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MINERALOGY AND MICROMORPHOLOGY OF SOILS

Minerals in the Three-Component Combination of Agrochernozems in the Kamennaya Steppe

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Abstract—Properties and mineralogy of fine fractions separated from agrochernozems forming a three-component noncontrasting soil combination in the Kamennaya Steppe have been characterized. The soil cover consists of zooturbated (Haplic Chernozems (Clayic, Aric, Pachic, Calcaric)), migrational-mycelial (Haplic Chernozems (Clayic, Aric, Pachic)), and clay-illuvial (Luvic Chernozems (Clayic, Aric, Pachic)) agrochernozems. All the soils are deeply quasi-gleyed because of periodical groundwater rise. The mineralogy of the fraction <1μm includes irregular mica–smectite interstratifications, di- and trioctahedral hydromicas, imperfect kaolinite, and magnesium–iron chlorite. The profile distribution of these minerals slightly varies depending on the subtype of spot-forming soils. A uniform distribution of clay minerals is observed in zooturbated agrochernozem; a poorly manifested eluvial–illuvial distribution of the smectite phase is observed in the clay-illuvial agrochernozem. The fractions of fine (1–5 μm) and medium (5–10 μm) silt consist of quartz, micas, potassium feldspars, plagioclases, kaolinite, and chlorite. There is no dominant mineral, because the share of each mineral is lower than 35–45%. The silt fractions differ in the quartz-to-mica ratio. The medium silt fraction contains more quartz, and the fine silt fraction contains more micas.

Keywords: soil cover structure, three-component soil combination, mineralogy, smectite phase, hydromicas, clay, fine silt, medium silt

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INTRODUCTION

The flat watershed areas and their gentle slopes on eroded plains of the forest-steppe and steppe zones in European Russia are characterized by three-component combinations of typical, leached, and turbated chernozems, which is due to the spatial redistribution of water in microrelief and the related migration and accumulation of carbonates in the soil profile, as well as the spatial differentiation of digging animal activity, on the construction of holes and connecting trenches between them and feeding sites. From the detailed mapping of soils, spottiness was revealed in the Central Chernozemic Reserve [28] and on adjacent fields [4, 10], in the Saratov Volga region [8], Belgorod oblast [2], Nizhnedevitsk district of Voronezh oblast [35], northern Kalach Upland [27], and Kamennaya Steppe [24, 25, 27]. This soil cover pattern implies changes in soil properties throughout the profile and in the space.

Each soil is characterized by a specific distribution of minerals along the profile, which is determined, on one hand, by the genesis of the parent material and, on the other hand, by the transformation and redistribution of minerals during pedogenesis. The distributions of minerals in the profiles of chernozems on different parent materials in different regions were studied [1, 11, 16–19, 29, 32, 33].

However, only isolated works deal with the study of the spatial distribution of fine-fraction minerals within an elementary soil area or the structure of soil cover. The first attempt was made at the Kursk Experimental Station, whose soil cover structure consists of differentially wetted spotted chernozems [20, 22]. The redistribution of the main mineral phases in the profiles of soils, including arable deep heavy loamy typical chernozems, arable leached chernozems, highly effervescent turbated chernozems, and meadow-chernozemic soil was examined [38].

Another study was performed in the area of an experiment on the effect of the technogenic leveling of hollows on the formation of recent microrelief in the Kamennaya Steppe (experiments of O.G. Kotlyarova, Dokuchaev Research Institute of Agriculture of the Central Chernozemic Region) [13]. The soil cover structure on plowed slopes is characterized by complex erosion-linear combinations of chernozems differing in the degrees of erosion, calcareousness, alkalinity, and salinity [21]. In the field experiment, relief was leveled by cutting and transporting the upper soil layer from interhollow watersheds to hollows, which favored the multiple reduction in the volume of runoff and the almost complete cessation of sheet wash and erosion. However, the mechanical leveling of hollows, which decreased the relief amplitude, resulted in the formation of a specific agrogenic heterogeneity of soil cover, the increase in yield diversity, and its general lowering in the first years after the establishment of the experiment [13]. The experiment was used for studying the consequences of intense agrogenic impact on the transformation of soil cover, soil properties, and clay minerals in soils. From repeated soil surveys of the experimental plot [23, 34] performed in 1988 and 1999, a rapid restoration of microrelief and changes in the transverse profile of the hollow were revealed during the 12-year-long period. The contents of clay and fine and medium silt in the plow horizons of chernozems along the transect measured in different years have similar variation ranges and mean values. The total variation range of clay along the transect indicates an appreciable spatial variability of texture in the plow horizons of the key plot, which was attributed to the transportation of material along the slope due to erosion and aggradation. The structural state of minerals and the proportions of the main mineral phases in clay of the plow horizons varied depending on the position in the hollow microrelief.

The aim of this work was to analyze the spatial distribution of fine fractions (>1, 1–5, and 5–10 μm) and their mineralogy within the soil combination composed of migrational-mycelial, zooturbated, and clay-illuvial agrochernozems on wide flat watersheds of the Kamennaya Steppe.

OBJECTS AND METHODS

The objects of study are soils of the Kamennaya Steppe, which is located at the boundary of the Oka–Don Lowland and the Kalach Upland [12] to the south of the regional center Talovaya in Voronezh oblast and is confined to the watershed of the Chigla River and the Talovaya Hollow. The main mesorelief forms are flat undulating watersheds with inclinations <1°, which change to relatively steep slopes in the eastern direction (toward the Talovaya Hollow) and to a long gentle slope dissected by numerous hollows and further deep hollows in the western direction (toward the Chigla River). Yellow-brown loess-like clays and loams 1 to 2.5 m thick underlined by reddish-brown clays are parent sediments [3].

The climate is dry continental. The mean air temperature is –9.4°C and –9.7°C in January and February, respectively, and +20.5°C in July; the frost-free period lasts 149 days on the average; the annual precipitation varies from 261 to 692 mm (414 mm on the average) [5, 15].

In the late 19th century, the watersheds occurred under autonomous conditions. Groundwater occurred at 6–8 m and deeper [6]. In the 20th century, measures were taken for the regulation of the water balance in the area. As a result, the groundwater level in the early 21st century varied from 1.5–4 m in humid years to 3–6 m in dry years, and automorphic chernozems gradually evolved to semihydromorphic meadow-chernozemic soils, according to the classification of soils of the USSR [10]. In accordance with the classification of Russian soils [9, 14], these are chernozems (under long-term fallows and forest belts) and deeply quasi-gleyed agrochernozems (on plowland).

The background soil combination of flat watershed areas in the Kamennaya Steppe represents a three-component spottiness composed by migrational-mycelial, zooturbated, and deeply quasi-gleyed clay-illuvial agrochernozems, whose elementary soil areas form a relatively complex pattern [25, 27].

The direct object of study was an 18-m-long trench established on key plot KS-01 (land of the Dokuchaev Research Institute of Agriculture of the Central Chernozemic Region, Talovaya district, Voronezh oblast). The trench has the following coordinates: beginning (0 m), 51°01′42.9″ N, 040°43′26.1″ E; end (18 m), 51°01′43.4″ N, 40°43′25.4″ E. The plot is located on a wide undulating watershed area complicated by slightly concave surfaces of hollow heads on the fields of selective crop rotation surrounded by forest belts 34 (in the north), 40 (in the east), 35 (in the south), and 30 (in the west). The beginning of the trench is located at about 200 m to the south of forest belt 34 and at 100 m to the west of forest belt 40. The trench is established on a gently sloped (gradient 0.007) surface of the northern exposure.

The general scheme of soil morphology along the trench in shown in Fig. 1. The distance along the trench was measured from east to west. Along the northern trench wall, chernozem strongly turbated throughout the profile (deep deeply quasi-gleyed zooturbated migrational-mycelial agrochernozem (ACzt) (Haplic Chernozem (Clayic, Aric, Pachic, Calcaric)) is penetrated from 0 to 9 m; typical chernozem (medium-deep deeply quasi-gleyed migrational-mycelial agrochernozem (ACmm) (Haplic Chernozem (Clayic, Aric, Pachic)) is penetrated from 9 to 11.5 m; leached chernozem (medium-deep deeply quasi-gleyed clay-illuvial agrochernozem (ACci) (Luvic Chernozem (Clayic, Aric, Pachic)) was penetrated from 11.5 to 18 m. The names of soils according to the 2004 and 2008 classifications of Russian soils and WRB-2014 [40] are given in the parentheses. The profile of deep deeply quasi-gleyed zooturbated migrational-mycelial agrochernozem (0–9 m along the trench) includes the following horizons: agro dark-humus PU horizon; dark-humus AUca,zoo horizon turbated by animals (attribute zoo) and containing calcium carbonates (attribute ca); carbonate-accumu-

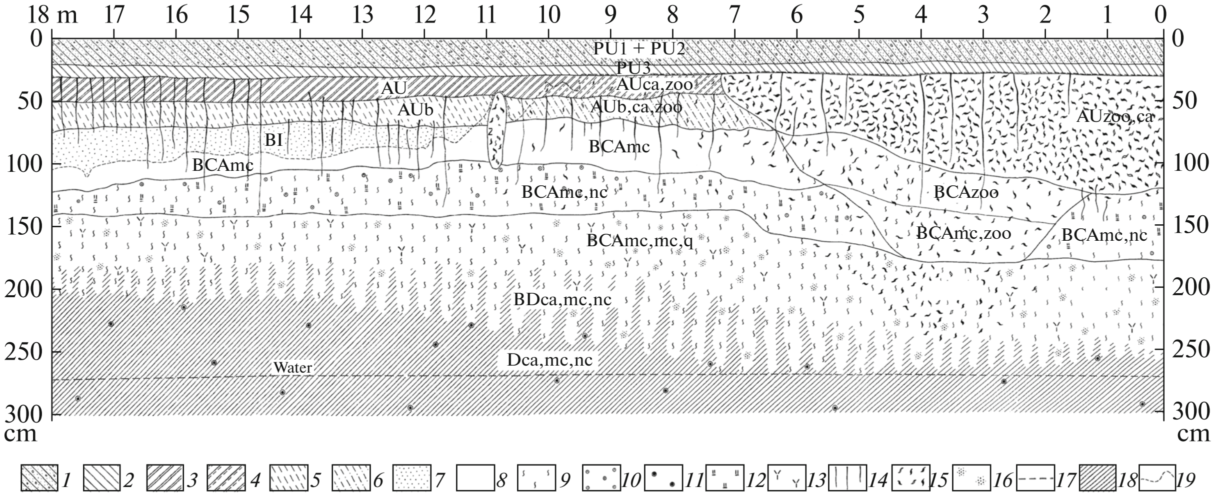

Fig. 1. Morphological structure of soils in trench T-0067: (*1*) plow horizon (PU1+PU2); (*2*) lower part of the plow PU3 horizon; (*3*) dark-humus AU horizon; (*4*) dark-humus AUca,zoo horizon turbated by animals and containing calcium carbonates; (*5*) lower part of the dark-humus AUb horizon; (*6*) AUb,ca,zoo horizon turbated by animals and containing calcium carbonates; (*7*) clay-illuvial BI horizon; (*8*) carbonate-accumulative BCAmc horizon; (*9*) calcium carbonate veins; (*10*) calcareous nodules; (*11*) dense calcareous nodules; (*12*) yellow-brown, brown, and gray-brown cutans on the faces of peds; (*13*) brownish-olive cutans; (*14*) shrinkage cracks filled with dark material from the humus horizon; (*15*) zoogenic forms of material mixing; (*16*) olive tint disappearing under drying; (*17*) groundwater level; (*18*) reddish-brown dense calcareous clay; (*19*) upper boundary of effervescence with HCl.

lative BCAmc,zoo horizon with carbonate veins (attribute mc) strongly turbated by animals and transitional to the rock; BCca,mc,q horizon with quasi-gleying signs (attribute q) as olive tint rapidly disappearing, when the sample is dried, and fine (0.25–0.5 mm in diameter) brown concretions. In the medium-deep deeply quasi-gleyed migrational-mycelial agrochernozem (9–11.5 m along the trench), the PU horizon is underlain by horizons AU, AUb,ca and, from 70–75 cm, BCAmc. In the medium-deep deeply quasi-gleyed clay-illuvial agrochernozem (12–18 cm along the trench), a clay-alluvial BI horizon appears between the upper humus-enriched horizons (PU–AU–AUb) and the carbonate-accumulative BCAmc horizon; the BI horizon is free from carbonates, with prismatic structure, fine dark cutans on the faces of peds, and abundant vertically oriented humified tongues of material filled from above. At depths from 180–200 to 200–250 cm under all soils in the trench, a transitional zone (horizon BDca,mc,nc) occurs between two lithological layers interpenetrating into each other as tongues yellow-brown in color from above and reddish-brown from below. Underlying reddish-brown clay (horizon Dca,mc,nc) occurs below, which was water-saturated almost the year round until 2009; after several droughty years (2010–2012), the water content in summer is lower than the field capacity. A more detailed description of the morphological structure was given earlier [26].

Particle size fractions (<1, 1–5, and 5–10 μm) were separated from soil samples after the removal of carbonates with an HCl solution and trituration in the state of thick paste by multiple decantation of suspension agitated and settled during the time period calculated from the Stokes Law by the Gorbunov method [7]. In this work, the contents of particle size fractions are given in percentage of carbonate-free sample. The mineralogy of fine fractions was studied by X-ray diffraction on an HZG-4a X-ray diffractometer. Magnesium-saturated oriented preparations were recorded in three states: air-dry, solvated with ethylene for two days, and after incineration at 550°C for 2 h. The proportions of the main mineral phases were calculated by the Biscaye method [37] in the clay fraction and by the Cook method in the silt fractions [39].

The content of C_{org} was determined by the Tyurin method in the Laboratory of Soil Biochemistry of the Dokuchaev Soil Science Institute (operator V.S. Buleeva); the content of carbonates was determined by Kozlovskii acidimetric method in the Instrumental Analytical Laboratory of the same institute. Statistical processing of data was performed using Excel. Results are presented as average arithmetic values ± standard deviations.

RESULTS AND DISCUSSION

Vertical distribution of C_{org} in the studied soils has the form typical for chernozems: a maximum in the surface horizon and a gradual decrease with depth (Fig. 2a). An appreciable increase of the humus horizon thickness in zooturbated agrochernozem is due to

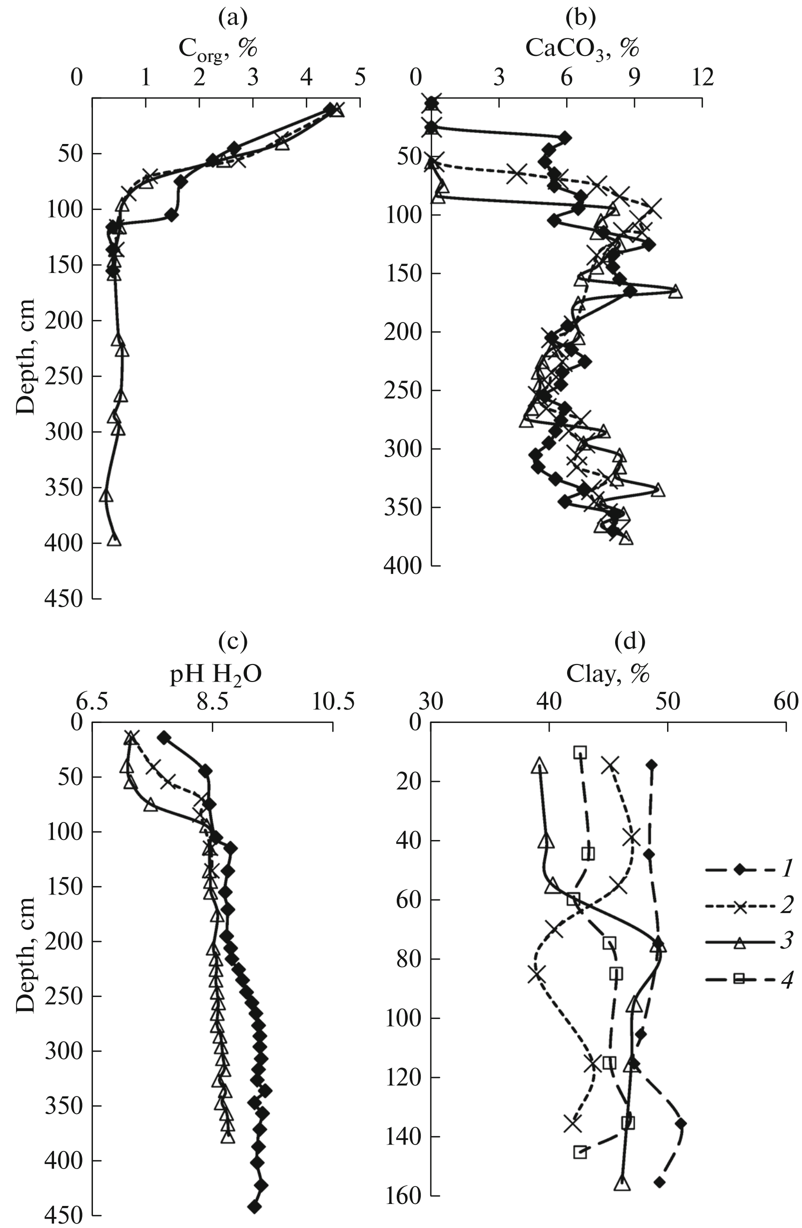

Fig. 2. Vertical distribution of (a) C_{org}; (b) $CaCO_3$; (c) pH_{H_2O}; (d) clay (<1 μm) in (*1* and *4*) zooturbated agrochernozem (T-0067, at 4 and 8.5 m, respectively); (*2*) migrational-mycelial agrochernozem (at 11 m), and (*3*) clay-illuvial agrochernozem (at 14 m).

the partial transportation of material from the humus horizons down the profile by digging animals.

The content of C_{org} varies from 4.23 to 4.69% (with an average of 4.51%) in the plow (PU1 + PU2, 0- to 20-cm) horizon and decreases to 1.83–3.43% (with an average of 2.54%) at a depth of 50–60 cm. The three components of the soil combination do not differ statistically in this parameter (Table 1). Some features of C_{org} variation in different horizons should be noted. A high standard deviation of C_{org} content is observed in the plow horizon of zooturbated agrochernozem compared to the two other components of the soil combination (0.12 and 0.05–0.06%, respectively; significant according to the Fisher test). This can be related to the periodic involvement of material from the morphologically heterogeneous zooturbated horizon (which combines fragments of the humus and carbonate horizons mixed by digging animals) in the plow horizon. A different situation is noted at a depth of 50–60 cm in the lower part of the humus layer. The highest variation of C_{org} is observed in the clay-illuvial agrochernozem. It significantly differs for the C_{org} variation in the two other soils. This can be related to the input of humified material from the upper horizons via period-

Table 1. Statistical parameters of C_{org} content in soils of the three-component combination in the Kamennaya Steppe

Soil	Distance along the trench, m	Depth, cm	*n*	C_{org}, %		
				range	*M*	*s*
ACzt	0–9	0–20	15	4.23–4.63	4.46	0.12
ACmm	9.5–11.5	0–20	9	4.42–4.57	4.49	0.05
ACci	12–18	0–20	13	4.52–4.69	4.59	0.06
Total	0–18	0–20	37	4.23–4.69	4.51	0.10
ACzt	0–9	50–60	15	1.95–2.91	2.42	0.27
ACmm	9.5–11.5	50–60	9	2.26–3.08	2.62	0.25
ACci	12–18	50–60	13	1.86–3.43	2.64	0.45
Total	0–18	50–60	37	1.86–3.43	2.54	0.35

(*n*) sample set size; (*M*) arithmetic mean; (*s*) standard deviation.

ically opened shrinkage cracks. This process is morphologically observed in the upper part of the clay-illuvial BI horizon; in the AUb horizon, a similar phenomenon is recorded only for the C_{org} variation. In the two other soils (migrational-mycelial and zooturbated agrochernozems), this process is not manifested because of the looser consistence and more active mixing of the horizon material by worms and digging animals.

The carbonate profiles of the three kinds of agrochernozems are clearly different in the upper part to a depth of about 1.1–1.2 m and are almost similar in deeper horizons, including the parent matrerial (Fig. 2b). In the migrational-mycelial agrochernozem (typical chernozem), the PU and AU horizons contain no carbonates; effervescence is observed in the lower part of the dark-humus horizon or at its lower boundary; in the BCAmc horizon, the maximum accumulation of carbonates (8.4 ± 0.9% $CaCO_3$) is observed at a depth of 70–180 cm; in the lower (200- to 350-cm) horizons, the content of carbonates is 6.1 ± 0.9%. Such profile distribution of carbonates is characteristic of typical chernozems in European Russia [29].

The active digging activity of animals favors the upward translocation of material from the lower calcareous horizons; therefore, the depth of efflorescence within the trench in the zooturbated agrochernozem corresponds to the lower boundary of the plow PU horizon (30–32 cm). In the zooturbated dark-humus AUca,zoo horizon, an almost uniform distribution of $CaCO_3$ is observed from 30 to 110 cm (with an average of 5.7 ± 0.6%). The maximum content of carbonates (8.4 ± 0.7%) occurs at a depth of 120–180 cm. In the underlying (200- to 350-cm) bed, the content of carbonates is lower: 5.7 ± 0.6%.

In the clay-illuvial agrochernozem, carbonates are leached to a depth of 90–110 cm (100 cm on the average). The content of carbonates abruptly increases to 7.8 ± 1.3% in the BCAmc and BCca,mc,q horizons (in the depth range 100–180 cm) and then decreases to 5.6 ± 1.4% in the underlying sediment (at 200–310 cm).

The contents of carbonates in the horizons of their maximum accumulation of all three agrochernozems do not differ statistically within the trench (8.2 ± 1.1%). An analogous situation is observed in the underlying sediment: the average content of $CaCO_3$ is 5.8 ± 1.0%.

The upper profiles of agrochernozems in the considered three-component combination have a neutral or weakly alkaline reaction (pH_{water}) with a regular tendency of its change in accordance with the vertical distribution of carbonates (Fig. 2c). The carbonate-leached horizons of clay-illuvial agrochernozems have pH from 7.0 to 7.5. In calcareous horizons of all soils, pH is from 8.0 to 8.4; in the underlying sediment, an alkaline reaction is observed at a depth of 2–4 m (pH from 8.5 to 9.3), which is related to the magnesium–sodium bicarbonate composition of groundwater (salt content 0.4–0.7 g/L).

Particle size distribution. Agrochernozems have a coarse light clayey silt-clay texture (Table 2). The content of the clay fraction (<1 μm) in the 0- to 200-cm layer along the entire trench varies from 38.9 to 51.8% (with an average of 44.7%); the content of fine silt (1–5 μm) is 10.9–18.1% (with an average of 14.9%); the content of medium silt (5–10 μm) is 4.8–11.0% (with an average of 8.4%); the content of physical sand (10–1000 μm) is 25.1–37.6% (with an average of 32.0%), the coarse silt fraction (10–50 μm) being predominant. The bedrock has a light clayey clay-coarse silt texture. The content of the clay fraction is lower: from 23.0 to 33.1% (with an average of 30.5%), and the content of physical clay is higher: 39.2–48.8% (with an average of 43.1%). The contents of fine and medium silt are in the same range that in the underlying layer with recent soils.

The plow PU horizon of the studied agrochernozems is composed by different structural elements: (1) dense angular monolithic blocks of 5–6 to 10–12 cm (rarely to 20 cm); (2) dense angular structures with opaque faces of 1–2 to 3–5 cm (resulted from the cracking and cleavage of large blocks); and (3) loose subangular blocky material. The heterogeneity of tex-

Table 2. Particle size distribution in agrochernozems and underlying reddish-brown clays

Distance along the trench, m	Horizon	Depth, cm	Content (% of carbonate-free sample) of particle size fractions of size, μm			
			<1	1–5	5–10	>10
4	PU	0–30	48.6	12.9	10.0	28.5
	AUzoo,ca	40–50	48.4	12.8	8.8	30.1
	AUzoo,ca	70–80	49.1	12.4	8.7	29.7
	AUzoo,ca	100–110	47.7	12.4	7.2	32.8
	BCAzoo	110–120	47.1	12.0	9.9	31.0
	BCAzoo	130–140	51.1	10.9	7.2	30.8
	BCAmc,zoo,q	150–160	49.2	13.1	5.5	32.2
8.5	PU	0–22	42.6	17.5	11.0	29.0
	AUca,zoo	40–50	43.3	12.8	6.2	37.6
	AUb,ca,zoo	55–65	42.1	14.7	6.0	37.2
	BCAmc	70–80	45.1	14.2	6.2	34.5
	BCAmc	80–90	45.6	11.6	6.2	36.5
	BCAmc	110–120	45.1	13.0	8.8	33.0
	BCAmc	130–140	46.7	13.3	6.9	33.1
	BCca,mc,q	140–150	42.6	16.5	8.3	32.7
11	PU	0–30	45.1	15.9	8.6	30.4
	AU	33–45	51.9	13.7	9.3	25.1
	AUb	50–60	45.8	14.8	10.0	29.5
	AUb,ca	65–75	40.4	17.4	8.6	33.7
	BCAmc	80–90	38.9	17.9	9.2	34.0
	BCAmc	110–120	43.6	15.5	8.9	32.0
	BCAmc,q	130–140	41.9	16.4	8.2	33.5
14	PU	0–30	39.1	18.1	9.5	33.3
	AU	35–45	39.7	15.4	9.0	35.8
	AUb	50–60	40.2	17.4	4.8	37.6
	BI	70–80	49.1	13.1	7.8	29.9
	BI	90–100	47.1	13.2	7.5	32.2
	BCAmc	110–120	46.9	13.4	7.8	31.9
	BCAmc,q	150–160	46.1	13.1	5.9	34.9
Underlying reddish-brown clays						
7	BDca,mc,nc	250–260	33.1	16.1	10.8	40.1
	Dca,mc,nc	350–360	32.6	12.2	9.2	46.0
	Dca,mc,nc	430–450	32.6	14.2	11.5	41.6
15	Dca,mc,nc	250–260	23.0	25.1	12.7	39.2
	Dca,mc,nc	350–360	31.3	10.6	9.3	48.8

ture is manifested in the regular alternation of zones with blocky and subangular blocky structures, which is determined by the partial mixing of two plow-horizon layers (PU1 and PU2) under moldboard plowing. For the analysis of their similarity or difference, dense and loose parts of plow horizons were sampled separately along the entire trench. It was found that the mean contents of particle size fractions from dense and loose fragments do not differ statistically (Table 3). However, the dense fragments differ significantly (according to the Fisher test) by the lower variation in the contents of clay (<1 μm) and fine silt (1–5 μm) than the loose fragments in 4–5 times. The variations in the content of medium silt (5–10 μm) do not differ.

Table 3. Statistical parameters of particle size distribution in samples of different consistence from the plow (0- to 30-cm) horizons of agrochernozems

Sample structure	Fraction, μm	Statistical parameters				
		n	minimum	maximum	*M*	*s*
Dense	<1	5	42.7	47.6	45.2	1.9
	1–5	5	15.0	18.2	16.4	1.3
	5–10	5	5.2	11.1	8.8	2.2
Loose	<1	4	30.8	51.8	41.0	9.8
	1–5	4	11.1	22.4	16.7	5.5
	5–10	4	8.2	12.5	10.8	1.9

Although the textures are similar, some differences in the vertical distribution of clay are observed among three agrochernozems within the trench (Fig. 2d). The zooturbated agrochernozem has a uniform distribution of clay due to the mechanical mixing of material from soil horizons by digging animals. However, two neighboring samples taken at 4 and 8.5 m along the trench have significantly different mean values for the whole profile: 48.7% in the center of the area (at 4 m) and 44.1% at its end (at 8.5 m).

A wider variation range of clay without any trend is observed within the profile of migrational-mycelial agrochernozem, while slight eluvial-illuvial redistribution of clay appears in the clay-illuvial agrochernozem. The content of clay is lowest (39–40%) in the humus (PU–AU–AUb) horizons, from the surface to a depth of about 60 cm; in the clay-illuvial BI horizon leached from carbonates, it increases to 47–49%.

Mineralogy of the fractions <1 μm isolated from the agrochernozems of the trench composing a three-component noncontrasting soil combination represents a paragenetic association typical of chernozems developed on loess-like loams [30]. In all of the studied profiles, the following mineral phases are identified: smectite, hydromicas, kaolinite, and chlorite. Finely grained quartz is also present. The smectite phase consists of irregular interstratifications with different combinations of mica and smectite layers in crystallites. This structure is identified from the reflection with d_{001} = 1.4 nm, which shifts to 1.7–1.8 nm after the solvation of the sample with ethylene glycol. The presence of an irregular mica–smectite interstratification with a high content (>50%) of smectite layers is revealed. Filling in the region from 1.0 to 1.4 nm in the X-ray diffraction patterns of air-dry samples, which shifts to the region of 1.7 nm after the solvation of samples with ethylene glycol, indicates the presence of an irregular mica–smectite interstratification with a low content (<50%) of smectite layers. The asymmetry of the 1.0-nm reflection in the region of 1.2–1.3 nm for the samples incinerated at 550°C indicates the presence of an irregular chlorite–smectite interstratification.

Hydromica is identified from the series of reflections multiple of 1.0, 0.5, and 0.33 nm, whose values do not change after the solvation of samples with ethylene glycol and incineration at 550°C for 2 h. The intensity ratio of the 001 and 003 reflections to the 002 reflection indicates the presence of trioctahedral and dioctahedral structures in the fraction.

Kaolinite is identified from the reflections in the region of 0.7 and 0.357 nm, which disappear after the incineration of samples at 550°C for 2 h. Chlorites are identified from the reflections multiple of 1.47 nm at 0.71, 0.474, and 0.353 nm. After the incineration of samples, reflections change their intensities; the 001 reflection at 1.4 nm becomes most intensive. Quartz is identified from reflections in the region of 0.334 and 0.426 nm.

The significant disordering of the structures of layered silicates, especially mica–smectite interstratifications, which involves a decrease in the reflection intensities of minerals, is a general feature of plow horizons.

The clay profile of *zooturbated agrochernozem* (at 4 m along the trench) has uniform distributions of the smectite phase and hydromicas within the 0- to 160-cm layer due to the active mixing of material from all horizons by digging animals (Table 4). We note only a general tendency of increasing reflection intensities of all minerals in the clay fraction from the upper horizons down the profile. A decrease in the content of components of the 0.7-nm phase is observed in the plow horizon mainly due to the decrease in the content of chlorite, which is proved by a significant decrease in the intensity of reflection at 1.38 nm for the clay sample incinerated at 550°C.

The clay profile of *zooturbated agrochernozem* located in the marginal part of the area at 8.5 m along the trench can be subdivided into three parts according to the smectite phase distribution: the upper part (0–65 cm), where the content of smectite is 53–55%; the middle part composing the major part of the calcareous BCAmc horizon at a depth of 70–120 cm, where this value increases to 58–63%; and the lower part at a

Table 4. Mineralogy of the fraction <1 μm from agrochernozems and underlying reddish-brown clays

Distance along the trench, m	Horizon	Depth, cm	Mineral phases					
			kaolinite + chlorite	hydromica	smectite phase	kaolinite + chlorite	hydromica	smectite phase
			% of the clay fraction			% of the whole soil		
4	PU	0–30	7	39	55	3.2	18.8	26.6
	AUzoo,ca	40–50	9	33	59	4.2	15.9	28.3
	AUzoo,ca	70–80	9	33	58	4.5	16.4	28.2
	AUzoo,ca	100–110	9	37	54	4.3	17.5	25.9
	BCAzoo	110–120	10	33	57	4.6	15.4	27.0
	BCAzoo	130–140	11	35	54	5.4	18.1	27.6
	BCAmc,zoo,q	150–160	10	33	57	4.7	16.4	28.1
8.5	PU	0–22	8	40	53	3.2	16.9	22.5
	AUca,zoo	40–50	8	40	53	3.3	17.1	22.8
	AUb,ca,zoo	55–65	7	38	55	2.9	16.1	23.2
	BCAmc	70–80	10	33	58	4.3	14.8	25.9
	BCAmc	80–90	9	32	60	4.1	14.4	27.1
	BCAmc	110–120	9	29	63	3.9	12.9	28.2
	BCAmc	130–140	7	22	71	3.4	10.1	33.2
	BCca,mc,q	140–150	7	23	70	3.0	9.9	29.7
11	PU	0–30	6	45	48	2.9	20.4	21.8
	AU	33–45	7	47	46	3.4	21.8	21.7
	AUb	50–60	9	45	46	4.0	20.6	21.3
	AUb,ca	65–75	9	40	51	3.5	16.2	20.7
	BCAmc	80–90	9	38	53	3.5	14.9	20.5
	BCAmc	110–120	7	30	63	3.1	13.3	27.3
	BCAmc,q	130–140	7	25	68	3.0	10.5	28.5
14	PU	0–30	6	33	61	2.2	13.0	23.9
	AU	35–45	7	38	55	2.7	15.0	22.0
	AUb	50–60	8	34	58	3.3	13.7	23.2
	BI	70–80	10	34	57	4.9	16.4	27.7
	BI	90–100	10	26	64	4.5	12.4	30.2
	BCAmc	110–120	7	20	73	3.0	9.4	34.4
	BCAmc,q	150–160	9	32	60	4.1	14.6	27.4
Underlying reddish-brown clays								
7	BDca,mc,nc	250–260	7	27	66	2.4	9.0	21.7
	Dca,mc,nc	350–360	7	35	59	2.3	11.2	19.1
	Dca,mc,nc	430–450	9	33	58	2.9	10.8	18.8
15	Dca,mc,nc	250–260	7	28	65	1.6	6.4	14.9
	Dca,mc,nc	350–360	7	26	67	2.1	8.1	21.1

depth of 130–150 cm, where the content of smectite reaches 70–71%.

The distribution of hydromicas shows an opposite trend: the content of hydromicas is maximum in the upper PU and AUca,zoo horizons and decreases to 22–29% down the profile. The observed tendency remains, when the results are recalculated for the whole soil sample.

In the clay profile of *migrational-mycelial agrochernozem* (typical chernozem) located at 11 m along the

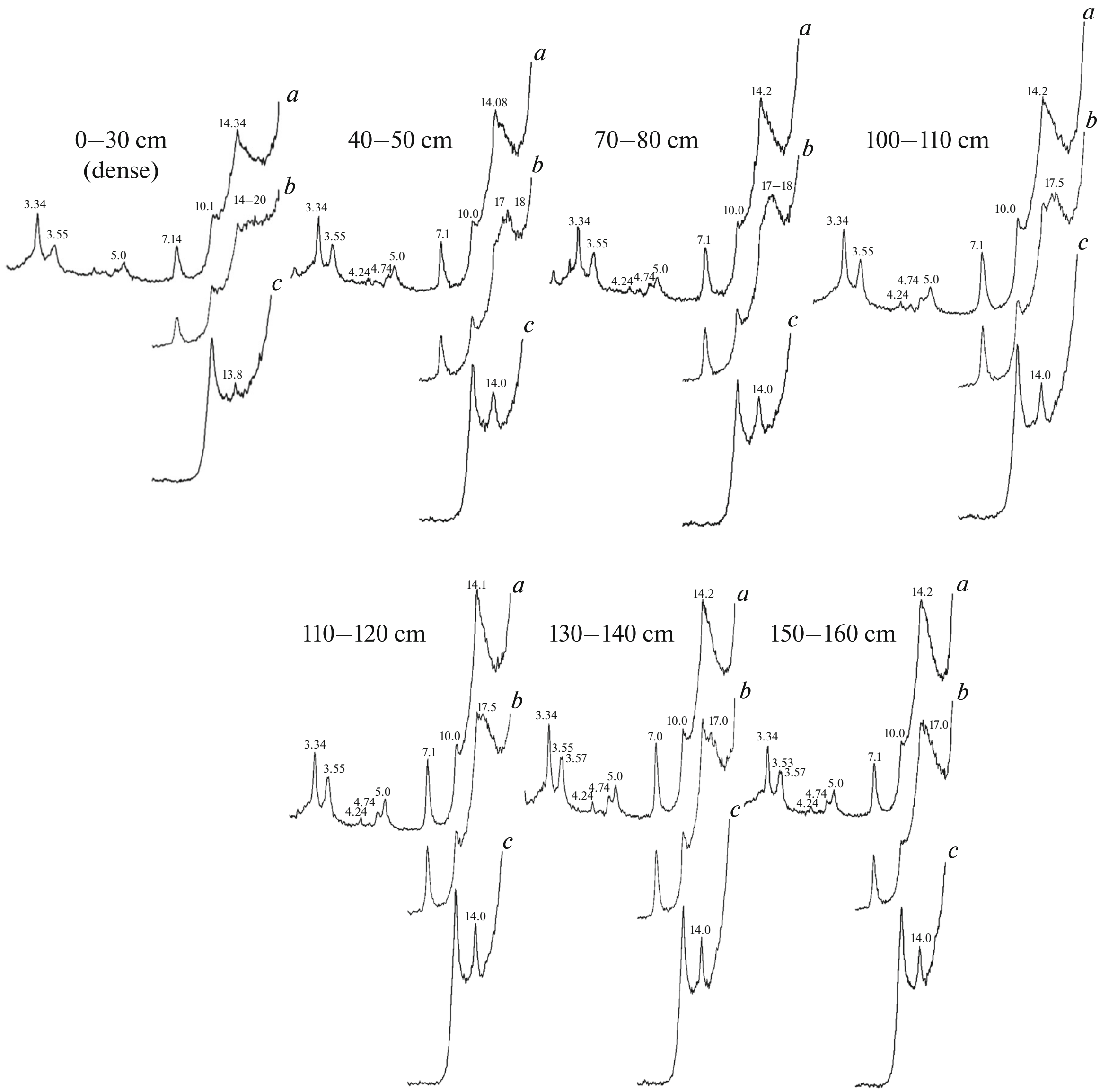

Fig. 3. X-ray diffraction patterns of the fraction <1 μm isolated from zooturbated agrochernozem (T-0067, at 4 m): (a) air-dry; (b) after solvation with ethylene glycol; (c) after heating at 550°C for 2 h.

trench, the lowest content of smectite (46–48%) is noted in the upper horizons free from carbonates to a depth of 60 cm. Down the profile, in the AUbca and BCAmc horizons, this parameter increases to 51–53% with a maximum of 68% in the BCAmc,q horizon. The distribution of hydromicas is opposite: the maximum content is found in the plow horizon, and the minimum content is in the lower part of the profile (Fig. 3).

In the *clay-illuvial agrochernozem*, a tendency of increasing content of smectite down the profile is also observed, from 55% in the AU horizon to 73% in the calcareous BCAmc horizon (Fig. 4), as well as a decrease in the content of hydromicas from 38% in the AU horizon to 20% in the BCAmc horizon.

In the plow horizons of all combination soils, the minimum content of total chlorite and kaolinite (6–8%) is due to the decomposition of chlorite. Deeper in the profile, the content of these minerals varies within a relatively narrow range from 7 to 11%.

In the bedrock (reddish-brown clay), the proportions of clay minerals are almost similar to those in the overlying soil horizons developed in loess-like clays. The content of smectite varies from 58 to 67%; the content of hydromicas varies from 26 to 35%, and that of total kaolinite and chlorite varies from 7 to 9%.

Thus, the changes in the contents of mineral phases along the profiles of the studied agrochernozems have common features typical for chernozems of European Russia [31]. However, there are some differences in

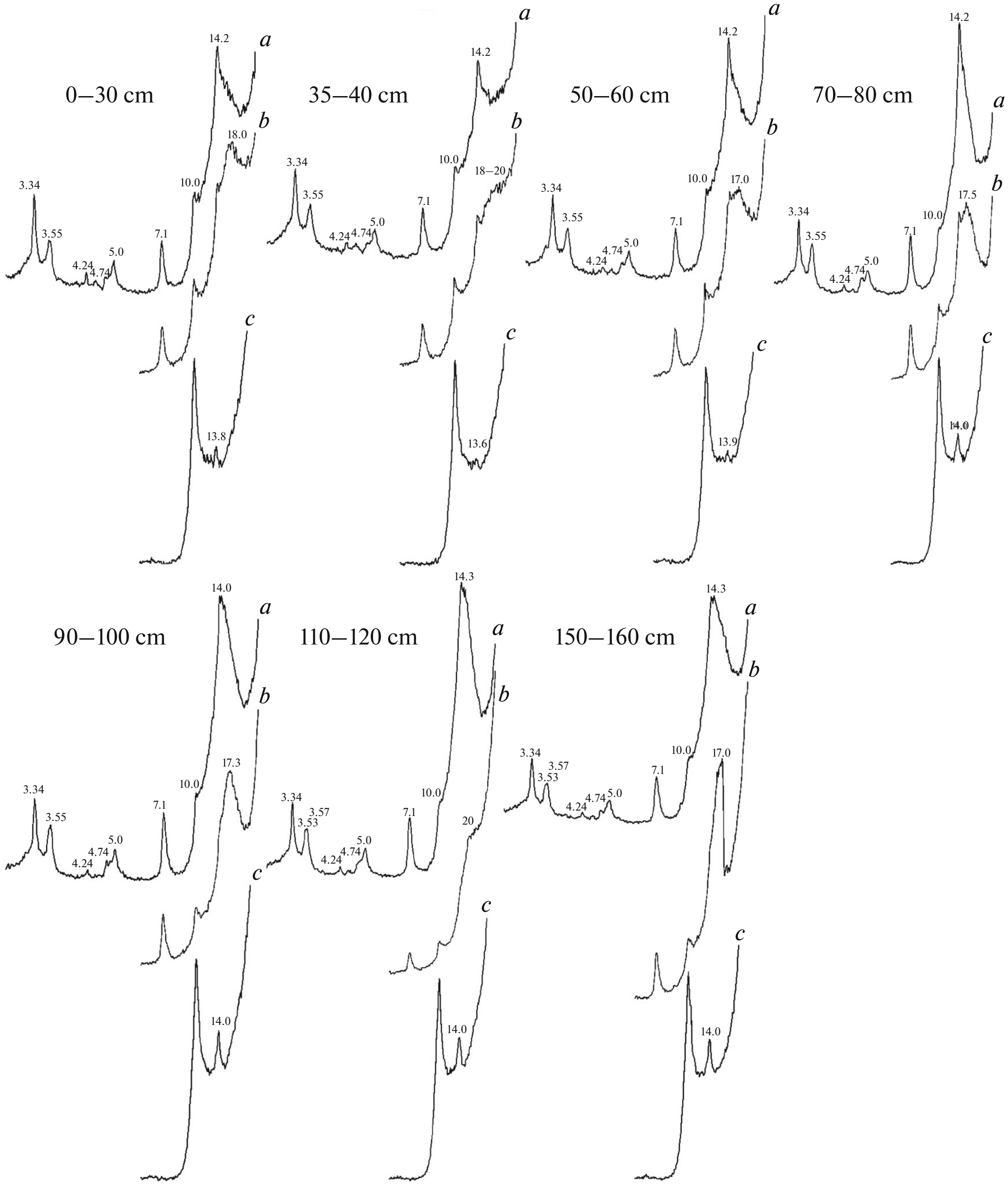

Fig. 4. X-ray diffraction patterns of the fraction <1 μm isolated from clay-illuvial agrochernozem (T-0067, at 14 m): (a) air-dry; (b) after solvation with ethylene glycol; (c) after heating at 550°C for 2 h.

the distribution of clay minerals within the profiles of three agrochernozems composing the noncontrasting combination. The central part of the area of zooturbated agrochernozems has a uniform distribution of smectite and hydromicas throughout the profile due to the mechanical mixing of soil material by digging animals, which is clearly manifested in macromorphological properties. The less significant disturbance of the profile by animals in the other soils of the combination is accompanied by the manifestation of a general tendency in the distribution of dominant clay minerals: the increase of smectite and the decrease of hydromicas down the profile. The leaching of carbonates at 10–20 cm below the lower boundary of the humus horizon observed in clay-illuvial agrochernozems results in a slight eluvial–illuvial redistribution of the clay fraction and enhances the contrast in the content of smectite phase calculated for the total silicate mass of the horizon.

Mineralogy of the fine silt fraction (1–5 μm) strongly differs from that of the clay fraction (Table 5). In fine silt, micas are the most abundant components

Table 5. Mineralogy of the fine silt (1–5 μm) fractions from agrochernozems and underlying reddish-brown clays

Distance along the trench, m	Depth, cm	ΣI, pulses/s	Minerals, %						$I_{1.0}/I_{0.5}$	$I_{1.0}/I_{0.334}$
			micas	quartz	K-feldspars	plagioclases	chlorite	kaolinite		
4	0–10	1390	39	24	14	9	7	7	2.3	0.27
	0–30(l)	2523	28	34	15	12	6	6	2.5	0.14
	0–30(d)	2175	33	29	15	11	6	6	2.4	0.19
	40–50	2676	33	27	13	11	7	9	3.0	0.20
	70–80	2856	33	25	14	11	7	9	3.2	0.22
	100–110	2851	32	24	16	13	7	9	2.9	0.23
	110–120	2695	29	27	16	13	5	9	4.0	0.18
	130–140	4019	29	29	15	13	5	9	3.2	0.16
	150–160	2898	39	20	13	12	6	10	3.3	0.32
14	0–30(l)	1601	33	31	15	11	6	5	1.9	0.18
	0–30(d)	2859	42	17	12	9	12	8	2.3	0.41
	35–45	1450	40	29	13	11	2	6	2.8	0.23
	50–60	2632	40	26	14	9	5	6	3.5	0.26
	70–80	3356	32	25	16	11	6	9	1.8	0.22
	90–100	3694	31	26	16	13	6	9	3.4	0.20
	110–120	3715	31	26	15	13	6	9	3.3	0.19
	150–160	3402	31	27	14	13	6	9	4.2	0.20
Underlying reddish-brown clays										
15	250–260	2665	44	23	11	8	5	10	2.6	0.32
	350–360	3400	32	30	16	12	4	7	3.2	0.18

(ΣI) total reflection intensity.

(from 28 to 44%, with an average of 34%), which are followed by quartz (from 17 to 34%, with an average of 26%), potassium feldspars (from 11 to 16%, with an average of 14%), plagioclases (from 8 to 13%, with an average of 11%), kaolinite (from 5 to 10%, with an average of 8%), and chlorite (from 2 to 12%, with an average of 6%). It follows from the intensity ratio of reflections at 1.0 and 0.5 nm varying from 1.8 to 4.2 that mixed micas are di- and trioctahedral layered silicates. In the major part of the profile, $I_{1.0}/I_{0.5} > 3$, which implies the predominance of softer trioctahedral (biotite) structures that are relatively easily weathered. In the plow horizons, this ratio approaches 2, which reflects the increase in the share of more rigid dioctahedral (muscovite) structures.

The highest variation of minerals in fine silt is noted for samples from the plow horizons of different textures. This fact is difficult to explain. The mechanical disintegration of coarser mica particles can be a possible reason. This supposition is indirectly confirmed by the 1.5 times lower content of micas (an average of 21%) in the medium silt fractions of the studied objects. According to Yarilova [36], in the neighboring profiles, the content of micas does not exceed 1% in the fraction 10–100 μm, and no micas are found in the fraction 100–250 μm.

The maximum share of micas (40%) in fine silt, as well as their minimum share (12–18%) in medium silt, is noted in the humus horizon of clay-illuvial agrochernozem.

In the resting part of the agrochernozem profiles, the distribution of minerals in fine silt is predominantly uniform. This is due to the low weathering intensity of minerals in chernozems.

Mineralogy of the medium silt fraction (5–10 μm) is specified by a predominance of quartz (from 17 to 45%, with an average of 34%), which is followed by di- and trioctahedral micas (from 12 to 38%, with an average of 21%) (Table 6). The contents of potassium feldspars (from 15 to 24%, with an average of 19%) and plagioclases (from 12 to 20, with an average of 16%) are slightly higher and the contents of kaolinite (from 3 to 7%, with an average of 5%) and chlorite (from 2 to 9%, with an average of 4%) are slightly lower than in fine silt.

Data on the contents of minerals in the fine and medium silt fractions obtained separately by preparative fractionation followed by X-ray diffraction analysis are comparable with the results obtained by Yari-

Table 6. Mineralogy of the medium silt (5–10 μm) fractions from agrochernozems and underlying reddish-brown clays

Distance along the trench, m	Depth, cm	ΣI, pulses/s	Minerals, %						$I_{1.0}/I_{0.5}$	$I_{1.0}/I_{0.334}$
			micas	quartz	K-feldspars	plagioclases	chlorite	kaolinite		
4	0–10	1841	38	17	17	12	9	6	3.0	0.37
	0–30(l)	2879	22	31	19	17	6	5	2.6	0.12
	0–30(d)	2425	17	37	21	17	4	4	2.8	0.08
	40–50	3375	27	34	15	14	4	7	3.0	0.13
	70–80	3917	16	43	16	16	4	5	2.7	0.06
	100–110	3100	24	29	18	17	6	6	3.2	0.14
	110–120	3240	28	25	16	18	5	7	3.5	0.19
	130–140	3422	21	34	18	18	3	7	2.4	0.10
	150–160	3341	24	33	15	17	5	7	3.0	0.12
14	0–30(d)	3024	17	31	24	20	5	3	2.0	0.09
	0–30(l)	2978	26	35	20	12	3	5	4.1	0.12
	35–45	3076	12	45	19	17	3	3	1.8	0.04
	50–60	3190	18	36	21	18	3	4	2.4	0.08
	70–80	4149	13	41	21	20	2	4	2.8	0.05
	90–100	3049	18	36	19	18	5	5	2.6	0.08
	110–120	3065	18	35	20	18	5	5	2.9	0.09
	150–160	2911	17	38	18	17	5	5	3.1	0.08
Underlying reddish-brown clays										
15	250–260	1348	25	33	17	15	5	7	3.1	0.13
	350–360	2933	25	36	20	12	3	5	4.0	0.12

lova [36] by the immersion method for the summary fraction 1–10 μm from soils of the Kamennaya Steppe, including profile 77 located in forest belt 40 at about 300 m from trench T-0067. A general tendency is observed for the distribution of minerals in coarse fractions. According to Yarilova, the fine sand fraction is absolutely dominated by quartz (60–80%) at the almost complete absence of micas (<0.5%). In the silt fractions, the share of quartz successively decreases and that of micas increases, when the particle size decreases (from coarse to fine silt). In medium silt, the share of quartz still remains higher than the share of micas, and the content of micas in fine silt exceeds the content of quartz.

CONCLUSIONS

The properties and mineralogy of soils composing the most common soil combination of flat watershed areas and their gentle slopes on the plains in the forest-steppe zone of European Russia were studied. A non-contrasting soil combination consists of three components: deep calcareous zooturbated deeply quasi-gleyed light clayey migrational-mycelial agrochernozems, medium-deep deeply quasi-gleyed light clayey migrational-mycelial agrochernozems, and medium-deep deeply quasi-gleyed light clayey clay-illuvial agrochernozems. All these soils are developed from light clayey loess-like sediments underlain by reddish-brown clay.

The studied soils have specific vertical distributions of organic matter and carbonates in separate areas of agrochernozems and horizontal distributions in the soil combination.

The clay fraction of agrochernozems contains smectite (46–73%), hydromicas (20–40%), and kaolinite and chlorite (in total, 6–11%). Finely dispersed quartz is also present. The smectite phase consists of irregular interstratifications with different combinations of mica and smectite layers in crystallites. Mica-smectite formations with the high content of smectite layers are predominant; mica-smectites with the low content of smectite layers are less abundant. Chlorite-smectites are also identified. Hydromicas are di- and trioctahedral. The contents of kaolinite and chlorite are lows. The composition and proportions of clay minerals are typical for the parent material (loess-like clays).

Pedogenesis resulted in the similar distributions of clay minerals in all agrochernozems forming the three-component combination. A significant disordering of layered silicate structures, especially mica-smectite interstratifications, occurs in the plow horizons, which is accompanied by a decrease in the reflection intensities of all minerals. The minimum content of smectite and the maximum content of hydromicas are noted in the upper part of the profile, especially in the plow horizon. However, there are some differences. Zooturbated agrochernozems are characterized by the uniform distribution of clay within the 30- to 110-cm layer due to the mechanical mixing of material from the dark-humus AU horizon and the calcareous BCA horizon by zoofauna. A slight eluvial–deluvial distribution of the clay fraction is noted in the clay-illuvial agrochernozem due to the decrease of its content in the AU and BI horizons.

The fine silt (1–5 μm) and medium silt (5–10 μm) fractions consist of quartz, micas, potassium feldspars, plagioclases, kaolinite, and chlorite. There is no dominant mineral, because the share of each mineral is lower than 35–45%. The silt fractions differ in the quartz-to-mica ratio. The share of quartz is higher in medium silt, and the share of micas is higher in fine silt.

In the major part of the profile, easily weathered trioctahedral structures are predominant micas of the silt fractions. In the plow horizons, the share of dioctahedral structures increases.

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