interglacial paleosol</td><td>5e</td><td>5e</td></tr>
<tr><td rowspan="7">Dnieper Glaciation</td><td colspan="2">Moscow loess</td><td rowspan="7">6</td><td rowspan="3">6</td></tr>
<tr><td colspan="2">Kursk interstadial paleosol</td></tr>
<tr><td rowspan="3">Dnieper loess</td><td>Loess</td></tr>
<tr><td>Romny (?) interstadial paleosol</td><td>7</td></tr>
<tr><td>Orchik (?) loess</td><td rowspan="3">8</td></tr>
<tr><td rowspan="3">Kamenka paleosol complex</td><td>Late Kamenka interstadial paleosol</td></tr>
<tr><td>Loess</td></tr>
<tr><td>Kamenka (Chekalin) Interglacial</td><td>Early Kamenka interglacial paleosol</td><td>7</td><td>9</td></tr>
<tr><td rowspan="3">Pechora Glaciation</td><td colspan="2">Borisoglebsk loess</td><td rowspan="3">8</td><td rowspan="3">10</td></tr>
<tr><td rowspan="3">Inzhavino paleosol complex</td><td>Late Inzhavino interstadial paleosol</td></tr>
<tr><td>Loess</td></tr>
<tr><td>Likhvin Interglacial</td><td>Early Inzhavino interglacial paleosol</td><td>9</td><td>11</td></tr>
<tr><td rowspan="3">Oka Glaciation</td><td rowspan="3" colspan="2">Oka loess</td><td>10</td><td rowspan="3">12</td></tr>
<tr><td>11</td></tr>
<tr><td>12</td></tr>
<tr><td>Ikoretskoye interglacial</td><td rowspan="3">Vorona paleosol complex</td><td>Late Vorona interstadial paleosol</td><td>13</td><td>13</td></tr>
<tr><td>glaciation</td><td>Loess</td><td>14</td><td>14</td></tr>
<tr><td>Muchkap interglacial</td><td>Early Vorona interglacial paleosol</td><td>15</td><td>15</td></tr>
<tr><td colspan="2">Don glaciation</td><td>Don loess</td><td>16</td><td>16</td></tr>
<tr><td colspan="2">Okatovo interglacial</td><td>Rzhaksa interglacial paleosol</td><td>17</td><td>17</td></tr>
<tr><td colspan="2">Setun glaciation</td><td>Bobrov loess</td><td>18</td><td>18</td></tr>
<tr><td colspan="5">Brunhes-Matuyama boundary</td></tr>
</table>

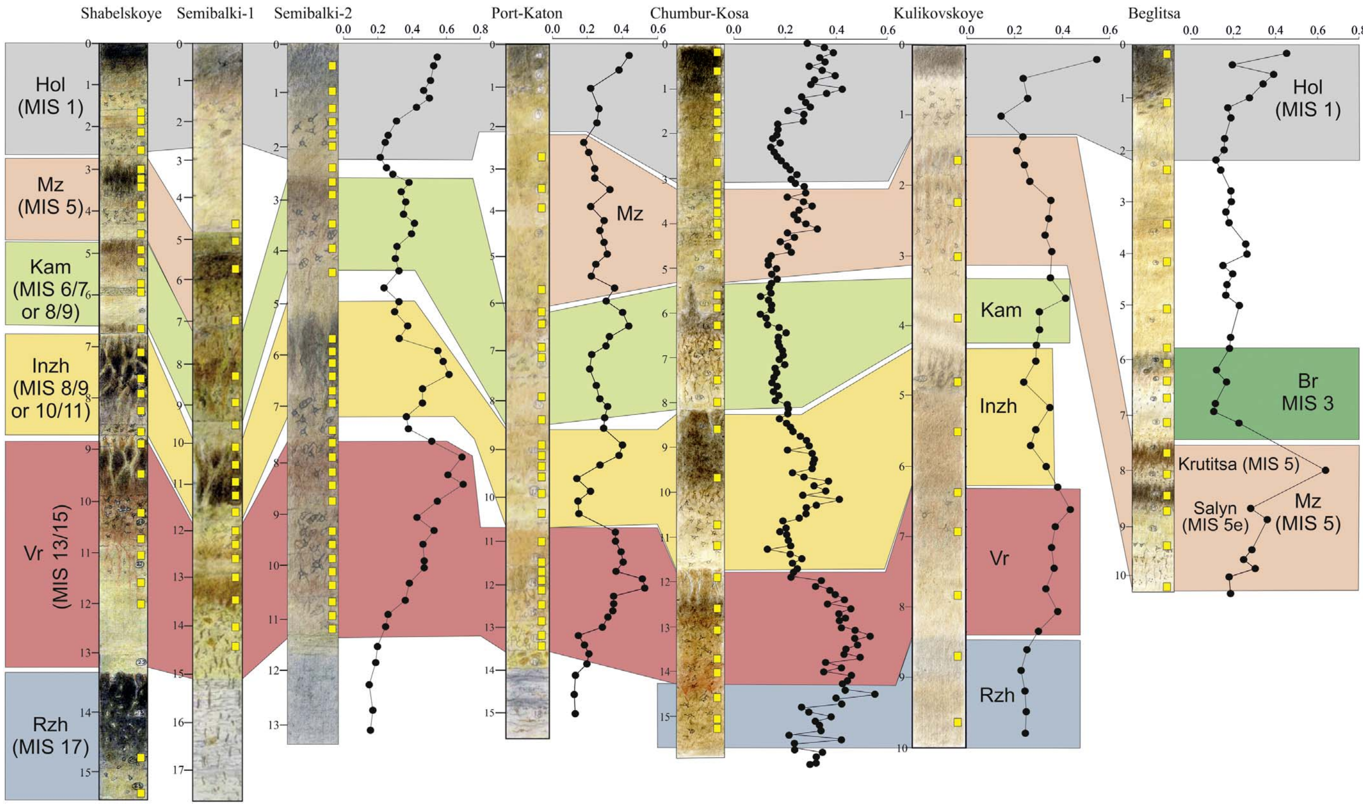

Fig. 2. The correlation of the LPS exposed in the main sections of the Azov Region based on the magnetic susceptibility values (10^{-3} SI). The units distinguished in the sections are: Hol – modern soil (Chernozem ordinary); Br – Bryansk interstadial paleosol; Mz – Mezin PC; Kam – Kamenka PC; Inzh – Inzhavino PC; Vr – Vorona PC; Rzh – Rzhaksa interglacial paleosol. The depth is indicated in meters. Places of sampling for micromorphology studies are shown by yellow squares. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Pleistocene up to the present days:

1) Vorona PC (denoted Vr in the figures), its main phase is correlatable with the Muchkap Interglacial (MIS 15);
2) Inzhavino PC (Inzh) correlated with the Likhvin Interglacial (MIS 9 or MIS 11);
3) Kamenka PC (Kam), correlated with the Kamenka Interglacial (MIS 7 or MIS 9);
4) Mezin PC (Mz), correlated with the Mikulino Interglacial (MIS 5e).

Besides the above listed, there is another – younger – paleosol occurring in the Beglitsa section above the Mezin PC and known as the Bryansk (Br) interstadial paleosol (MIS 3). In a few sections – Chumbur-Kosa, Shabelskoye, Kulikovskoye – there is distinctly seen Rzhaksa (Rzh) interglacial paleosol (MIS 17).

All the paleosols were described in detail during the field works, as well as photographed and sampled. Soil samples were taken from every genetic horizon at 15–20 cm intervals, the Chumbur-Kosa section was sampled at 5 cm intervals. The soil samples were tested for magnetic susceptibility using Meter SM30. The magnetic susceptibility is one of indicators of paleoclimatic changes. That conclusion by Heller and Liu (1984, 1986) was based on MS measurements in LPS deposits in China. As follows from the results published by those specialists, MS values obtained for paleosols formed at the interglacial intervals are higher than those in loess correlatable with glaciations. For every sample the average magnetic susceptibility value was calculated from three measurements. The modern soils were sampled for the purpose of comparison.

The paleosol microstructure was studied in thin sections < 30 μm thick. The undisturbed samples were air dried and impregnated with polysynthetic resin and made into thin sections (Jongerius and Heintzberger, 1975). The thin sections were described and the soil-forming process interpretation was given according to methods described in literature (Bullock et al., 1985; Gerasimova et al., 1992, 2011; Stoops, 2003; Stoops et al., 2010). The thin section photographs were taken on the polarized-light microscope Motic BA310Pol at 4X/0.1 magnification.

The correlation of LPS in the Azov region is given in Fig. 2. Places of sampling for micromorphology studies are indicated by yellow squares on the sections. Most sections are supplied with MS graphs. Summary tables of the soil and sediment morphology (Table 2) and micromorphological descriptions (Table 3) are given for the main two sequences Beglitsa and Chumbur-Kosa where all the paleosol levels of the studied region are best represented. Generalized information on the paleosol morphology studied in all the sections and on their microstructure is given in the text.

The indexes used in Tables 2 and 3 to designate genetic horizons of the soil profiles, as well as micromorphological characteristics and quantitative characteristics (pore types, vughs, pedofeatures, their quantity and other values) are given in accordance with FAO (2006) and Stoops (2003) recommendations.

3. Results

3.1. The soil morphology description

Morphological descriptions of the LPS in the Azov Region permitted to recognize six levels of the soil formation. The paleosol levels are well recognizable by color - typically brown, gray-brown, or reddish hues notably different from pale-yellow and straw-yellow colors of loess. There are cryogenic deformations clearly seen as cracks or wedges at the contact of paleosol and loess layers. The fissures and wedges of that type are noticeable between interstadials and interglacial paleosols.

Table 2 presents descriptions of the modern soil and the Late

Table 2
Morphology of LPS in the Beglitsa and Chumbur-Kosa sections.

Section	Horizon	Depth/thickness, m	Color (Munsell)	The soil textural classes, pedofeatures, structure, biological features	Horizon boundaries. distinctness, topography	Other
BEGLITSA	THE MODERN SOIL (HOLOCENE) – MIS-1					
	Ap	0.0–0.7/0.70	7.5 yr 4/2–4	LS, GR, E.	G	
	ABk	0.7–1.15/0.45	7.5 yr 6/4–6	LS, GR, BI, E.	C, S	The mole passages from 20 to 5 cm in diameter
	B	1.15–3.35/2.20	7.5 yr 6/4–6	LS, PM, BI.	C, W	Roots up to 1 cm diameter; the mole passages with a diameter of up to 10 cm (rarely up to 20 cm)
	BCcys	3.35–5.9/2.55	7.5 yr 6/4	SL, GR, CR, SC, PM-SL.	C, W	
	BRYANSK INTERSTADIAL PALEOSOL (LATE PLEISTOCENE) – MIS 3					
	Aqs	5.9–6.15/0.25	10 yr 6/3–4	SL, GR, PM-SL, BI.	D, I	Humus in voids
	ABqy	6.15–6.67/0.52	10 yr 6/4–3	SL, GR, CR, PM-SL, BI.	C, W	
	Bqys	6.67–7.00/0.33	10 yr 7/3	LS, CR, PM-ST.	C, W	Roots up to 1–2 mm diameter
	BCky	7.00–7.30/0.30	10 yr 6/3–4	SL, PM-ST, GR, CR.	A, W	
	MEZIN PC (LATE PLEISTOCENE)					
	Krutitsa interstadial paleosol – MIS 5					
	Acs	7.30–7.90/0.60	7.5 yr 5/4	SL, PR, PM-SL, BI.	A, S	The mole passages 5–6 cm in diameter
	ABy@	7.90–8.30/0.40	10 yr 6/4	LS, PR, PM- ST.	C, W	
	Salyn interglacial paleosol – MIS 5e					
	A	8.30–8.60/0.30	7.5 yr 4/2	LS, SB, GR, HC, BI.	C, W	Fibers 1–2 cm thick (subvertical)
	Bcy@	8.60–8.80/0.20	10 yr 5/2	LS, SB, GR, BI, PM-ST.	C, W	
	Bcks	8.80–9.60/0.80	10 yr 7–4/6–4	LS, GR, PM- ST, SC, BI.	C, W	The mole passages 6-8 cm in diameter with filling from the humus horizon
	BCks	9.60–10.5/0.90	10 yr 6/8	LS, SC- ST, SC- SL, BI.	G	Many ancient roots
CHUMBUR-KOSA	KAMENKA PC (MIDDLE PLEISTOCENE)					
	Late Kamenka interstadial paleosol – MIS 6					
	Acks@	5.30–6.10/0.80	10 yr 4/3	L, CR, GR, PM-SL	G	
	ABcks@	6.10–6.55/0.45	10 yr 4/3–3/3	L, PR, PM-SL	C, I	
	Early Kamenka interglacial paleosol – MIS 7 or MIS 9					
	ABcks@	6.55–7.15/0.60	10 yr 6/6	L, PR, SC-ST, BI	C, I	Fe-Mn pedofeatures, The mole passages ~5–8 cm in diameter
	Bcks	7.15–7.65/0.50	10 yr 6/6–7/6	L, PR, SC-ST, BI	G	The mole passages 12 cm in diameter
	Bks	7.65–8.25/0.60	10 yr 7/6	L, PR, SC-SL	G	
	INZHAVINO PC (MIDDLE PLEISTOCENE)					
	Late Inzhavino interstadial paleosol – MIS 8					
	Acks@	8.25–8.85/0.60	2.5 yr 4/2	L, PR, CR, SC-SL	G	Fe-Mn pedofeatures
	Early Inzhavino interglacial paleosol – MIS 9 or MIS 11					
	Ak	8.85–10.10/1.25	2.5 yr 3/4–3/2	L, PR, CL, SC-SL	C, I	
	ABcks	10.10–11.80/0.70	10 yr 5/6	L, PR, CL, SC-ST	C, I	
	VORONA PC (EARLY PLEISTOCENE)					
	Late Vorona interstadial paleosol – MIS 13					
	A@	11.80–12.50/0.70	2.5 yr 6/4–6/2	L, PR, CL, SC-SL	C, I	
	Early Vorona interglacial paleosol – MIS 15					
	Aks@	12.50–12.90/0.40	2.5yr 2/4	L, PR, CL, PM-SL, BI	C, I	Fe-Mn pedofeatures 1–2 mm
	ABks@	12.90–13.25/0.35	2.5 yr 3/4–3/6	L, PR, CL, PM-SL, BI	C, I	
	Bcks@	13.25–13.90/0.65	2.5 yr 3/6	L, PR, CL, SC-EX	C, I	Fe-Mn pedofeatures
	Bck@	13.90–14.25/0.35	2.5 yr 3/6–4/6	L, PR, CL, SC-EX, BI	C, I	Fe-Mn pedofeatures
	RZHAKSA INTERGLACIAL PALEOSOL (EARLY PLEISTOCENE) – MIS 17					
	ABcs@	14.25–15.90/1.65	7.5 yr 6/6–5/6	L, PR, SC-MO, BI	–	Fe-Mn pedofeatures

Table 3
Micromorphology of LPS in the Beglitsa and Chumbur-Kosa sections.

Section	Horizon/thickness (m)	Voids ([a])	Groundmass b-fabric	C/F related distribution	Microstructures	Aggregates	The nature of mineral concentrations/ the abundance of mineral concentrations/ the kinds of mineral concentrations	Organic matter
BEGLITSA	THE MODERN SOIL (HOLOCENE) – MIS 1							
	Ap/0.7	Ch (++); Pl (++++); Vu (+++++)	Undifferentiated	Open Porphyric	Granular; Subangular blocky; Vughy	Granule; Ped	–	Organ residue; Organic fine material; Organic pigment
	ABk/0.45	Ch (+++++); Pl (+++); Vu (+++)	Stipple speckled	Porphyric	Granular; Vughy	Granule; Ped	FM/+/HC	Organic fine material; Organic pigment
	B/2.20	Ch (++); Pl (++); Vu (++)	Stipple speckled	Porphyric; Open Porphyric	Channel; Granular; Vughy	Granule; Ped	–	Organic fine material; Organic pigment
	BCcys/2.55	Ch (++); Pl (++); Vu (++)	Stipple speckled	Porphyric; Open Porphyric	Granular; Vughy; Fissure; Massive	Granule; Ped	GY/+++++/T FM/+++/HC; K/+/HC; GY/+++/Crystal intergrowths	Organic fine material; Organic pigment
	BRYANSK INTERSTADIAL PALEOSOL (LATE PLEISTOCENE) – MIS 3							
	Aqs/0.25	Ch (+++); Vu (++)	Undifferentiated	Enaulic	Intergrain microaggregate	Ped	FM/++/HC	Organic fine material; Organic pigment
	ABqy/0.52	Ch (++); Vu (+)	Undifferentiated	Enaulic	Intergrain microaggregate	Ped	GY/++/T	Organic pigment
	Bqys/0.33	Ch (++); Vu (+)	Undifferentiated	Gefuric	Intergrain microaggregate	Granule	FM/++/N; GY/++/T	Organic pigment
	BCky/0.30	Ch (+++); Pl (++); Vu (++)	Stipple speckled	Open Porphyric	Granular; Channel; Subangular blocky; Vughy	Granule; Ped; Blocky	K/+/HC; GY/++/T	–
	MEZIN PC (LATE PLEISTOCENE)							
	Krutitsa interstadial paleosol – MIS 5							
	Acs/0.60	Ch (++); Pl (++); Vu (++++)	Undifferentiated	Porphyric	Granular; Vughy; Massive	Granule; Ped	FM/+/Aggregate nodule	Organic pigment

(continued on next page)

Table 3 (*continued*)

	ABy@/0.40	Pv (+); Ch (+); Pl (+++); Vu (+++)	Undifferentiated	Porphyric	Granular; Vughy; Fissure; Massive	Granule; Ped	GY/++/T	Organic pigment
	Salyn interglacial paleosol – MIS 5e							
	A/0.30	Pv (+); Ch (+); Pl (+++); Vu (+++)	Undifferentiated	Porphyric	Granular; Vughy; Fissure; Massive	Granule; Ped	–	Organic fine material
	Bcy@/0.20	Ch (++); Pl (++++); Vu (+++)	Stipple speckled	Open Porphyric	Granular; Vughy; Fissure	Granule; Ped; Blocky	FM/++/HC; GY/++++/T; GY/C/Crystal intergrowths	–
	Bcks/0.80	Ch (++++); Pl (+++); Vu (+++)	Stipple speckled	Open Porphyric	Granular; Vughy; Channel	Granule; Ped	FM/++/HC; FM/++/N; K/+++/HC; FM/++/TC	Organic fine material
	BCks/0.90	Ch (+++); Pl (+++); Vu (+++)	Stipple speckled; Concentric-striated	Open Porphyric	Granular; Vughy; Channel	Granule; Ped	FM/+++/HC; K/+/T	–
CHUMBUR-KOSA	KAMENKA PC (MIDDLE PLEISTOCENE)							
	Late Kamenka interstadial paleosol – MIS 6							
	Acks@/0.80	Pl (+++++); Vu (+)	Speckled	Porphyric, Open Porphyric	Granular; Crumb; Subangular blocky	Crumb; Ped; Blocky	FM/++++/N; K/+++/N	Organic fine material; Organic pigment
	ABcks@/0.45	Pl (++); Vu (++)	Speckled	Porphyric, Open Porphyric	Crumb; Subangular blocky;	Crumb; Blocky	FM/+++/Aggregate nodule; FM/++++/N; K/+++/N	Organic fine material; Organic pigment
	Early Kamenka interglacial paleosol – MIS 7 or MIS 9							
	ABcks@/0.60	Pl (++++); Vu (+++++)	Stipple speckled, Concentric-striated	Porphyric	Granular; Crumb; Subangular blocky; Fissure	Granule; Crumb; Ped; Blocky	FM/++++/N; K/+++/N	Organic fine material; Organic pigment
	Bcks/0.50	Ch (+); Pl (++++); Vu (+++++)	Undifferentiated	Porphyric	Granular; Crumb; Subangular blocky; Fissure;	Crumb; Blocky; Granule	FM/+/Aggregate nodule; FM/++/N; K/+/N; K/+/TC	Organic fine material
	Bks/0.60	Ch (+++); Pl (+++++); Vu (++++)	Undifferentiated	Porphyric	Granular; Crumb; Subangular blocky; Fissure	Granule; Crumb; Ped; Blocky	FM/+++/Aggregate nodule	–

(*continued on next page*)

Table 3 (*continued*)

INZHAVINO PC (MIDDLE PLEISTOCENE)							
Late Inzhavino interstadial paleosol – MIS 8							
Acks@/0.60	Ves (+); Ch (++++); Pl (+++); Vu (+)	Stipple speckled	Porphyric	Granular; Fissure; Spongy	Granule; Ped	FM/++/Aggregate nodule	Organic fine material; Organic pigment
Early Inzhavino interglacial paleosol – MIS 9 or MIS 11							
Ak/1.25	Ves (+++); Ch (+); Pl (+); Vu (+)	Stipple speckled, Concentric-striated	Porphyric	Granular; Fissure;	Granule; Ped	FM/+/Aggregate nodule	Organic fine material
ABcks/1.70	Ves (+++); Ch (+++); Pl (++++); Vu (+)	Stipple speckled, Concentric-striated	Porphyric	Granular; Subangular blocky; Fissure	Granule; Ped	K/++++/N; K/++/HC; FM/++/TC; FM/+/HC; FM/+/N; FM/++/Aggregate nodule; Rhizoliths/+/< 2 mm	–
VORONA PC (EARLY PLEISTOCENE)							
Late Vorona interstadial paleosol – MIS 13							
A@/0.70	Ch (++); Pl (+++); Vu (++++)	Stipple speckled	Porphyric	Granular; Subangular blocky; Fissure	Granule; Ped; Blocky	FM/++/Aggregate nodule	Organic fine material
Early Vorona interglacial paleosol – MIS 15							
Aks@/0.40	Ch (+); Pl (++)	Stipple speckled	Porphyric	Granular	Granule	FM/++/Aggregate nodule	Organic fine material
ABks@/0.35	Ch (++++); Pl (++); Vu (++)	Stipple speckled	Porphyric	Subangular blocky; Fissure	Blocky; Ped	FM/++/Aggregate nodule; FM/++/HC	Organic fine material
Bcks@/0.65	Pl (++++); Vu (++)	Stipple speckled, Concentric-striated	Porphyric	Granular; Subangular blocky; Fissure	Granule; Ped; Blocky	FM/++/Aggregate nodule; K/++++/N	Organic fine material
Bck@/0.85	Ch (+++); Pl (+++++); Vu (++)	Stipple speckled, Concentric-striated	Porphyric	Granular; Subangular blocky; Fissure	Granule; Ped; Blocky	K/++++/N	–
RZHAKSA INTERGLACIAL PALEOSOL (EARLY PLEISTOCENE) – MIS 17							
ABcs@/1.15	Ves (++); Ch (+++++); Pl (+++++); Vu (++)	Stipple speckled	Porphyric, Open Porphyric	Granular; Subangular blocky; Fissure	Granule; Ped; Blocky	FM/++/Aggregate nodule; FM/+/HC	Organic fine material

To describe the micromorphology characteristics and their quantitative composition, the following notation was used: The classification corresponds to the recommendation of Stoops (2003) and is as follows: + = very few, ++ = common, +++ = frequent, ++++ = dominant, +++++ = very dominant.
Classification of voids: Pv – packing void; Ves – vesicular; Ch – channel, chamber; Pl – planes; Vu – vughs.
The nature of mineral concentrations: K – carbonates, GY – gypsum, FM – iron–manganese, F – iron, C – clay.
Classification of the kinds of mineral concentrations: T – crystal, N – nodule, HC – hypo-coating, TC – typic (coating), rhizoliths.

Fig. 3. The Inzhavino PC morphology in the Shabelskoye section: the photograph and field sketch by A.A. Velichko. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

Pleistocene paleosols exposed in the Beglitsa section, as well as those of Middle and Early Pleistocene paleosols from Chumbur-Kosa. Besides, we refer to some materials on the Semibalki section published by Velichko et al. (2009).

3.1.1. Modern soils - Chernozems ordinary (Chernozems (Pachic))

The profile of the Chernozems ordinary (Chernozems (Pachic)) – in the region under study is as follows: Ap-ABk-B-BCcys. The greater part of humus horizons was repeatedly ploughed; they are dark gray in color, with granular structure. The horizon B is dark brown loam, calcareous, with crumby structure. Quite common are mole burrows 7 to 10 cm and more in diameter.

3.1.2. The Late Pleistocene Bryansk interstadials paleosol

Within the studied region it is only in the Beglitsa section that the Bryansk interstadial paleosol is morphologically well pronounced (Velichko et al., 2017a, 2017b). The typical profile of the paleosol is Aqs-ABqy-Bqys-BCky < 1.5 m thick (Table 2). The humus horizon is composed of gray loam with yellowish hue; organic spots are noticeable in small-size pores. The horizons Bqys and BCky are sandy silt, pale yellow to whitish, with a gray hue, abounding in fine carbonate particles.

3.1.3. The Late Pleistocene Mezin paleosol complex

The Mezin PC consists of two paleosols: Salyn interglacial paleosol (Mikulino interglacial - MIS 5e) and Krutitsa interstadial paleosol (MIS 5c) ones, with the Sevsk loess between them (Table 1). Within the studied region such a distinct subdivision of the Mezin PC was recorded in the Beglitsa section only (Fig. 2, Table 2). There the horizon Acs of the interstadial paleosol is dark brown with grayish hue, of prismatic structure, includes spots of Fe-Mn and gypsum crystals. Mole burrows are found occasionally. The horizon ABy@ of that paleosol is light brownish-gray, with numerous small clusters of carbonates. The Salyn interglacial paleosol has a horizon A of dark-gray color with a brownish hue, occasionally very dark gray. Its horizons Bcy@-Bcks-BCks are a gray-brown sandy loam, not very well sorted, with some burrows up to 8 cm in diameter and inclusions of gypsum druses.

The Mezin PC is also well pronounced in the Chumbur-Kosa section (Fig. 2), though unlike the Beglitsa section there is no loess horizon between the paleosols. The interstadial paleosol has a profile of small thickness consisting of humus horizon (dark brown dense loam, crumby in structure). The layer contains abundant small-size veinlets of fine-grained carbonates and gypsum forming a system of blotches 2 to 5 cm in diameter. The profile of the Salyn interglacial paleosol consists of a series of genetic horizons (ABcsy-Bky1-Bky2-Bk). The profile composed mostly of loam, with abundant accumulations of fine silt, probably brought in through grass root channels or pores. The dominant color is grayish-brown.

In the Semibalki-1 section (Fig. 2) the Mezin PC is represented as the humus horizon of the interstadial paleosol and more complete profile of the interglacial paleosol with the genetic profile including Ay-Bcksy horizons. The entire PC is broken with vertical fissures filled with loess material. The humus horizon of the interstadial paleosol is composed of light-colored brownish-gray loam probably formed during the final phase of the soil formation (Velichko et al., 2009).

The Mezin PC is also recognizable in the Port-Katon section at a depth of 2.15–4.15 m from the surface (Fig. 2). Unlike the Semibalki section, the paleosol there is noted for a thicker profile (~4 m), with two identifiable paleosols (interstadial and interglacial ones). The Mezin PC is also quite well identifiable in sections Kulikovskoye and Shabelskoye, in spite of being heavily disturbed, most probably due to deep freezing of the paleosol superficial horizons. In the Shabelskoye section the cracks and fissures are about 1 m deep and penetrate the entire soil profile.

3.1.4. The Middle Pleistocene Kamenka paleosol complex

In a number of studied sections (Chumbur-Kosa, Port-Katon, Semibalki-1 and Semibalki-2) the late Kamenka interstadial paleosol consists of humus horizons subjected to cryogenic processes. They are composed of sandy and silty loam, mostly brownish in color, of compact consistence and broken by large vertical fissures filled with material from the overlying layer. The pillar-like vertical bodies of humus material contain little, also vertical or sub-vertical, veinlets 2.0 to 0.3 cm wide. There are noted also small-size vertical humified aggregates 2–5 cm wide and 10–15 cm high. There are large soil pillars traceable along the paleosol layers.

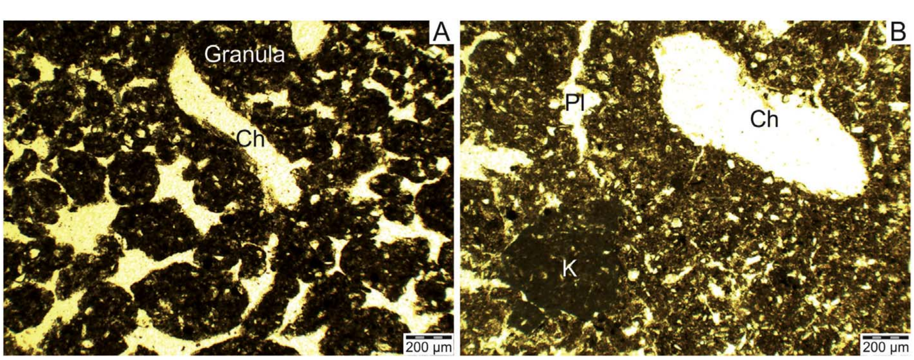

Fig. 4. Micromorphology of the modern soil: A – humus horizon, Chumbur-Kosa section (PPL); B – horizon Bt, the same section (PPL). Symbols in the figure: Ch – channel, Pl – planes, Granule – granular microstructure, K – carbonate nodule. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

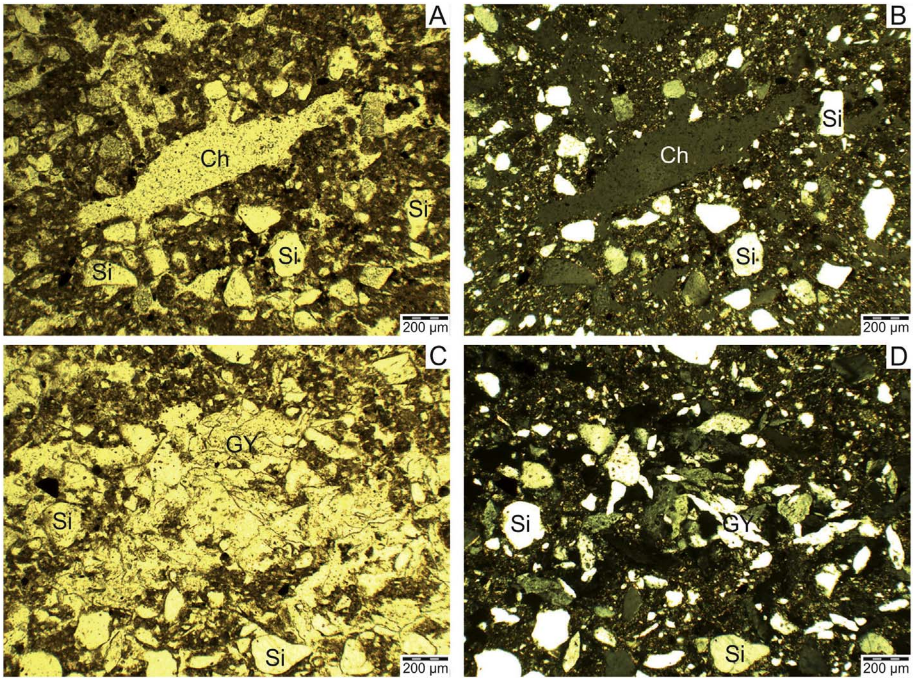

Fig. 5. Micromorphology of the Bryansk interstadial paleosol: A – humus horizon, Beglitsa section (PPL); B – the same (XPL); C – horizon Bqys with gypsum pedofeatures, Beglitsa section (PPL); D – the same (XPL). Symbols in the figures: Ch – channel, Si – quartz grains, GY – gypsum pedofeatures.

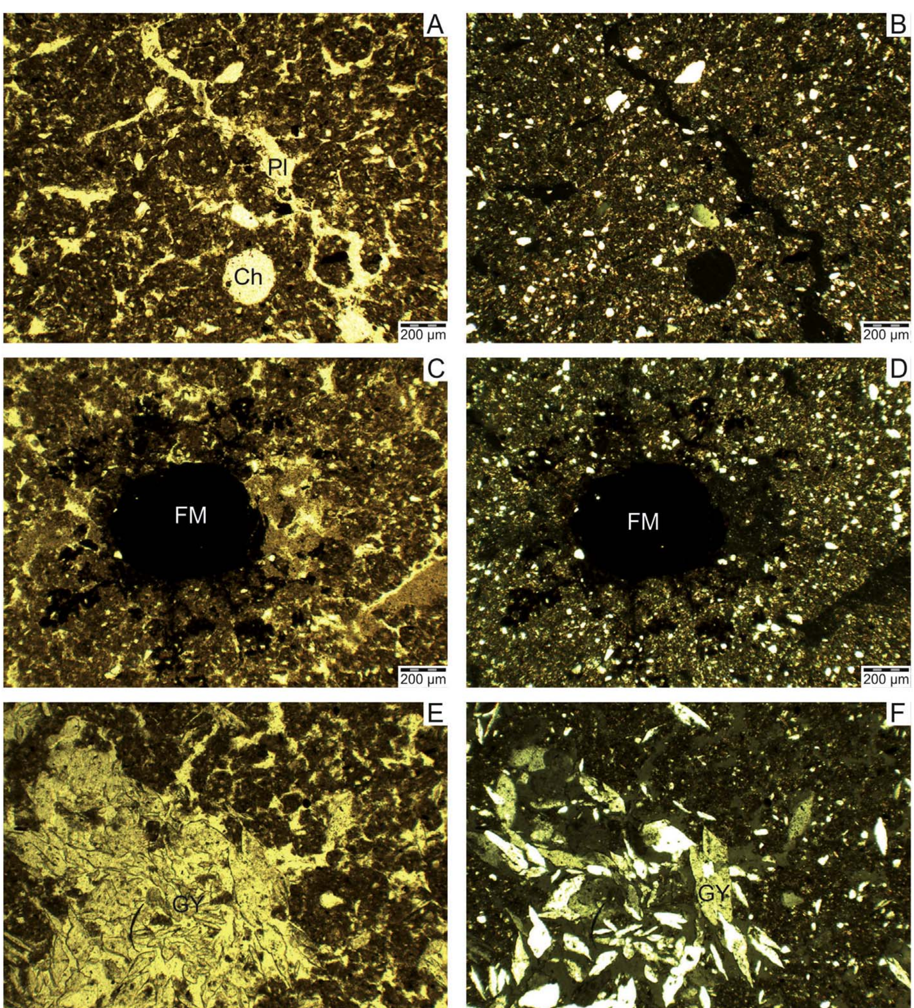

Fig. 6. Micromorphology of the Krutitsa interstadial paleosol: A – b-fabric of the horizon Acs, Beglitsa section (PPL); B – the same (XPL); C – Fe-Mn nodule in the horizon Aky, Chumbur-Kosa section (XPL); D – the same (XPL); E – gypsum microcrystals in the ABy@ horizon, Beglitsa section (PPL); F – the same (XPL). Symbols in the figures: Ch – channel, FM – Fe-Mn nodules, GY – gypsum pedofeatures, Pl – planes.

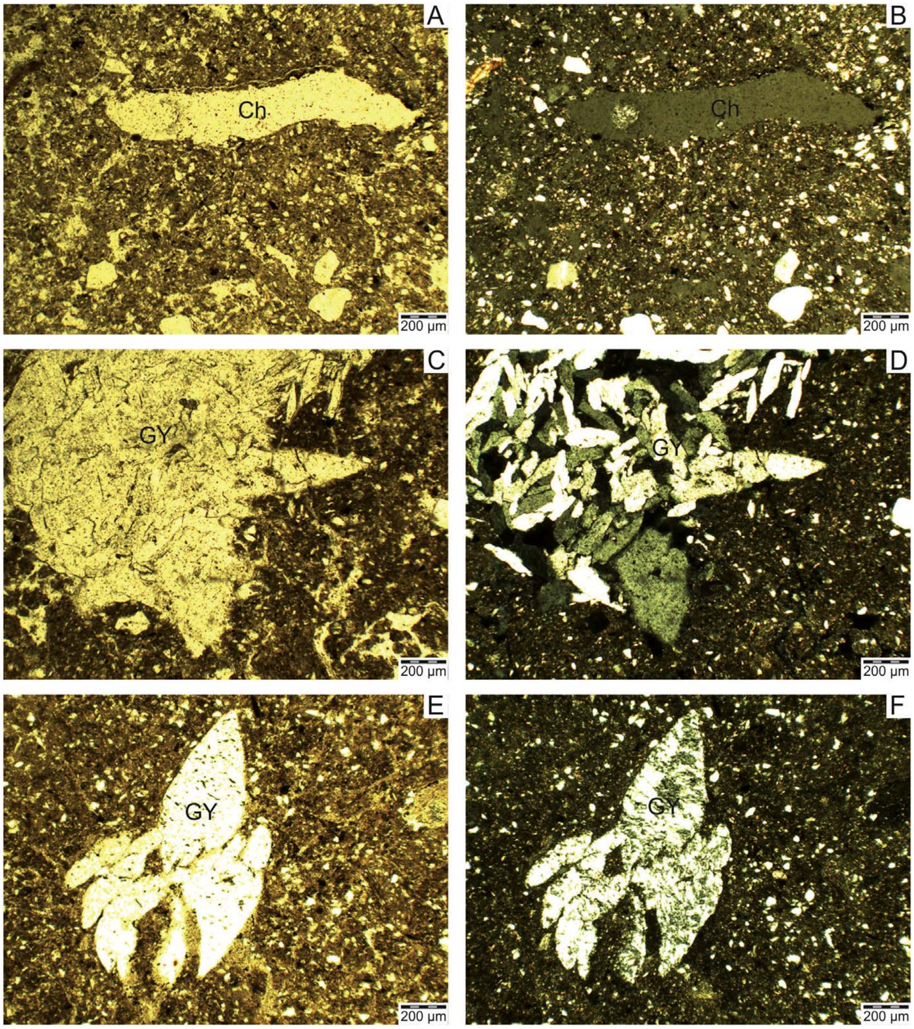

Fig. 7. Micromorphology of the Salyn interglacial paleosol: A – b-fabric of the humus horizon, Beglitsa section (PPL); B – the same (XPL); C – gypsum druse in the horizon Bcks, Beglitsa section (PPL); D – the same (XPL); E – large gypsum crystals in the horizon Bky, Chumbur-Kosa section (XPL); F – the same (XPL). Symbols in the figures: Ch – channel, GY – gypsum pedofeatures.

In the profile of the early Kamenka interglacial paleosol dominant are horizons (ABcks@-Bcks-Bks) as may be seen in the Kulikovskoye section (Fig. 2). The soil layers are mostly composed of gray-brown loam, with thin blotches of Fe-Mn and organic matter. The layers are enriched with large carbonate inclusions of the "byeloglazka" (white-eye) type, 2–3 cm in diameter on average. There are also mole burrows 8–15 cm wide.

3.1.5. The Middle Pleistocene Inzhavino paleosol complex

The Inzhavino PC presents one of extremely well pronounced levels of soil formation identified in the loess-paleosol sequences in the Azov region. It is well recognizable by a bright brown color and the presence of fissures dissecting it and filled with light brown material. In the sections Chumbur-Kosa, Port-Katon, Kulikovskoye, Shabelskoye its thickness averages 2.3 m, the late Inzhavino interstadial and early Inzhavino interglacial are easily distinguishable (Fig. 2, Table 2). The interstadial paleosols are noted for the presence of humus dark brown horizons, calcareous, with spots of Fe-Mn. The interglacial paleosol profile includes carbonate-rich AB and B horizons, mostly gray-brown in color with a slight yellow hue. In the Shabelskoye section Inzhavino PC is heavily fissured, the wedge-like fissures filled with light-yellow material (Fig. 3).

3.1.6. The Early Pleistocene Vorona paleosol complex

The Vorona PC is distinguished from all the considered PC by the greatest thickness (4.25 m on the average). It is marked by brown color with reddish hue and a compact consistence. The late Vorona interstadial paleosol is represented by a brown humus horizon penetrated by light-brown wedges. In the early Vorona interglacial paleosol, there is also a humus horizon (Aks@) besides AB and B horizons. That soil is unique in that it is of bright red color, with thin patches of Fe-Mn. Some cryoturbations were also observed there.

3.1.7. The Early Pleistocene Rzhaksa interglacial paleosol

The Rzhaksa interglacial paleosol has been described in Shabelskoye, Kulikovskoye, and Chumbur-Kosa sections. The paleosol exposed in the Shabelskoye section attributed to the hydromorphic type is more than two meters thick, with the profile Ackqs@-Ccqs@. The humus horizon is clay loam, dark with greenish hue, dense, with numerous Fe-Mn nodules 2–3 mm in diameter. There are large carbonate concretions 3 to 8 cm in size, mostly rounded, though occasionally angular. The lower-lying horizon is composed of brownish-gray clay, compact, contains Fe-Mn nodules 2–3 mm in diameter and carbonate concretions up to 5 cm. Downwards the horizon changes color to pale yellow, with greenish hue, and notable spots of Fe-Mn.

Automorphic paleosols (Rozanov, 1974) of that age developed under conditions of ground-water occurrence at a considerable depth are known from the Chumbur-Kosa and Kulikovskoye sections. In the latter the Rzhaksa paleosol profile 1.5 m thick is as follows: ABcs@ -BCcs@. In the Chumbur-Kosa section that paleosol is actually pedo-sediment ABcs@ 1.15 m thick. The humus horizon of the paleosol is mostly bluish-yellow in color, with brownish hue. The lower-lying BC horizon is dominated by brownish-grayish colors with a slight yellowish hue (Kulikovskoye section). There are Fe-Mn nodules, as well as organics and carbonate concretions.

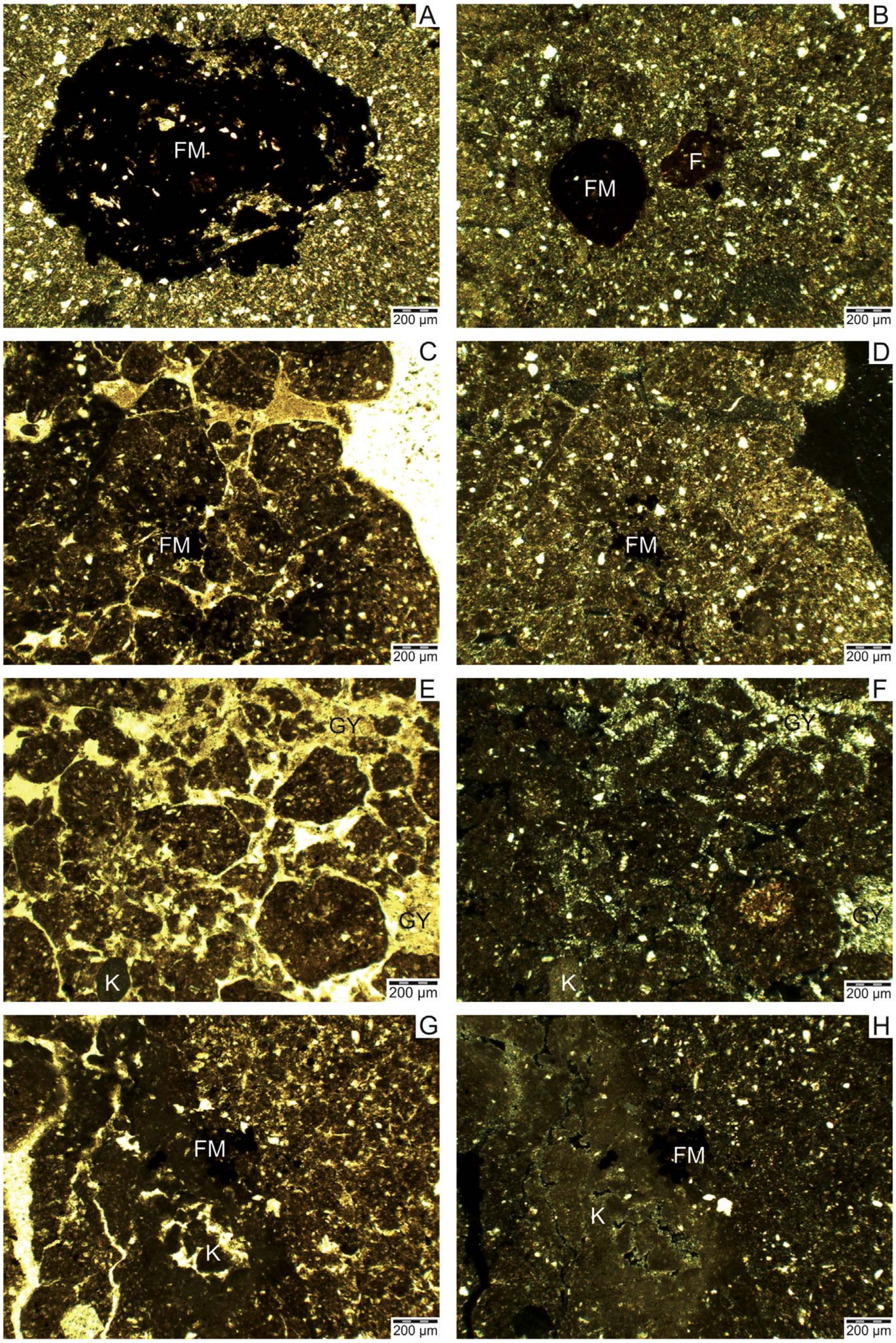

Fig. 8. Micromorphology of the Kamenka PC: A, B – Fe-Mn nodules in the horizon of the interstadial paleosol, Chumbur-Kosa section (XPL); C – granular microstructure of the horizon Bcks of the interglacial paleosol, Chumbur-Kosa section (PPL); D – the same (XPL); E – secondary gypsum pedofeatures in the Kulikovskoye section (PPL); F – the same (XPL); G – carbonate coating of the interglacial paleosol, Chumbur-Kosa section (PPL); H – the same (XPL). Symbols in the figure: FM – Fe-Mn nodules, F – ferruginous nodule, K – carbonate pedofeature, GY – gypsum pedofeatures.

3.2. Micromorphology

The study of LPS in many sections of the region revealed many features in common in their fabric. To take but a few examples, pale yellow and light brown colors are dominant in the loess, as well as predominantly silty composition of groundmass (except for the Bryansk interstadial paleosol with sandy groundmass). Pedofeatures of iron, gypsum, and carbonates are mostly confined to the paleosol levels.

Table 3 contains micromorphological characteristics of the modern soil and those of the Late Pleistocene paleosols studied in the Beglitsa section, as well as paleosols described in the Chumbur-Kosa section and attributed to the Early and Middle Pleistocene.

3.2.1. Modern soil – Chernozem ordinary (Chernozem (Pachic))

The modern soil – that is Chernozem ordinary (Chernozem (Pachic)), is described in details in the sections Beglitsa, Semibalki-2 and Chumbur-Kosa. The A and AB horizons of the Chernozem ordinary (Chernozem (Pachic)) is noted typically for dark gray color of the groundmass, homogeneous coloration, granular microstructure, moderately separated granular, bioturbations (Fig. 4A). Plant remains and dark gray humus concentrations are present. With transition to the Bk horizons, the biogenic pores (hollows) occur in greater amount, the b-fabric is stipple speckled, the color changes to brown (Fig. 4B). The modern soils in the studied region fit well with Chernozems ordinary as described in the National Soil Atlas of Russia (Shoba, 2011).

3.2.2. The Late Pleistocene Bryansk interstadial paleosol

The fabric of the Bryansk interstadial paleosol was studied micromorphologically in the Beglitsa section. The groundmass contains sand grains in a considerable proportion and is slightly gypseous (Fig. 5A–D).

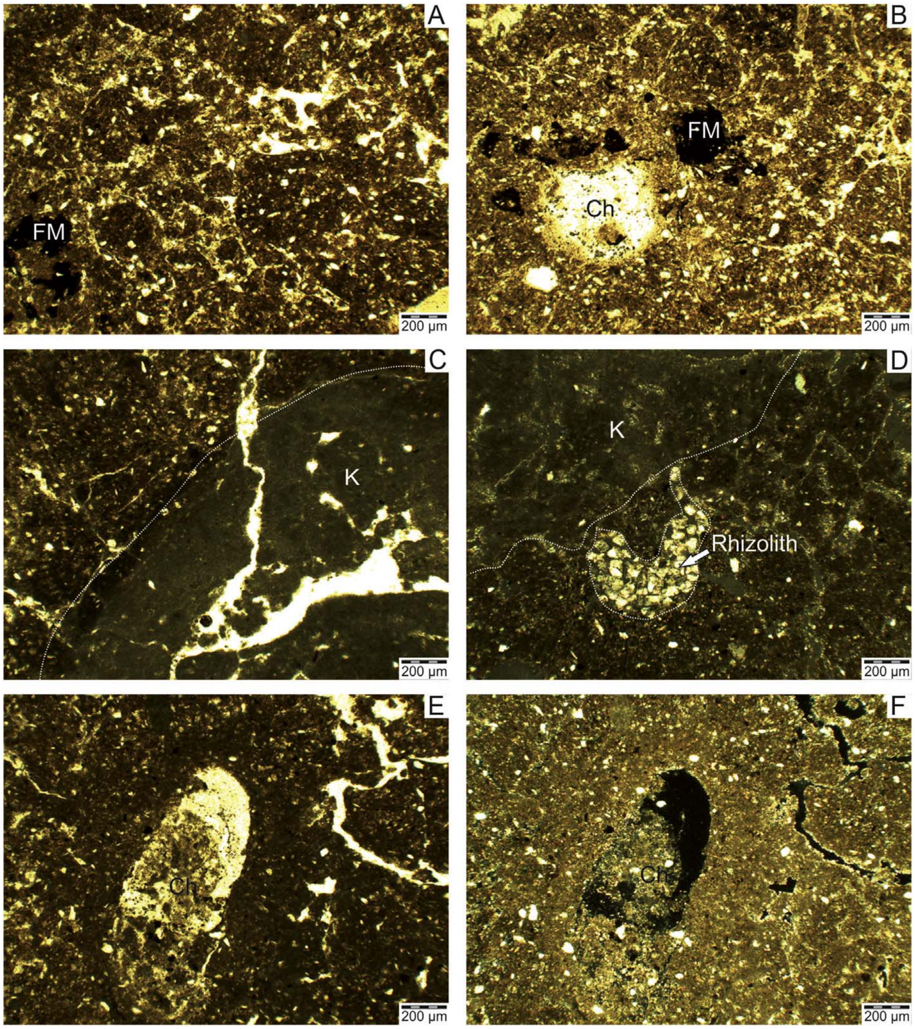

Fig. 9. Micromorphology of the Inzhavino PC: A – granular microstructure of the humus horizon of the interstadial paleosol, Chumbur-Kosa section (PPL); B – biogenic pore in the humus horizon of the interstadial paleosol, Chumbur-Kosa section (PPL); C – carbonate nodule in the horizon ABcks of the interglacial paleosol, Chumbur-Kosa section (PPL); D – carbonate nodule in the horizon ABcks of the interglacial paleosol and a rhizolith, Chumbur-Kosa section (XPL); E – biogenic pore of the interglacial paleosol, Chumbur-Kosa section (PPL); F – the same (XPL). Symbols in the figure: Ch – pore, K – carbonate pedofeatures, Rhizolith – calcinated plant roots. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

Gypsum pedofeatures are finely crystalline, rounded, partly destroyed. There are vesicles and biogenic channels (Fig. 5A, B).

3.2.3. The Late Pleistocene Mezin paleosol complex

The humus horizon of the Krutitsa interstadial paleosol is typically characterized by the following general properties: the groundmass is humus-clayey, silty, aggregated (Fig. 6A, B), of fissured, porous, impregnated with silty carbonates; there are inclusions of fine crystals of gypsum and ferrous pedofeatures (Fig. 6C, D). In the ABy@ horizon the groundmass is brownish, porous, undifferentiated; there are biogenic pores and pedofeatures of fine crystals of gypsum (Fig. 6E, F).

The humus horizon of the Salyn interglacial paleosol does not contain gypsum formations, the groundmass is aggregated (aggregates of the 1st and 2nd order are present), there are biogenic pores > 1 mm in size (Fig. 7A, B). The humus content is less than in the Krutitsa paleosol. In Bcy horizon the groundmass is silty-clayey, granular, finely crumbed, occasional druses of gypsum (Fig. 7C, D) and individual rhomb-shaped crystals (Fig. 7E, F). Individual Fe-Mn nodules occur in the B horizons.

3.2.4. The Middle Pleistocene Kamenka paleosol complex

A characteristic feature of the Kamenka PC, as distinguished from the Late Pleistocene and recent soils, is the presence of a great amount of concentric impregnative orthic aggregate nodules of iron hydroxide (Fig. 8A, B). The soil fabric of the late Kamenka interstadial paleosol is typically dense groundmass silty-clayey in composition, impregnated with humus matter (Fig. 8C, D). In the Kulikovskoye, Semibalki-1 and Semibalki-2 sections there have been found secondary gypsum pedofeatures (probably transported from the Mezin PC) (Fig. 8E, F). Otherwise, the gypsum is not characteristic of the Kamenka PC. Some compact nodules of carbonates also occur here.

The early Kamenka interglacial paleosol, besides the Fe pedofeatures, includes carbonate concretions < 1 mm in size and calcareous hypo-coatings (Fig. 8G, H). The groundmass is silty-clayey, though not infrequently fissured, porous, the pores are of biogenic origin.

3.2.5. The Middle Pleistocene Inzhavino paleosol complex

The Inzhavino PC also has some characteristics that appear only in this pedocomplex. In the late Inzhavino interstadial paleosol the groundmass is brown, granular and subangular blocky microstructure, display numerous granular aggregates (Fig. 9A), of silty-clay composition, impregnated with humus matter. Fe-Mn pedofeatures are rarely found, those of gypsum and carbonates are completely absent. There are pores of biogenic origin (Fig. 9B).

In the early Inzhavino interglacial paleosol the groundmass is brown, silty-clay in composition, with large-size carbonate concretions (Fig. 9C) and Fe-Mn pedofeatures. Calcified rootlets (rhizoliths) are found in the Chumbur-Kosa section (Fig. 9D). The groundmass is of porous, fissured, channel microstructure (Fig. 9E, F).

3.2.6. The Early Pleistocene Vorona paleosol complex

The microstructures of the late Vorona interstadial paleosol is massive, granular, with silty-clay granular groundmass (Fig. 10A). There are rare inclusions of Fe-Mn pedofeatures (Fig. 10B) and carbonate concretions < 1 mm in size. The Vorona interglacial paleosol groundmass is silty-clay (Fig. 10C, D). Fe-Mn pedofeatures are present

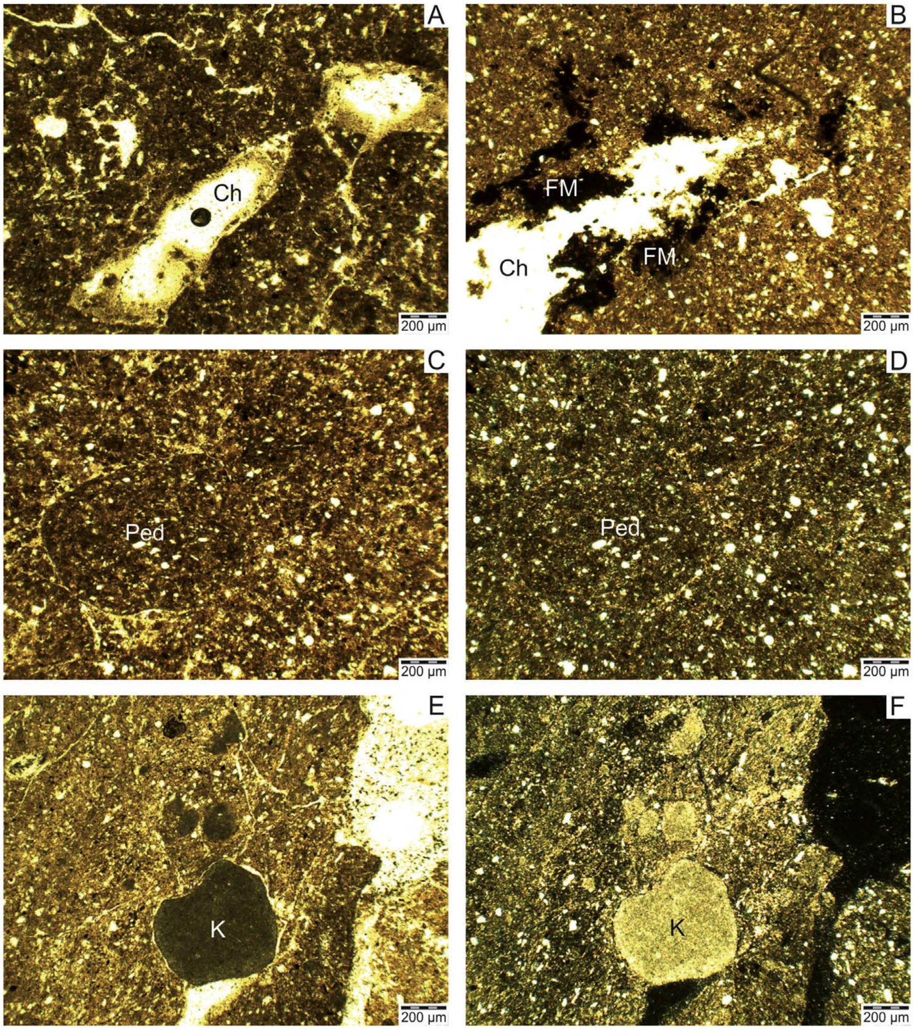

Fig. 10. Micromorphology of the Vorona PC: A, B – soil fabric of the interstadial paleosol, Chumbur-Kosa section (PPL); C – soil fabric of the interglacial paleosol, Chumbur-Kosa section (PPL); D – the same (XPL); E – carbonate nodule in the horizon Bcks@ of the interglacial paleosol, Chumbur-Kosa section (PPL); F – the same (XPL). Symbols in the figure: FM – Fe-Mn pedofeatures, K – carbonate nodule, Ped – soil aggregate, Ch – pore.

in abundance as concretions and coatings, with occasional large carbonate concretion (Fig. 10E, F). The hydromorphic variety displays ferruginous pedofeatures > 2 mm in size. There are biogenic pores present, > 1 mm in diameter; the paleosol is well aggregated.

3.2.7. The Early Pleistocene Rzhaksa interglacial paleosol

The soil fabric of the Rzhaksa interglacial paleosol is insufficiently studied in the region. Its hydromorphic type was described in the Shabelskoye section, the automorphic type – in the Chumbur-Kosa and Kulikovskoye sections.

The soil fabric of the hydromorphic variety of the Rzhaksa paleosol is as follows: the upper horizon is massive, silty-clay in composition, with rare fissures, large-size inclusions of Fe-Mn pedofeatures (Fig. 11A) and orthic carbonate nodules (< 1 mm). In the lower horizons the groundmass changes to silty, becomes denser, with pores of biogenic origin, carbonate concretions increase in number (Fig. 11B), silty particles are discernible in the concretions.

The groundmass of the automorphic soil is compact, with Fe-Mn pedofeatures (Fig. 11C, D), carbonate concretions are absent. The groundmass is well aggregated, the aggregates are rounded (Fig. 11E, F).

3.3. Magnetic susceptibility

The data on are shown in Fig. 2. As can be easily seen in the graphs, its maximum values are confined to humus horizons. In the modern soil, for example, the magnetic susceptibility values of the upper humus horizons are as follows: $0.54 * 10^{-3}$ SI in the Semibalki-1 section, $0.43 * 10^{-3}$ SI in the Port-Katon section; $0.54 * 10^{-3}$ SI in the Kulikovskoye section. Lower in the sequence, in the illuvial horizons (Bk, BCk), magnetic susceptibility values are reduced almost by half ($0.22 * 10^{-3}$ SI in the Semibalki-1 section; $0.19 * 10^{-3}$ SI in the Port-Katon section; and $0.14 * 10^{-3}$ SI in the Kulikovskoye section). Similar regularity is recorded in the paleosol levels, the magnetic susceptibility values of paleosols display are in marked contrast with those of loess. However, unlike the modern soil, the PCs consist of two paleosols, the magnetic susceptibility values slightly changing at the transitions. Thus, in the Beglitsa section the Krutitsa interstadial paleosol notably differs from the Salyn interglacial one ($0.63 * 10^{-3}$ SI–$0.33 * 10^{-3}$ SI). In the Kamenka PC of the Port-Katon section this characteristic amounts to $0.38 * 10^{-3}$ SI and $0.41 * 10^{-3}$ SI in the interstadial and interglacial paleosols respectively. The Inzhavino interstadial paleosol in the Chumbur-Kosa section gave its value equal to $0.37 * 10^{-3}$ SI, while the interglacial Inzhavino paleosol yielded $0.41 * 10^{-3}$ SI in the same section. Among the highest values of the magnetic susceptibility are those recorded in the Vorona PC, ($0.67 * 10^{-3}$ SI in the interstadial and $0.52 * 10^{-3}$ SI in the interglacial paleosol, Semibalki-1 section). Much lower values are obtained from the Bryansk interstadial paleosol in the Beglitsa section ($0.19 * 10^{-3}$ SI) and in Rzhaksa interglacial paleosol in the Kulikovskoye section ($0.38 * 10^{-3}$ SI), the corresponding value in BC horizon is $0.24 * 10^{-3}$ SI.

4. Discussion

4.1. The modern soil – Chernozem ordinary (Chernozem (Pachic))

The modern soils developed under steppe vegetation and were

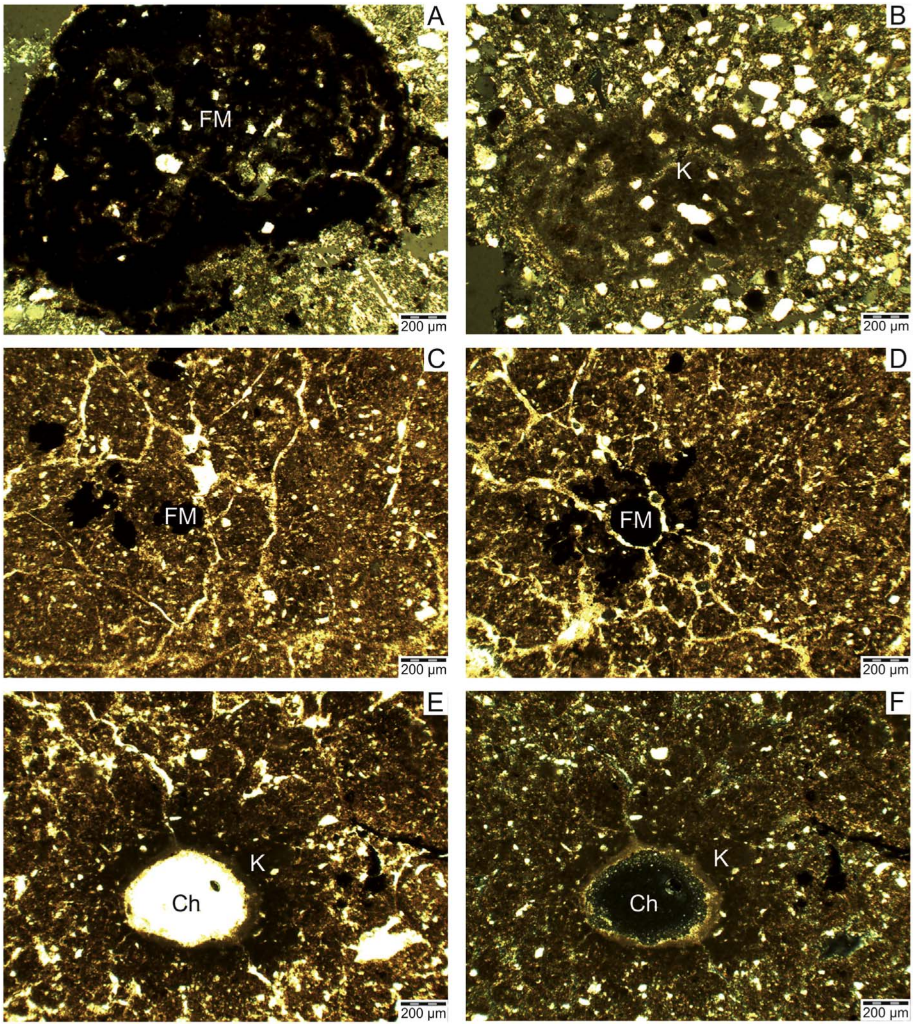

Fig. 11. Micromorphology of the Rzhaksa interglacial paleosol: A – Fe-Mn nodule, Shabelskoye section (XPL); B – carbonate nodule, Shabelskoye section (XPL); C, D – soil fabric of the interstadial paleosol, Chumbur-Kosa section (PPL); E – carbonate coating (PPL); F – the same (XPL). Symbols in figures: FM – Fe-Mn pedofeatures; K – carbonate pedofeatures; Ch – pore.

subjected to a strong human impact (ploughing). Annual rainfall is about 580 mm, the distribution over a year is irregular. The principal soil-forming processes in the region are humus accumulation, soil aggregation due to biogenic processes and coagulation, and redistribution of carbonates due to eluvial and illuvial processes.

Some characteristics of the modern soil and paleosols are given in Table 4. Micromorphological characteristics of the modern soils and paleosols studied in the LPS sections are given in Table 5.

4.2. Bryansk interstadial paleosol

The Bryansk interstadial paleosol attributed to MIS 3 has been well studied in various regions of Eurasia at the level of both morphology and micromorphology (Morozova, 1981; Velichko, 1990; Morozova and Nechaev, 1997; Rusakov and Korkka, 2004; Rusakov et al., 2007; Rusakov and Sedov, 2012;Terhorst et al., 2015; Sheinkmana et al., 2016; Sycheva and Khokhlova, 2016; Sauer et al., 2016; Sedov et al., 2016). As has been stated above, in the south of the East European Plain (the Azov Sea region) the Bryansk interstadial paleosol is known from the Beglitsa section only. Its specific feature in this section is a high proportion of sand all over the profile. The humus horizon is indistinct and represented by small spots of organic matter. It was dated by ^{14}C at 29340 ± 1500 yr BP (34,070 cal yr BP) (Velichko et al., 2017a).

Neither the paleosol morphology, nor its micromorphological analysis revealed any signs of cryoturbations. As stated above, the entire profile of the Bryansk paleosol is uniformly colored, mostly pale yellow. That part of the sequence is distinct for the presence of fine sand, its proportion decreasing with depth. Similar paleosols dated to the Bryansk interval in the central part of the East European Plain are noted for well pronounced traces of cryogenic processes. They are composed primarily of loam with a small admixture of sand (Morozova, 1981; Rusakov and Korkka, 2004; Zykina and Zykin, 2012).

When studied in thin sections under the microscope, there are sandy particles evenly distributed over the thin section surface (which is typical of the wind-transported material). As noted by some authors (Sheinkmana et al., 2016; Rusakov and Sedov, 2012), the soil fabric studied under microscope included isolated quartz grains distributed in the groundmass at random as a result of cryogenic processes. According to Morozova (1981) and Zykina and Zykin (2012), characteristic features of the Bryansk interstadial paleosol and its analog in West Siberia (Iskitim soil complex) are: granular aggregates, silty-loam groundmass, ferruginous pedofeatures. The granular aggregates considered to be cryogenic process indicators (Morozova, 1965; Gerasimova et al., 1992; Van Vliet-Lanoë, 1998, 2010; Todisco and Bhiry, 2008; Villagran et al., 2013) are found practically in all the paleosols attributed to the Bryansk interstadial.

In the north of European Russia (the Upper Volga drainage basin) they were diagnosed as Reductaquic Cryosols (Sedov et al., 2016), in the central European Russia as Umbric Gley Soil (Rusakov and Korkka, 2004), and were described as Chernozems in loess sequences of Southern Siberia (Zykina and Zykin, 2012). In the case under consideration, however, the Bryansk interstadial paleosol has none of the above specific features. It is poorly ferruginous, has a sandy-loamy groundmass, and no granular aggregates; those characteristics suggest

Table 4
Characteristics of the modern soils and paleosols studied in the LPS sections.

Sections	Soil profile	Soil thickness (m)	Magnetic susceptibility, min-max,*10^{-3}SI
THE MODERN SOIL (HOLOCENE)			
Beglitsa	Ap-AB-Bk-BCk	2.55	0.12 – 0.46
Port-Katon	Ap-ABp-Bk1-Bk2	2.15	0.18 – 0.43
Kulikovskoye	Ap-ABp-Bk-Bk@	1.40	0.14 – 0.54
Shabelskoye	Ap-ABp-Bk-BC-BCcs-Bk@	2.65	No data
Chumbur-Kosa	Ap-ABp-Bk1-Bk2-BCk	3.25	0.14 – 0.42
Semibalki-1	Ap-AB-Bk-BCk	2.65	No data
Semibalki 2	Ap-ABk-Bk-BCk	2.70	0.22 – 0.54
BRYANSK INTERSTADIAL PALEOSOL (LATE PLEISTOCENE)			
Beglitsa	Aqs-ABqy-Bqys-BCky	1.40	0.12 – 0.19
MEZIN PC (LATE PLEISTOCENE)			
Krutitsa interstadial paleosol			
Beglitsa	Acs-ABy@	1.00	0.61
Port-Katon	ABcks	0.80	0.21 – 0.24
Kulikovskoye	ABcs@	0.42	0.20 – 0.26
Shabelskoye	A@-ABky@	1.35	No data
Chumbur-Kosa	Aky	0.40	0.21 – 0.28
Semibalki-1	Ak	0.47	No data
Salyn interglacial paleosol			
Beglitsa	A-Bcy@-Bcks-BCks	2.20	0.19 – 0.38
Port-Katon	ABcs-Bcks-BCcks	3.20	0.21 – 0.35
Kulikovskoye	ABcy@-Bcks@	1.33	0.32 – 0.35
Shabelskoye	ABk-Bcy-Bk	1.00	No data
Chumbur-Kosa	ABcsy-Bky1-Bky2-Bk	2.05	0.13 – 0.31
Semibalki-1	Ay-Bcksy	1.85	No data
KAMENKA PC (MIDDLE PLEISTOCENE)			
Late Kamenka interstadial paleosol			
Beglitsa	Acs@	0.20	0.19 – 0.30
Port-Katon	ABcks	0.65	0.30 – 0.43
Shabelskoye	Acs	0.30	No data
Chumbur-Kosa	Acks@-ABcks@	1.25	0.10 – 0.20
Semibalki-1	Ay@	0.84	No data
Semibalki-2	Ay	0.35	0.29 – 0.38
Early Kamenka interglacial paleosol			
Beglitsa	ABcs@-BCcks@-BCcs@-BCcs-BCcs@1-BCcs@2	3.20	0.12 – 0.26
Port-Katon	Bcs-BCcks	1.70	0.21 – 0.31
Kulikovskoye	BCcksy@	1.18	0.30 – 0.41
Shabelskoye	ABcs-Bcs-BC1-BC2	1.90	No data
Chumbur-Kosa	ABcks@-Bcks-Bks	1.70	0.15 – 0.21
Semibalki-1	Bck-BCk	1.79	No data
Semibalki-2	ABk-BCcks	2.35	0.23 – 0.41
INZHAVINO PC (MIDDLE PLEISTOCENE)			
Late Inzhavino interstadial paleosol			
Kulikovskoye	ABcy@	1.18	0.24 – 0.29
Port-Katon	ABcks	0.95	0.27 – 0.40
Shabelskoye	A@-Acsy@	1.20	No data
Chumbur-Kosa	Acks@	0.60	0.18 – 0.26
Semibalki-1	Ak@	0.50	No data
Semibalki-2	Acs@	1.40	0.32 – 0.61
Early Inzhavino interglacial paleosol			
Port-Katon	Bcks	1.10	0.14 – 0.21
Kulikovskoye	BCcsy@	1.30	0.26 – 0.35
Shabelskoye	ABcs-Bck	0.70	No data
Chumbur-Kosa	Ak-ABcks	2.95	0.13 – 0.41
Semibalki-1	Aks@-Bks@	1.50	No data
Semibalki-2	ABcks@-Bcs	0.85	0.36 – 0.51
VORONA PC (EARLY PLEISTOCENE)			
Late Vorona interstadial paleosol			
Kulikovskoye	ABk@	0.70	0.38 – 0.43
Port-Katon	ABks	1.00	0.36 – 0.53
Shabelskoye	Acks@	0.20	No data
Chumbur-Kosa	A@	0.70	0.32 – 0.42
Semibalki-1	Acks@	0.88	No data
Semibalki-2	Acks@	1.05	0.55 – 0.69
Early Vorona interglacial paleosol			
Kulikovskoye	BCcs@	1.55	0.30 – 0.38
Port-Katon	ABcs@-Bcks@-BCcks	1.95	0.28 – 0.35
Shabelskoye	A@-Bcks-Bck-BC	4.35	No data
Chumbur-Kosa	Aks@-ABks@-Bcks@-Bck@	2.25	0.35 – 0.55
Semibalki-1	ABcks-BCcks	2.17	No data
Semibalki-2	ABcs-Bcks-BCcs1-BCcs2	2.70	0.26 – 0.52
RZHAKSA INTERGLACIAL PALEOSOL (EARLY PLEISTOCENE)			
Kulikovskoye	ABcs@-BCcs@	1.55	0.23 – 0.25
Shabelskoye	Ackqs@-Ccqs@	1.90	No data
Chumbur-Kosa	ABcs@	1.15	0.22 – 0.35

Table 5
Comparison characteristics of the modern soil and paleosols microstructure (– = absent; + = very few, ++ = common, +++ = frequent, ++++ = dominant).

Sections	Voids	Aggregates	Pedofeatures		
			Carbonate	Fe-Mn	Gypsum
THE MODERN SOIL (HOLOCENE)					
Beglitsa	+++	++++	++	+	+
Shabelskoye	+++	++++	+	+	–
Chumbur-Kosa	++++	++++	++	–	–
Semibalki-2	++++	+++	++	+	–
BRYANSK INTERSTADIAL PALEOSOL (LATE PLEISTOCENE)					
Beglitsa	++	+++	+	++	+++
MEZIN PC (LATE PLEISTOCENE)					
Krutitsa interstadial paleosol					
Beglitsa	+++	++	–	++	++++
Port-Katon	++	+	+	+	–
Kulikovskoye	++++	++	–	+	–
Shabelskoye	++	+++	–	+	+++
Chumbur-Kosa	++	++	–	–	++++
Semibalki-1	+++	++	+	–	–
Salyn interglacial paleosol					
Beglitsa	++	+++	+	++	++++
Port-Katon	++	+++	++	++	–
Kulikovskoye	+++	+++	+	+	+++
Shabelskoye	++	++	–	+	++++
Chumbur-Kosa	++	+++	+	++	++
Semibalki-1	++	++	+	+	++++
KAMENKA PC (MIDDLE PLEISTOCENE)					
Late Kamenka interstadial paleosol					
Beglitsa	++	++	–	++	–
Port-Katon	++	+++	+	++	–
Shabelskoye	++	+	–	++	–
Chumbur-Kosa	++	+++	++	++++	–
Semibalki-1	+++	+++	–	–	+
Semibalki-2	++	+++	–	–	++++
Early Kamenka interglacial paleosol					
Beglitsa	++	++	++	++++	–
Port-Katon	++	++	++	++++	–
Kulikovskoye	+++	+++	+	+	++++
Shabelskoye	++	++	+	+++	–
Chumbur-Kosa	+++	++++	++	++++	–
Semibalki-1	++	+++	++	+	–
Semibalki-2	+++	+++	+	+	–
INZHAVINO PC (MIDDLE PLEISTOCENE)					
Late Inzhavino interstadial paleosol					
Kulikovskoye	++++	+++	–	+	++++
Port-Katon	++	++	++	++	–
Shabelskoye	++	++	–	+	+
Chumbur-Kosa	++	++	–	+	–
Semibalki-1	++	+++	++	–	–
Semibalki-2	++	+++	+	+	–
Early Inzhavino interglacial paleosol					
Kulikovskoye	++	++	–	+	++++
Port-Katon	++	++	++	+	–
Shabelskoye	++	++	++	+	–
Chumbur-Kosa	+++	++	++++	+++	–
Semibalki-1	++	+++	+++	++	–
Semibalki-2	++	+++	+	+	–
VORONA PC (EARLY PLEISTOCENE)					
Late Vorona interstadial paleosol					
Kulikovskoye	++	++	–	+	–
Port-Katon	+++	++	–	++	–
Shabelskoye	++	+	++	+	–
Chumbur-Kosa	+++	+++	–	+	–
Semibalki-1	+++	+++	++	+	–
Semibalki-2	++	++	+	+	–
Early Vorona interglacial paleosol					
Kulikovskoye	++	++	–	+	–
Port-Katon	+++	++	++++	++	–
Shabelskoye	++	–	+	+	–
Chumbur-Kosa	+++	+++	++++	+	–
Semibalki-1	+++	++	+++	++	–
Semibalki-2	+++	+++	++	++	–
RZHAKSA INTERGLACIAL PALEOSOL (EARLY PLEISTOCENE)					
Kulikovskoye	+++	++	–	++	–
Shabelskoye	++	+	+	+	–
Chumbur-Kosa	+++	+++	–	++	–

an insignificant cryogenic influence on the soils at that time in this region. In all probability, the sandy particles were of local provenance and had not been transported farther north.

Taking into account all the above, we may conclude that the Bryansk interstadial paleosols formed under less cold and more arid climatic conditions than their analogs in the northern regions. The principal soil-forming processes here were the humus accumulation, the carbonate redistribution by eluvial-illuvial processes (Velichko et al., 2017b), the gypsum leaching from the upper horizons and deposition in the lower part of the soil profile. According to the data by T.D. Morozova (Velichko et al., 2017b), those paleosols may be determined as soddy shallow soils (Cambisols). However, considering their sandy composition and morphologically immature profile with poorly pronounced differentiation into horizons, those may be classed with brown desert-steppe soils (Luvic Calcisols), widely spread in semi-deserts of Western Caspian Lowland at present (Shoba, 2011).

4.3. The Late Pleistocene Mezin paleosol complex

The Mezin PC is one of the best studied ones not only in the Azov region (Velichko et al., 2009, 2017a; Liang et al., 2016), but also in other regions of Europe (Bronger, 2003; Marković et al., 2008; Smalley et al., 2011; Haesaerts et al., 2016; Schirmer, 2016) and of Russia (Morozova, 1981; Velichko, 1990; Velichko et al., 2006a, 2006b; Velichko and Morozova, 2010; Little et al., 2002; Zykina and Zykin, 2012; Sycheva, 1998; Sycheva and Sedov, 2012; Grigor'eva et al., 2012; Panin, 2007, 2015; Glushankova, 2008; a.o.). The Mezin PC consists of the Salyn paleosol attributed to the Mikulino interglacial (MIS 5e ~135–117 ka BP) and the Krutitsa interstadial paleosol correlatable with MIS 5c ~105–98 ka BP.

In the studied region the Mezin PC was described in several sections, namely Beglitsa, Port-Katon, Kulikovskoye, Shabelskoye, Chumbur-Kosa, Semibalki-1. In most of LPS the interstadial paleosol is difficult to distinguish from the interglacial one. The Sevsk loess horizon that occurs between the Krutitsa and Salyn soils was essentially transformed by the soil-forming processes at a later stage and is partly included into the humus horizon of the paleosol. In the Beglitsa section, however, both paleosols of the Mezin PC are morphologically distinguishable, their profiles being separated from each other.

As can be seen in Table 4, the Krutitsa interstadial paleosol is present as humus horizons A and AB, loam of light brown and gray color prevailing in the profile. In the Semibalki-1 and Kulikovskoye sections the paleosol is broken with vertical fissures filled with loessial material. In other sections the cryoturbalions and frost fissures are not so well manifested. The Krutitsa paleosol thickness varies from 0.40 m (Chumbur-Kosa section) to 1.35 m (Shabelskoye section), that is 2 to 3 times less than that of the modern soil. The Salyn interglacial paleosol thickness is practically comparable to the modern soils, the maximum thickness was recorded in the Port-Katon section. Cryoturbations are nearly absent, except for Kulikovskoye section where the interglacial paleosol is broken with wedges filled with pale yellow fine material. The values of magnetic susceptibility measured in the Krutitsa paleosol in the studied sections are close to each other; they mostly vary within the interval $0.20–0.28 * 10^{-3}$ SI. The maximum values of the magnetic susceptibility measured in the Salyn interglacial paleosol are about $0.31–0.38 * 10^{-3}$ SI. (Table 4). The higher values recorded in the interglacial Salyn paleosol might be ascribed to active processes of soil formation and to the longer period of its development, as distinct from shorter-living interstadial paleosol.

Somewhat different values of MS were obtained on the samples from the Beglitsa section. The Krutitsa paleosol, for example, yielded MS values equal to $0.61 * 10^{-3}$ SI. The measurements on the Salyn paleosol in the Beglitsa section were performed less thoroughly, which makes difficult the comparison between the two paleosols of the Mezin PC. The higher MS values in the Krutitsa paleosol of the Beglitsa section are most probably related to specific features of the Late Pleistocene deposition there. Unlike all the rest sections under study, the sequence exposed in Beglitsa includes a well pronounced Bryansk paleosol.

When studied under the microscope, both Krutitsa and Salyn paleosols display silty-clayey aggregated groundmass. In the interglacial paleosol, in addition to granulated aggregates, some large rhomboid ones appear, confined to B horizons. Silty carbonate inclusions are found in the groundmass occasionally, biogenic turbations are traceable. The groundmass of the humus horizons contains flaky dark gray to black concentrations of humus. The transitional horizons of the interstadial paleosol contain microcrystalline gypsum (Table 5); in the interglacial paleosol the gypsum occurs as large crystals of a regular rhomboidal configuration. As follows from the data published by Gerasimova (Gerasimova et al., 1992), such large-size regular crystals of gypsum develop under conditions of constant or long-term moisture supply to the horizon, which makes possible an active growth of crystals.

So it may be concluded that the gypsum accumulated deep in the interglacial paleosol under conditions of high humidity that made possible the crystal growth. In the interstadial paleosol gypsum is found as small-size crystals, probably due to abrupt fluctuations in moisture and prolonged intervals of the soil profile drying up (Minashina and Shishov, 2002; Poch et al., 2010). The listed characteristic features of the Mezin PC have been recorded in all the sections of the Azov region, including Semibalki-1, Chumbur-Kosa, Beglitsa, Kulikovskoye, Shabelskoye, with the only exception of Port-Katon. The interstadial and interglacial paleosols of the Mezin PC may be easily distinguished both at micro- and macrolevels by the presence of large and medium-size crystals of gypsum. The larger crystals are typically present in the Salyn paleosol, – the fact attributable to high moisture content in the soil profile, so that gypsum could accumulate and crystals grow in the pores. At the later stages of the paleosol formation the climate became drier, and gypsum druses formed (Minashina and Shishov, 2002; Poch et al., 2010). Still later, the climate appeared to change drastically towards cooling, and the Sevsk loess horizon lacking gypsum crystals was deposited on the surface of the Salyn paleosol. During the subsequent interstadial the Krutitsa paleosol formed with finely crystalline gypsum in the transitional AB horizon. No large ferruginous pedofeatures has been found. All the above characteristics suggest the rains falling seasonally and the moisture quickly evaporating from the soil. Therefore, the gypsum is not of a secondary origin, it did not penetrate into the soil from the above-lying series, but crystallized in the soil profile in situ.

Unlike other sections, the Mezin PC described in Port-Katon contains carbonate nodules, with carbonates present as small-size crystals. The carbonate content is greater in the interglacial paleosol, where ferruginous pedofeatures are also present as aggregates and typical nodules. Many authors (Bullock et al., 1985; Stoops et al., 2010; Zaidel'man and Nikiforova, 2010) agree in that calcareous and ferruginous pedofeatures are indicators of an abundant moisture supply and a very high stand of groundwater table (or of temporary perched water layer). According to Yamnova and Golovanov (2010), the maximum gypsum content in soil forms under conditions of the groundwater table at a depth of 1 to 2 m from the surface. In the Port-Katon section the groundwater most probably occurred at < 1 m depth in the paleosol profile, as suggested by the presence of Fe-Mn and carbonate pedofeatures.

It follows from the above that the soils formed in the southern regions during the Mikulino Interglacial belonged to the groups of chernozems southern residual-solonetzic (Haplic Chernozems (Sodic)) or dark chestnut solonetzic soils (Haplic Kastanozems (Sodic)). During the interstadial the chernozemic solodic shallow soils (Chernozems (Sodic)) formed. In the regions farther north the Salyn interglacial paleosol is noted for its texture-differentiated profile, including the eluvial horizon E (Panin, 2007, 2015; Glushankova, 2008; Haesaerts et al., 2016). It may be concluded from the above that the soil formation in the studied region proceeded under conditions of a dryer climate than that in the central East European Plain or in Europe.

4.4. Middle Pleistocene Kamenka paleosol complex

The Kamenka PC includes the early Kamenka interglacial paleosol dated to the Kamenka interglacial (MIS 7 or 9, ~200–250 ka BP) and the late Kamenka interstadial paleosol correlatable with MIS 6 or 8. Unlike other paleosols, the Kamenka PC is rather indistinct in the loess sequence; in the Kulikovskoye section it is presented by one horizon BCcksy@ only. In other sections – Semibalki-1 and Semibalki-2, Shabelskoye, Chumbur-Kosa – it is morphologically identifiable, though interstadial and interglacial paleosols can be distinguished only in Chumbur-Kosa and Semibalki-1 sections. In the Chumbur-Kosa section the humus horizon is presented as vertically oriented bodies; most probably, the horizon was broken by large fissures, the latter being filled later with the material of the overlying Mezin PC. The column-like bodies of the humus matter themselves contain small vertical and sub-vertical veinlets 2.0 to 0.3 cm in size. There were found also vertically oriented humified aggregates 2.0–5.0 cm wide and 10.0–15.0 cm high. The upper boundary of the interglacial paleosol is recognizable by column-like wedges composed of the humified material derived from the upper horizon of the early Kamenka interglacial paleosol.

Typically, the late Kamenka interstadial paleosol consists of a single genetic horizon – humus or humus-illuvial one. In most cases there are numerous cryoturbations, wedges, desiccation cracks, etc. The soil thickness does not usually exceed 1 m, except in the Chumbur-Kosa section, where the soil profile consists of two horizons, their total thickness is 1.25 m (Table 4). As to the magnetic susceptibility indexes, they vary widely and hardly may be used for the purposes of the paleosol identification (unlike the Mezin PC, where the magnetic susceptibility values measured in various sections practically coincide).

The early Kamenka interglacial paleosol is typically brown (with grayish hue), getting lighter towards the base of the layer. Its profile consists of a series of genetic horizons (mostly illuvial). In the upper horizons there are cryoturbations presumably originated during a short-term cooling between the interglacial and interstadial warm stages. In most of profiles the humus horizons had been eroded, their remains are found in the transitional humus-illuvial horizons only. The magnetic susceptibility also cannot serve as unambiguous identifier, its values varying chaotically from 0.12 to $0.26 * 10^{-3}$ SI or from 0.21 to $0.31 * 10^{-3}$ SI, $0.41 * 10^{-3}$ SI as a maximum. No general regularity has been found in the magnetic susceptibility variations within those paleosols, which can be attributed to a different degree of paleosol preservation, or – probably – to a low sampling resolution.

The interstadial paleosol fabric is porous, well aggregated (Table 5). Carbonate concretions are present in a small number. Their appearance is due to processes of carbonate illuviation from the Salyn interglacial paleosol. Unlike the Krutitsa interstadial paleosol and the modern soil, Fe-Mn pedofeatures are present in abundance as nodules of various size (the maximum nodule diameter – up to 1 mm – was recorded in the Chumbur-Kosa section) and occasional hypo-coatings (the Beglitsa section). Gypsum pedofeatures are not typical of the late Kamenka interstadial paleosol, except for Semibalki-1 and Semibalki-2 sections where a high content of gypsum druses may be result of a secondary salinization from the upper member of the Mezin PC.

Specific features of the interglacial paleosol microstructure are a high content of compact Fe-Mn pedofeatures with small-size concentrations of silty particles. The horizons are of blocky structure, individual blocks are 1.00–1.20 cm in size. There are also smaller blocky aggregates separated by pores-fissures. Optical orientation of the clayey mass is speckled or striated.

Gypsum pedofeatures are not typical of the Kamenka paleosol. The only exception – their presence in the Kulikovskoye section – may be attributed to the absence of the fully developed Kamenka PC; the latter is represented by BCcksy@ horizon only, so the gypsum could penetrate into the paleosol profile.

The brownish color of groundmass (due to dispersed iron), a great quantity of Fe-Mn and Fe nodules, as well as striated b-fabric of the optically-oriented clay, – all the characteristics suggest the moisture presence in abundance and water stagnation at that level (Gerasimova et al., 1992; Zaidel'man et al., 2009; Zaidel'man and Nikiforova, 2010; Lindbo et al., 2010).

Considering all the above, it may be safely concluded that the Kamenka PC developed under conditions of a greater moisture supply than the Mezin PC and the modern soil. The main process that took part in the development of the late Kamenka interstadial paleosol was the humus accumulation. In the early Kamenka interglacial paleosol formation, apart from the accumulation of humus, eluvial-illuvial process of carbonate redistribution took an active part. The presence of Fe and Mn pedofeatures in both paleosols is most probably due to the gleyzation processes. However, the complete absence of gray-blue or light gray spots indicative of gleying in the paleosol profiles argues against a prolonged stagnancy of water and anaerobic processes in the soil profile. Quite possibly, a regime of periodical leaching was dominant at the time of the interglacial paleosol development.

Thus, the specific features of the Kamenka PC suggest formation of paleosols similar to the present-day meadow-chernozemic shallow soils (Regosolos (Ochric, Oxyaquic)) in the interstadial time and meadow-chestnut ones (Someric Kastanozems (Oxyaquic)) during the interglacial.

In the central part of the East European Plain (Little et al., 2002; Velichko et al., 2006b; Chizhikova et al., 2007; Panin, 2007, 2015) the Kamenka Interglacial was marked by development of soils with Fe-Mn pedofeatures present in the profile, while no eluvial horizon was found. Ferriferous pedofeatures are represented by nodules and abundant coatings and hypo-coatings; carbonate nodules, however, are practically absent here, in contrast to southern regions. That suggests more humid conditions of soil formation in the center of the East European Plain, than in the south, though soil-forming processes had much in common in both regions. Considering all the above, it may be safely concluded that at the Kamenka interglacial humid type of soil formation was dominant over the entire East European Plain, with some features of aridity appearing towards the south.

4.5. Middle Pleistocene Inzhavino paleosol complex

The Inzhavino PC is one of the most easily recognizable in the loess sequence of the Azov region. It includes two paleosols: the early Inzhavino interglacial and late Inzhavino interstadial ones. The time of the early Inzhavino interglacial paleosol corresponds to the Likhvin Interglacial and may be correlated with MIS 9 or 11 (~310–340 ka BP); the late Inzhavino interstadial paleosol is correlatable with a warming during the Fuhne glaciation (MIS 8 or 10) (Velichko and Morozova, 2015). A thick soil profile – up to 3.55 m, in the Chumbur-Kosa section – is dark gray in color, the humus horizons are distinctly seen; numerous fractures breaking the profile are filled with pale-yellow loess material. Those typical features of the soil morphology are quite well pronounced in all the sections, in Shabelskoye in particular. The most active fissuring could take place at the Pechora pleniglacial – an interval marked by deposition of the Borisoglebsk loess.

Profiles of the interstadial and interglacial paleosols show distinctions in their macro- and micromorphology. Thus, the profile of late Inzhavino interstadial paleosol consists typically of humus-accumulative horizons similar to those in Mezin and Kamenka PCs, though much less thick. For example, the average thickness of the interstadial late Inzhavino paleosol amounts to 0.97 m, while that of Mezin is 0.60 m and of Kamenka – 0.74 m. Also in common with Kamenka PC, magnetic susceptibility in Inzhavino PC varies widely, the maximum is $0.61 * 10^{-3}$ SI (Table 4), equal to that of the Krutitsa interstadial paleosol (Mezin PC).

The interglacial paleosol consists of several genetic horizons, subjected later to cryogenesis. The AB and B horizons contain abundant carbonate inclusions in the form of “byeloglazka” (white spots 1.0–1.5 cm in diameter). Some large mole burrows (up to 10 cm in

Table 6
Changes of the soils in the Azov region from the Early Pleistocene to the Holocene.

MIS	Names of soil horizons	Soil name in Russian classification	Soil name according to World Reference Base, 2015	Average soil thickness, m
MIS 1	Modern soil	Chernozem Ordinary	Chernozems (Pachic)	2.48
Interstadial paleosols				
MIS 3	Bryansk	Brown desert-steppe	Luvic Calcisols	1.40
MIS 5	Krutitsa	Chernozemic solodic shallow	Chernozems (Sodic)	0.74
MIS 6 or 8	Late Kamenka	Meadow-chernozemic shallow	Regosolos (Ochric, Oxyaquic)	0.60
MIS 8 or 10	Late Inzhavino	Meadow-chernozemic	Chernozems (Siltic)	0.97
MIS13	Late Vorona	Humus-accumulative reddish-brown	Chromic Cambisol (Ferric)	0.76
Interglacial paleosols				
MIS 5e	Salyn	Chernozems southern residual-solonetzic or dark chestnut solonetzic soil	Haplic Chernozems (Sodic) or Haplic Kastanozems (Sodic)	1.94
MIS 7 or 9	Early Kamenka	Meadow-chestnut	Someric Kastanozems (Oxyaquic)	1.97
MIS 9 or 11	Early Inzhavino	Meadow-chernozem texture-calcareous	Calcic Chernozems	1.40
MIS 15	Early Vorona	Calcareous thick reddish	Cambisol (Calcaric, Ferric)	2.50
MIS 17	Rzhaksa	Meadow-chernozem gley and meadow-chestnut gley	Gleyic Chernozems and Gleyic Phaeozems	1.65

diameter) are found there. The magnetic susceptibility values vary in the range from 0.14 to $0.41 * 10^{-3}$ SI.

The Inzhavino PC bears clear evidence of two phases of the soil formation: the final (interstadial) and main (dated to the Likhvin Interglacial). As seen in Table 5, the interstadial paleosol is well aggregated, porous, and noted for a high humus content. There are calcareous pedofeatures present in the form of hypo-coatings and small nodules up to 0.25 mm in size, along with Fe-Mn aggregate nodules. Some rounded aggregates seen in microstructure strongly suggest the cryogenesis impact on the uppermost humus horizon (Morozova, 1965; Van Vliet-Lanoë, 1998, 2010).

The carbonate pedofeatures are more numerous in the interglacial paleosol, their diameter exceeds 1 mm. Fe-Mn pedofeatures also increase in number. As follows from the data published by many specialists (Zaidel'man et al., 2000; Durand et al., 2010; a.o.), carbonate nodules are indicators of a high stand of the groundwater table. Their presence might be reckoned as an indicator of the meadow soil-forming process (Zaidel'man et al., 2000). Gypsum pedofeatures are not typical for the Inzhavino PC. A considerable number of gypsum druses discovered in this PC in the Kulikovskoye section resulted from the absence of fully developed Kamenka PC above the Inzhavino paleosols, so that nothing interfered with gypsum penetration from above into the paleosol under consideration. A small quantity of gypsum crystals found in the interstadial paleosol exposed in the Shabelskoye section is of secondary origin.

So, the abundance of carbonate and Fe-Mn pedofeatures (concentric nodules, various coatings, features of impregnative nature, hypo-coatings, etc.) is a distinctive feature of the early Inzhavino interglacial paleosol.

Taking all the above into consideration, the interstadial paleosols of the Inzhavino PC appear to be similar to those of the Mezin and Kamenka PCs. The dominant soil-forming process in all the cases was humus accumulation, with a small participation of gleying. However, unlike other interstadial paleosols, the late Inzhavino one developed under conditions of greater aridity favorable to deposition of carbonate pedofeatures. The period of the Inzhavino paleosol formation was longer than that of other PCs, as indicated by the greater thickness of its profile (~1 m on average). The processes that caused wide wedge-like fissures in its profile exceeded those in the upper-lying PCs in intensity. The profile of the late Inzhavino interstadial paleosol is comparable with the modern meadow-chernozemic soil (Chernozems (Siltic)). The early Inzhavino interglacial paleosol was defined by T.D. Morozova (Velichko and Morozova, 2015) as chernozem-like prairie soil (Haplic Phaeozems). We would like to specify the term and suggest the name of Meadow-Chernozem Texture-Calcareous (Calcic Chernozems).

In central Europe the Likhvin Interglacial was marked by widely distributed texture-differentiated soils distinguished for the eluvial horizon presence in their profile (Panin, 2007, 2015; Sprafke et al., 2014; Velichko and Morozova, 2015). At present the texture-differentiated soils typically develop under broadleaf and coniferous forests under conditions of humid climate, the soils are mostly of gray forest type; in the Azov region the soils under steppes and forest-steppes are predominantly chernozems. It may be easily seen that the soil types of the Likhvin Interglacial practically coincided in their spatial distribution with the modern soil zonality. The climate, however, was somewhat more humid than at present. It is suggested by the absence of a distinct eluvial horizon in the modern gray forest soils; according to Zaidel'man (2007), such a horizon forms under conditions of stagnant-percolative water regime. As to the modern Chernozems ordinary (Chernozems (Pachic)), they are also devoid of Fe-Mn pedofeatures indicative of abundant moisture.

4.6. The Early Pleistocene Vorona paleosol complex

The Vorona PC is not very widespread. In the central East European Plain it was described in sections Sebryakovo-Mikhailovka (N 50°07′02″, E 43°12′46″), Strelitsa (N 51°37′16″, E 38°54′10″) (Velichko et al., 2006b) and Korostelevo (N 51°50′28″, E 42°24′58″) (Dlussky, 2001; Velichko, 2002); farther west, it was documented in the Ukraine territory (Tsatskin et al., 1998, 2001).

The Vorona PC includes the early Vorona interglacial paleosol dated to the Muchkap interglacial correlatable with the Late Cromerian (MIS

15, ~570–610 ka BP) and the late Vorona interstadial paleosol (MIS 13, ~480–500 ka BP).

In common with other interstadial paleosols, the late Vorona paleosol formation was dominated by humus-accumulative processes. Its profile is mostly brown with reddish hue, its thickness – 0.76 m – is comparable with that of the Krutitsa interstadial paleosol (0.74 m on average). The late Vorona paleosol underwent cryogenic processes that left fissures filled with pale yellow loam material as can be seen in Shabelskoye section (Fig. 3). Its magnetic susceptibility values fall into the range of 0.32 to $0.53 * 10^{-3}$ SI everywhere except the Semibalki-2 section (Table 4).

The interglacial paleosol is one of best pronounced and thick paleosols described in the LPS of the Azov region. The dominant colors are deep red (7.5 yr in the Munsell color system), the soil thickness is 2.50 on average. The B and BC horizons abound in carbonate pedofeatures, mostly of 'byeloglazka' type 1–2 cm in diameter. Mole burrows occur occasionally. Magnetic susceptibility varies between 0.26 and $0.55 * 10^{-3}$ SI.

In the PC microstructure there is a noticeable difference between the interstadial and interglacial paleosols. Both the late Vorona and early Vorona paleosols are well aggregated, porous, depleted of gypsum pedofeatures. The amount of carbonate and iron-manganese pedofeatures in the interstadial paleosol is notably less than in interglacial one (Table 5). There are concentrations of clay or clayey-ferruginous matter discernible in the paleosol fabric. Flocs of hydroxides are seen at the base of the interglacial paleosol noted for coarse blocky microstructure.

The paleosols of the Vorona PC developed mostly under meadows and forests, under conditions of variable humidity. The reddish hues of the soil profile are characteristic for the soils of subtropics (Zech et al., 2014).

Taking the above into account, the paleosols of the Vorona PC attributed to the interstadial interval may be classified with humus-accumulative reddish-brown soils (Chromic Cambisol (Ferric)). At present soils of that type are found in the Mediterranean region (Spain, Croatia, etc.) (Jones et al., 2005). The interglacial paleosols of the same PC may be also grouped with the Mediterranean subtropical soils; considering the abundance of carbonate concretions, they may be defined as calcareous thick reddish (Cambisol (Calcaric, Ferric)).

4.7. The Early Pleistocene Rzhaksa interglacial paleosol

The Rzhaksa interglacial paleosol is assigned to MIS 17 (~660–680 ka BP) and correlated with the Okatovo Interglacial. The automorphic Rzhaksa paleosol has been described in the Chumbur-Kosa and Kulikovskoye sections, its hydromorphic analog – in the Shabelskoye section. The paleosol is insufficiently studied as yet, its profile is heavily disturbed by erosion and cryoturbations. T.D. Morozova (Velichko and Morozova, 2015) described that soil as humus-accumulative chernozem-like prairie soil (Haplic Chernozems). Earlier that paleosol was described in the central part of the East European Plain (Velichko et al., 2006b).

The Rzhaksa paleosol is the oldest soil in the region under study; its profile is well preserved in the Shabelskoye section only, where it is represented by a thick (up to 1.90 m) humus dark-gray clay with a greenish hue. In its automorphic varieties dominant are brownish colors with a gray hue. The magnetic susceptibility values vary over a limited range $0.22–0.35 * 10^{-3}$ SI (Table 4).

There are granular aggregates distinctly seen in the automorphic soil microstructure indicative of cryogenic processes (Table 5). The presence of Fe-Mn pedofeatures (hypo-coatings and nodules) suggests wet climate. The hydromorphic paleosol contains carbonate and Fe-Mn pedofeatures – evidence of a high stand of groundwater.

Having analyzed the main characteristics of the Rzhaksa paleosol, we may confidently suppose that it developed under meadow and steppe vegetation, under conditions of abundant rainfall, humus accumulation and gleyization being leading processes. The soil described in the Shabelskoye section may be defined as meadow-chernozem gley (Gleyic Chernozems), and the automorphic type – as meadow-chestnut gley (Gleyic Phaeozems).

5. Conclusions

1. Table 6 presents the soils that existed in the studied region since the early Pleistocene to the Holocene.
2. The regional soil evolution displays a general trend towards a reduction in the heat and moisture supply and increase of aridity from earlier to later stages of the Pleistocene. That agrees well with the earlier conclusions by Velichko et al. (2012). The newly obtained data reveal, however, some distinctions from the earlier concept. In particular, the climate of the Kamenka interglacial appeared to be more humid than that of the Likhvin interglacial, as suggested by the presence of Fe-Mn pedofeatures in the early Kamenka interglacial paleosol in quantity much greater than in the early Inzhavino paleosol.
3. The newly obtained data on the paleosol macro- and micromorphology made possible the paleosol correlation in the loess-paleosol sequences based on their principal characteristics. The Bryansk paleosol is distinct for a presence of sand in its profile, the Salyn interglacial paleosol contains large rhomboid crystals of gypsum; the early Kamenka one abounds in Fe-Mn pedofeatures; the early Inzhavino interglacial paleosol is distinguished by a clearly pronounced frost fissures and abundant calcareous pedofeatures; the profile of early Vorona interglacial paleosol features red color and abundant calcareous nodules; and finally, distinctive properties of the Rzhaksa paleosol are a gleyed profile and practically complete absence of carbonate pedofeatures.

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