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Monitoring of micromorphological changes in a virgin Solonetz under regional changes in hydrology and climate (Northern Caspian Lowland, Russia)

Evaluación de los cambios micromorfológicos en un Solonetz virgen sometido a cambios en la hidrología y el clima regionales (Norte de las Llanuras del Caspio, Rusia)
Monitorização das alterações micromorfológicas num Solonetz virgem submetido a alterações hidrológicas e climáticas regionais (Norte da planície do Cáspio, Rússia)

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ABSTRACT

Over the past 40 years, a clear trend towards an increasing humidity and a rising groundwater table has been observed in the south-eastern semidesert part of European Russia. According to the published data, two clear periods of climate are distinguished: 1950s-1970s and 1970s-2000s. The thin sections of a Solonetz sampled in different periods of time (1950s, 1960s, 1970s, 1982, 2002 and 2013) at the Dzhanybek research station were studied micromorphologically to observe how these natural changes influenced soil pedofeatures. A comparison of thin sections showed no significant changes in soil properties between 1950s and 1982, when the hydrological (ground water table) and climatic parameters remained relatively stable. However, between 1982 and 2013, due to a significant increase in climatic moisture and rising groundwater, the following changes in soil microfeatures took place: the activation of humus accumulation and biogenic structuring, the eluviation of the silty clay-humus matter, the development of solodic features, gleyization of the soil mass, and the accumulation of opaque black organic grains about 2-3 µm formed in the topsoil due to the long stagnation during the springtime after snow melting. The water table rise leads to the consequent rise of the upper boundary of the accumulation of gypsum and carbonates.

RESUMEN

En los últimos 40 años se ha observado una clara tendencia a un aumento de humedad y al ascenso de la capa freática en la parte semidesértica del sudeste de la Rusia europea. Según los datos publicados, se distinguen claramente dos periodos climáticos muy patentes: 1950s-1970s y 1970s-2000s. Con objeto de analizar la influencia de estos cambios naturales en los edaforrasgos, se estudió la micromorfología de láminas delgadas de un Solonetz muestreado en diferentes periodos (1950s, 1960s, 1970s, 1982, 2002 y 2013) en la estación de investigación Dzhanybek. La comparación entre laminas delgadas no mostró cambios significativos en las propiedades del suelo entre 1950s y 1982, periodo en el cual los parámetros hidrológicos (capa freática) y climáticos permanecieron relativamente estables. Sin embargo, entre 1982 y 2013 y a consecuencia de un incremento importante de la humedad y del ascenso de la capa freática, se produjeron los siguientes microedaforrasgos: la activación de la acumulación de humus y de la estructuración biogénica, la eluviación del material arcillo-húmico limoso, el desarrollo de rasgos solódicos, la gleyzación de la masa del suelo, y la acumulación de granos orgánicos negros opacos de un tamaño aproximado de

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2-3 µm formados en la superficie del suelo debido al largo estancamiento de agua durante la primavera después del deshielo. El ascenso de la capa freática dio lugar al consecuente ascenso del límite superior de la acumulación de yeso y carbonatos.

RESUMO

Nos últimos 40 anos, tem sido observada uma tendência clara para um aumento da humidade e uma subida da toalha freática na parte sudeste semidesértica da Rússia Europeia. De acordo com os dados publicados, distinguem-se claramente dois períodos: anos 1950 a 1970 e 1970 a 2000. Com o objetivo de analisar a influência destas alterações naturais nas características micromorfológicas do solo, estudaram-se lâminas delgadas de um Solonetz colhido em diferentes períodos (1950, 1960, 1970, 1982, 2002 e 2013) na estação de investigação Dzhanybek. As lâminas delgadas não mostraram alterações significativas nas propriedades do solo entre 1950 e 1982, quando os parâmetros hidrológicos (lençol freático) e climáticos se mantiveram relativamente estáveis. Contudo, entre 1982 e 2013, devido a um significativo aumento da humidade e da subida do nível freático, ocorreram as seguintes alterações nas características micromorfológicas do solo: a activação da acumulação de húmus e a estruturação biogénica, a eluviação dos complexos limo-argilo-húmicos, o desenvolvimento de características solódicas, a gleização da massa do solo, e a acumulação de grãos negros orgânicos, opacos, de tamanho aproximado de 2-3 µm formados na superfície do solo devido ao longo período de encharcamento do solo durante a primavera após a fusão da neve. A subida do nível freático determinou a consequente subida do limite superior da acumulação de gesso e de carbonatos.

KEY WORDS
Climate change, rising ground water, sodic soils, soil forming processes, hydromorphic features, biological activity.

PALABRAS CLAVE
Cambio climático, ascenso de aguas subterráneas, suelos sódicos, procesos de formación del suelo, rasgos hidromórficos, actividad biológica.

PALAVRAS-CHAVE
Alterações climáticas, subida do nível freático, solos sódicos, processos de formação do solo, características hidromórficas, actividade biológica.

1. Introduction

Over the past decades, several natural changes have occurred within the Caspian Lowland in the south-eastern semidesert European part of Russia, which might have a significant influence on soil properties in dry regions.

Warming of the winter season. According to the meteorological data, winters have become warmer in the north of the Caspian Lowland (Titkova 2003; Sotneva 2004; Sapanov and Sizemskaya 2016). As a consequence, there is a lack of snow accumulation during the winter season and insufficient meltwater redistribution over the micro- and mesotopography in spring. Direct moisture percolation into the soil, without redistribution over the land surface, implies significant changes in the hydrological regime of the entire soil complex.

Increasing precipitation. The amplitude of mean annual precipitation fluctuation has significantly changed over the last 60 years (Figure 1). For example, within the period of 1950-1983, the mean annual precipitation was 250-320 mm, i.e., the amplitude of fluctuations was 70 mm, but after 1983 the mean annual precipitation fluctuated from 250 to 400 mm with an amplitude of 150 mm. Rainfall during the warm season was the major contribution towards that change. The amount of precipitation during the cold season remained generally stable. During the wettest period of 1987-1995, the mean annual precipitation was at and above 350 mm, while the precipitation to evaporation ratio grew up to 0.55 and even 0.8 (values characteristic of typical steppe and forest-steppe, i.e. typical of more humid conditions).

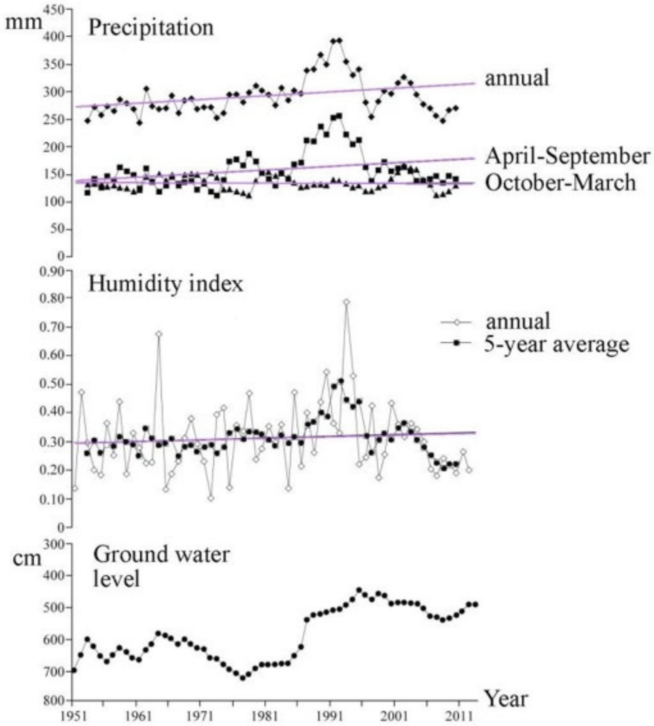


Figure 1. Dynamics of environmental parameters: precipitation, precipitation to evaporation ratio (humidity index) and ground water level at the study site (Sapanov and Sizemskaya 2016).

Rise of the groundwater table. An increase in climate humidity, which started in the late 1980s – early 1990s, was accompanied by rise of the groundwater table from 6-7 to 4-5 m depth (on average by 2 m) by the end of the twentieth century. This decadal change in the groundwater table significantly exceeds the seasonal variability which is about 10-40 cm according to Sapanov (2007). Despite the fact that climate humidity began to decrease since 1996, the groundwater table still remains at the same (higher) level. It is likely that, if humidity continues to be low, the groundwater table will gradually begin to lower. Such cycles of rising-sinking of the groundwater table are typical for the Caspian Lowland.

The influence of recorded environmental changes on soils can be estimated on the basis of regular monitoring with intervals of 10 years or longer as was justified in the work of Rode (1976) devoted to the principles of monitoring of soil processes. A unique example of continuous monitoring experience since 1952 is presented by the Dzhanybek Research Station of the Institute of Forest Science of the Russian Academy of Sciences (Rode 1974).

The soil cover of the northern Caspian Lowland where the research station is located is mainly represented by the Solonetzic soil associations where Solonetzs occupy from 25 to more than 50% of soil cover (Ivanova 1964). At the Dzhanybek Research Station where our studies were implemented, the portion of Solonetzs amounts to 50% (excluding the areas of *padinas*, mesodepressions with dark-coloured Chernozem-like soils) (Rode and Pol'sky 1961; Konyushkova 2014). Due to the predominance of these soils in the soil cover of the research station as well as the Caspian Lowland in total, they were chosen as the first object for the study of the short-term changes in soils under the impact of environmental changes.

The micromorphological features of Solonetzs are well studied for the Caspian lowland in the south of Russia (Yarilova 1966; Gerasimova et al. 1996; Lebedeva (Verba) and Gerasimova 2009; Lebedeva (Verba) and Sizemskaya 2011;

Lebedeva and Konyushkova 2011). However, for Solonetzes from other countries these data are sparse (Alexander and Nettleton 1977; Fedoroff and Courty 1986; Oliveira et al. 2004a, 2004b; Kuhn et al. 2010).

In our study, the microfabrics of samples taken in different years (1982, 2002 and 2013) from a shallow Solonetz at the same study site (49.39943°N, 46.81062°E) located within the Dzhanybek Research Station were compared. Also, published data on Solonetz at this Station were also used (Pol'sky 1958; Yarilova 1966; Bazykina 1978). Some results of the comparative analysis of data from 1982 and 2002 have already been published by the authors (Lebedeva and Konyushkova 2010; Lebedeva and Konyushkova 2011). In this paper, the short-term changes in microfabrics of soils as related to the environmental changes over a broader period (1950s-2010s) have been studied in order to track the processes which occurred in soils during this span of time.

2. Materials and Methods

The study area is located in the north-eastern part of the Caspian Lowland (**Figure 2**). The climate is strongly continental, with a mean annual evaporation (about 1000 mm) much higher than the mean annual precipitation (289 mm for a period of 1952-1998). The mean annual temperature is +7.1 ºC, with a maximum of +42 ºC in summer and a minimum of -38 ºC in winter (Sotneva 2004). The depth of soil freezing can reach 1 m. The study area is situated within a closed-drainage plain with well-developed mesotopography – large depressions and wet estuaries (limans). The terrain between those depressions is occupied by a Solonetz complex, which includes (1) Amphi-Salic Solonetz under *Artemisia pauciflora* – *Kochia prostrata* communities, (2) Calcic Kastanozem under communities dominated by *Festuca valesiaca* or *Tanacetum achilleifolium* and (3) Haplic Kastanozems under polydominant meadow communities (*Stipa capillata, Medicago romanica, Veronica spicata, Gramineae*).

Figure 2. Location and coordinates of the study site.

The local soils and vegetation have a complex nature, which is related to the redistribution of precipitation (mainly, by runoff of snow meltwater) over elements of uneven microtopography (Rode and Pol'sky 1963). Microhighs with a relative elevation of several decimeters receive only atmospheric water and contain a considerable concentration of salts within the depth of soil profile. Such soil is solonchakous Solonetz (saline-sodic soil) under a sparse vegetation of semidesert type.

The presence of a low-permeable solonetzic (natric) horizon accounts for a nonpercolative water regime and an absence of salt leaching. Salts precipitate from soil solutions in subsurface horizons.

According to the Field Guide to Soils of Russia (2008), the soil studied can be attributed to light-coloured quasi-gley Solonetz. Judging from the eluvial horizon thickness (up to 10 cm), the same soil also corresponds to a shallow Solonetz. According to the World Reference Base for Soil Resources (IUSS Working Group WRB 2015), this soil is classified as an Amphi-Salic Solonetz (Albic, Siltic, Columnic, Cutanic, Differentic). The studied Solonetz was characterized by the presence of a well-developed bleached eluvial horizon, 7(10) cm thick, underlain by the natric horizon, about 25 cm thick, with prismatic structure and, in its lower part, morphologically clearly seen gypsum veins and carbonate accumulations. Below, there is a salic horizon containing gypsum (Figure 3).

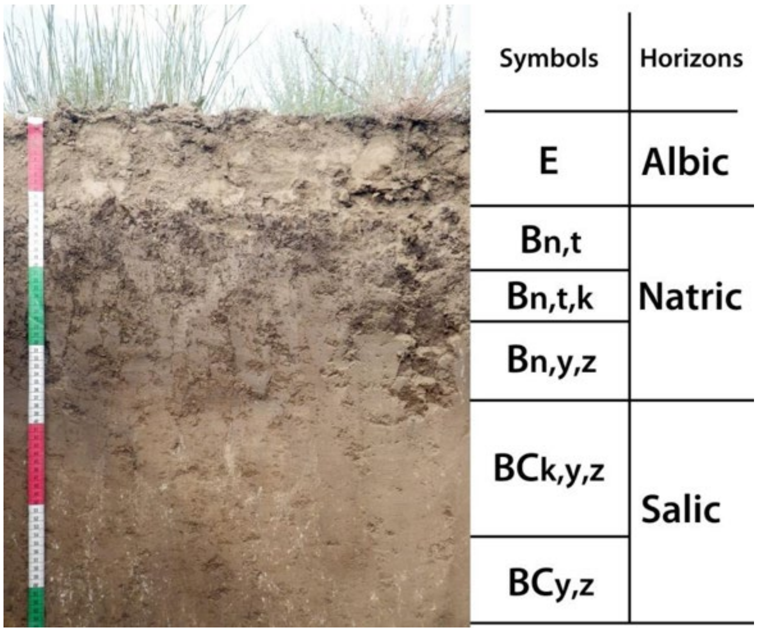


Figure 3. Virgin Solonetz profile (pit 7M-13) in 2013. Horizons: Albic (E) (0-7(10) cm); Natric (Bn) (7-36 cm) subdivided into subhorizons Bn,t (7(10)-14 cm) – horizon without morphological features of salt accumulation; Bn,t,k (14-24(26) cm) –horizon with dispersed carbonates; Bn,y,z (24(26)-33(36) cm) –horizon with salic features and dispersed carbonates; Salic (BCy,z) (33(36)-100 cm) subdivided into subhorizons: (BCk,y,z) (33(36)-57 cm) –salt-affected and gypsiferous horizon of maximum (secondary) carbonate accumulation; BCy,z (57-100 cm) – transient horizon between B and C hor. with salts and gypsum. Symbols are given according to FAO (2006).

Samples for micromorphological studies were taken in June in different years (1982, 2002 and 2013) from similar depths from soil pits located at a short distance (less than 20 m) from each other. It is worth noting that it was not possible to take samples from the similar pit in different years as the ”pit-induced” transformations took place in the area of old pits.

In order to study the temporal changes in soil moisture content and bulk density, the soil from the close location where these properties were studied previously (in 1985) was sampled in 2015. The coordinates of this pit are 49.3871°N, 46.7904°E. The soil moisture content and bulk density were determined by gravimetric method. Chemical and physicochemical analyses were performed at the Analytical Laboratory of the V.V. Dokuchaev Soil Science Institute by standard methods generally accepted in Russia (Vorob'eva 2006). Calcium and magnesium concentrations in water extracts (1:5) were determined by the complexometric titration method; sodium and potassium concentrations

– by the flame photometry method; the total alkalinity – by titration with sulfuric acid (with methyl orange indicator); the concentration of chlorine ions – by argentometry (according to Mohr); the concentration of sulphate ions – by titration with $BaCl_2$. The exchangeable cations were determined by the Pfeffer method in modification by Molodtsov and Ignatova with ethanol extraction.

The thin sections were prepared by M.A. Lebedev at the Dokuchaev Soil Science Institute. The micromorphological analyses were conducted using standard techniques and an Olympus BX51 polarizing microscope with an Olympus DP26 digital camera. The soil microfabrics were compared using large (4 × 5 cm) thin sections in two replications and also vertical cross-sections of samples collected from the main genetic horizons. Specialized computer software supplied with the Olympus BX51 microscope (Japan) was used for visualization of the features observed. International terminology was used for describing the soil fabric (Stoops 2003).

3. Results and Discussion

3.1. The chemical composition of the Solonetz.

In 2013, the soil pit was situated on a microhigh (49.39943ºN, 46.81062ºE) under a sparse vegetation (15% cover), which consisted of bulbous meadow grass (*Poa bulbosa*), clasping pepperweed (*Lepidium perfoliatum*), Austrian wormwood (*Artemisia austriaca*) and kochia (*Kochia prostrata*). The groundwater table was at a depth of 4.7 m (June 2013). The groundwater had a salt concentration of 4 g/l and calcium-magnesium-sulphate composition. In the soil profile, effervescence was observed from the depth of 15 cm.

In 2002, at the same location the groundwater table was at a depth of 4.5 m (June 2002). The groundwater had a salt concentration of 4.3 g/l with a magnesium-sodium-calcium-sulphate composition. There was no significant change in the effervescence depth (14 cm).

The exchangeable sodium percentage of the Bn,t natric subhorizon of soil in 2013 was 36% (**Table 1**), which is almost equal to that (32%) of the Solonetz in 2002 (Lebedeva and Konyushkova 2011).

Table 1. The content of exchangeable cations of the Amphi-Salic Solonetz sampled in 2013

Sampling depth (cm)	Horizon	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	The percentage of Na^{+} to total sum (ESP)
		cmol$_{(+)}$/kg				%
0-7	E	5.36	2.64	0.69	0.83	7.2
7-14	Bn,t	4.68	5.36	5.82	0.39	35.8
14-24	Bn,t,k	2.48	9.65	10.11	0.52	44.4
24-33	Bn,y,z	1.6	10.42	8.94	0.52	41.6
33-57	BCk,y,z	2.27	6.92	7.09	0.44	42.4
57-100	BCy,z	2.6	5.12	6.62	0.35	45.1
100-141		2.37	5.82	6.68	0.36	43.9
141-160		2.55	6.13	7.07	0.35	43.9

The composition of water extract (1:5) from the soil studied in 2013 was indicative of a weak sodium-chloride salinity even in the upper part of the solonetzic B horizon, from the depth of 7 cm (**Table 2**). The middle and lower parts of the solonetzic B horizon (14-33 cm) were characterized by a strong sodium-chloride-sulphate salinity. At depths more than 33 cm, there was a strong, mostly sodium-sulphate salinity, with participation of gypsum.

Table 2. The composition of water extract (1:5) of the Amphi-Salic Solonetz sampled in 2013

Sampling depth (cm)	pH water 1:5	Total alkalinity HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	Na^+	K^+	Total sum of dissolved ions
				$cmol_{(+)}/kg$					%
0-7	7.32	0.2	0.08	0.08	0.05	0.05	0.42	0.05	0.032
7-14	8.36	0.38	1.21	0.36	0.17	0.05	2.01	0.06	0.136
14-24	8.31	0.28	5.18	4.84	0.35	0.32	9.95	0.01	0.673
24-33	8.59	0.54	6.34	9.72	0.57	1.4	14.65	0.04	1.091
33-57	8.63	0.2	6.12	51.16	30.15	8.47	18.61	0.08	3.821
57-100	8.92	0.2	5.7	12.76	2.32	2.8	14.71	0.04	1.247
100-141	8.78	0.14	4.84	20.28	6.42	3.9	15.09	0.04	1.678
141-160	8.9	0.3	4.34	12.44	1.9	2.75	13.5	0.03	1.152

According to the Russian classification of texture, the soil is clayey (horizons between 7 and 100 cm) with slight eluviation in the upper E horizon (0-7 cm), which leads to medium loamy texture in it, and with heavy loamy texture below the depth of 100 cm (**Table 3**).

Table 3. The particle-size distribution in the Amphi-Salic Solonetz sampled in 2002 (%)

Depth (cm)	Horizon	Particle size (mm)					
		1.0-0.25	0.25-0.05	0.05-0.01	0.01-0.005	0.005-0.001	< 0.001
0-7	E	0.1	17.9	48.4	9.6	17.9	6.2
7-14	Bn,t	0.0	5.8	38.2	10.1	14.4	31.4
14-24	Bn,t,k	0.0	4.0	36.2	9.1	15.4	35.3
24-33	Bn,y,z	0.0	8.1	33.0	8.2	27.7	23.0
33-57	BCk,y,z	0.0	13.3	32.0	5.7	28.5	20.6
57-100	BCy,z	0.0	14.3	35.2	5.2	20.7	24.6
100-141		0.0	18.2	36.5	3.6	19.7	22.0
141-160		0.7	16.6	36.8	5.3	20.4	20.3

3.2. Temporal changes in micromorphological characteristics of Solonetzs in 2002-2013

At a macro-scale, the compared Solonetz pits of 2002 and 2013 had many common features: (1) soil profiles were clearly differentiated by the content of clayey and calcareous finely dispersed materials; (2) there were crumb-structured zones within predominant platy structure of their eluvial horizons (**Figure 4A**); (3) maximal numbers of large gypsum crystals appeared at a depth of more than 140 cm in both pits.

However, there were also macromorphological differences in the diagnostic horizons studied. Comparing Solonetz pits of 2013 and 2002, the former had the following distinctions: (1) higher content of plant residues with traces of their biogenic transformation (appearance of larger amounts of organic residues with the formation of plant fibers at the surface) within certain microzones at the depth of 0-3 cm in the *E* horizon and formation of the crumb structure (**Figure 4A**); (2) highly porous columnar peds with rounded bleached tops that could more easily be separated into angular peds with some rounded edges in the *natric* (B) horizon (**Figure 4B**); (3) significantly higher contents of clay-humus coatings in large pores and on ped faces (**Figure 4C**) as well as ferruginous and ferromanganese pedofeatures (concretions and, especially, dendroid pedofeatures) in the lower part of *natric* horizon; (4) less distinct manifestation of pseudosand ('sand-like') microaggregation (naming according to Pol'sky 1958), the formation of which is related to the salt aggregation of clay into the microaggregates of sand size in the *salic* horizons (**Figure 4D**); (5) higher quantity of labile carbonate and salt pedofeatures faces and walls of large pores; (6) deeper upper limit of the distribution of diverse forms of gypsum pedofeatures (coatings, aggregates and infillings). Their distribution limit was at 34-36 cm in 2013, but at 20-22 cm in 2002, when the maximum concentration and diversity of such pedofeatures began from the lower part of the *natric* horizon (**Table 4**).

(A) (B) (C) (D)

Figure 4. Specific elements of the structural organization of different genetic horizons of the Solonetz studied in 2013 (pit 7M-13): A – crumb to fine platy structure of the E horizon (0-7 cm). B – columnar structure with solodized (dealkalized) top in the Bn,t horizon (7-14 cm). C – clay-humus coating on the walls of the main crack with fibers of fine roots in the Bn,t,k horizon (14-24 cm). D – pseudosandy microaggregation and white elongated accumulation made up of gypsum crystals in the saline BCk,y,z horizon (33-57 cm).

It should be emphasized that the subsolonetzic horizons were characterized in the 2013's field descriptions by a less prominent pseudosandy microaggregation, which could be related to the observed environmental changes in the last decades. Pseudosandy microaggregation is formed in the dry subsurface horizons of the Solonetz due to the crystal infillings of sodium and calcium sulphates (thenardite and gypsum) between clay-carbonate aggregates. In the 1950s, the ground water table was deeper (about 7 m, according to Rode 1961), and the layer 50-150 cm was extremely dry. Since the 1980s the ground water table has been continuously rising and reached 4-5 m in the late 1990s which led to the soil moisture increase in subsurface horizons (**Figure 5A**). The crystals of sulphates are dissolved in soil solution in these conditions which leads to the compaction of microaggregates into more massive aggregates (**Figure 5B**).

Table 4. Morphological properties of the virgin Solonetz (Pit 7M-02 from Lebedeva & Konyushkova 2011). Described according to FAO (2006)

Horizon, depth (cm)	Year	Munsell color (dry) / Texture***	Field consistence/ Stickiness	Structure	Coatings	Pedofeatures		Roots	Biological activity
					Nature/ Location	Nature/ Kind	Size/ Abundance	Abundance/ Diameter	Abundance/ Kind
E 0-7	2002	10YR7/2 Medium loam	Soft when dry / non sticky	Platy	–*	–	–	Common / very fine + fine	Common / channels and nests mesofauna
	2013		-“-/-“-**	Platy + subangular blocky + single grain	–	–	–	Many / very fine + fine + medium + coarse	Many / pedotubules + channels and nests mesofauna
Bn,t 7-14	2002	10YR7/2+ 10YR6/4 Clay	Slightly hard when dry / slightly sticky	Columnar → subangular and angular blocky	Silt / voids+ pedfaces	–	–	Common / very fine + fine	–
	2013		-“-/-“-	Columnar →angular and subangular blocky	Silt+ clay and humus / voids	Fe-Mn + iron / nodule + soft segregation	Fine / few	Many / very fine + fine + medium	Many / pedotubules + channels and nests mesofauna
Bn,t,k 14-24	2002	7.5YR5/4 Clay	Firm / sticky	Prismatic → angular blocky	Clay and humus / vertical pedfaces + pedfaces	Carbonates / soft segregation + concretion	Fine / few	Common / very fine + fine	–
	2013		-“-/-“-	Prismatic → subangular and angular blocky	Clay and humus / vertical pedfaces	–	–	Common / very fine + medium + coarse	Many / pedotubules
Bn,y,z 24-33	2002	7.5YR6/4 Clay	Firm / sticky	Prismatic → angular blocky	Clay and humus + clay / vertical pedfaces + pedfaces	Salts + carbonates + gypsum / soft concretion + soft segregation + concretion	Very fine / many	Few / coarse	–
	2013		-“-/-“-	Prismatic → subangular blocky	Clay and humus + clay / vertical pedfaces	Carbonates + gypsum + salts / pore infilling	Very fine / very few	Common / medium + coarse	Common / pedotubules
BCk,y,z 33-57	2002	7.5YR7/4 Clay	Very friable when moist / non sticky	Crumbly	Salts / vertical pedfaces	Carbonates + salts + gypsum / soft concretion + pore infilling + soft segregation + other	Medium + coarse / many	Very few / coarse	–
	2013		Friable when moist / non sticky	Cloddy	Salts / voids	Salts + gypsum / -“-/-“-	Fine + medium + coarse / many	Very few / medium + coarse	Few / pedotubules + burrows

Table 4. Morphological properties of the virgin Solonetz (Pit 7M-02 from Lebedeva & Konyushkova 2011). Described according to FAO (2006)

Horizon, depth (cm)	Year	Munsell color (dry) / Texture***	Field consistence/ Stickiness	Structure	Coatings	Pedofeatures		Roots	Biological activity
					Nature/ Location	Nature/ Kind	Size/ Abundance	Abundance/ Diameter	Abundance/ Kind
BC y,z 57-100	2002	10YR7/4 Clay	Friable when moist / slightly sticky	Lumpy	–	Iron + Fe-Mn + salts + gypsum / soft concretion + pore infilling	Very fine + fine + coarse / common; coarse / few (for salts + gypsum)	Very few / coarse	–
	2013		Friable when moist / slightly sticky	Cloddy	Gypsum + salts / voids	Salts + gypsum / -“-/-“-	Very fine + fine + coarse / common	Very few / medium + coarse	–
100-141	2002	10YR7/4 Heavy loam	Friable when moist / slightly sticky	Lumpy	–	Salts + gypsum / -“-/-“-	Fine / few (for salts + gypsum); coarse / many (for Fe-Mn)	Very few / coarse	–
	2013		Friable when moist / slightly sticky	Cloddy	–	Fe-Mn + salts + gypsum / nodule +other	Salts + gypsum / very few; coarse / many (for Fe-Mn)	–	–
141-160	2002	10YR7/5 Heavy loam	Friable when moist / slightly sticky	Lumpy	–	Gypsum / crystals	Coarse / many	–	–
	2013		Friable when moist / slightly sticky	Cloddy	–	Gypsum + Fe-Mn / crystals + other	-“-/-“-	–	–

* - Feature is not observed.
** -“- The same feature.
Size of mineral concentrations (mm): very fine (< 2); fine (2-6); medium (6-20); coarse (> 20).
***Soil texture was determined according to the Russian classification due to different particle sizes used in Russia (1 mm/0.001 mm instead of 2 mm/0.002 mm).

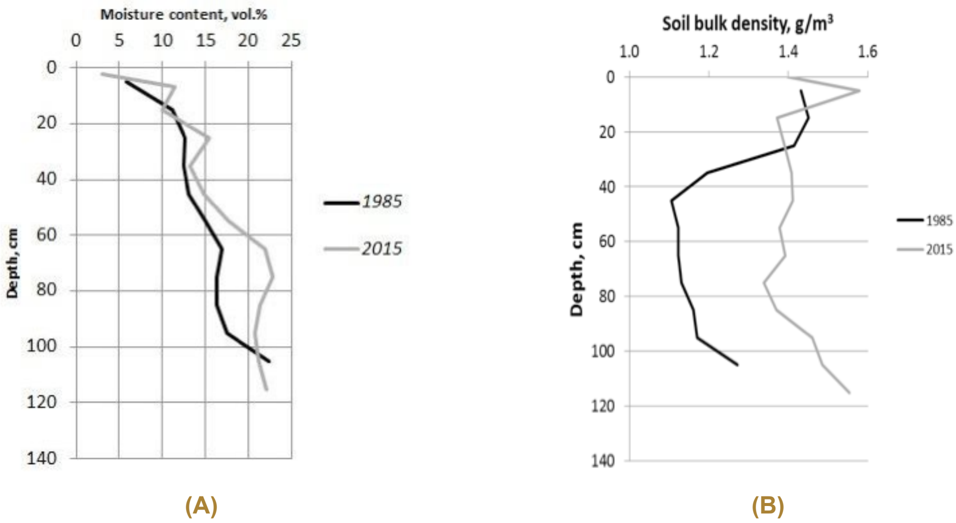


Figure 5. The change in moisture content (A) and bulk density (B) in the Amphi-Salic Solonetz from 1985 to 2015.

The studied subsolonetzic (salic) horizons have the following micromorphological features (Table 5): angular blocky microstructure with partially accommodated aggregates having sharply expressed boundaries, speckled b-fabric in the aggregate centers and monostriated b-fabric at their peripheries merging into stress coatings; organo-clay coatings; humus-enriched infillings; no calcite and gypsum pedofeatures (Gerasimova et al. 1996; Lebedeva et al. 2009).

3.3. Temporal changes in micromorphological characteristics of Solonetzs in 1982-2002

As was previously shown (Lebedeva and Konyushkova 2011), the studied Solonetz underwent the following changes between 1982 and 2002:

- In the *eluvial* (*above-solonetzic*) horizons: (1) the content of clay particles slightly decreased, which is evident from the comparison of fine material in the thin sections of different years; (2) the numbers of varied-size plant residues, flocculated humus particles and iron concentrations increased; (3) an indistinct platy structure was transformed into a clearly pronounced lens-shaped structure due to ice, and we see a clearly differentiated particle-size distribution within lens-shaped aggregates (clay particles accumulated on their lower sides at the expense of clay depletion in the upper part of the aggregates) and (4) in 2002, gypsum coatings appeared around the roots.
- In the *natric* (*solonetzic*) horizons: (1) the content of fine material slightly increased, (2) the angular blocky structure became more prominent and (3) the degree of manifestation of poro-, grano- and parallel striated b-fabric in groundmass increased due to swelling and shrinking. At the same time, no new illuvial-clay coatings appeared on pore walls. These elements of microfabrics, probably, can be connected to the clay illuviation in the period between 1982 and 2002 and attenuation of this process by 2002.
- In the *saline* (*subsolonetzic*) horizons: (1) the degree of compaction of the pseudosandy salt-bearing material increased in the Bk,y,z horizon, (2) the degree of impregnation of groundmass around some voids with fine-grained calcite (micrite) increased, (3) the amount of gypsiferous infillings in the pores also increased and the gypsum crystals became larger, which can be seen by comparison of predominant crystals of gypsum from the same depth at different years.

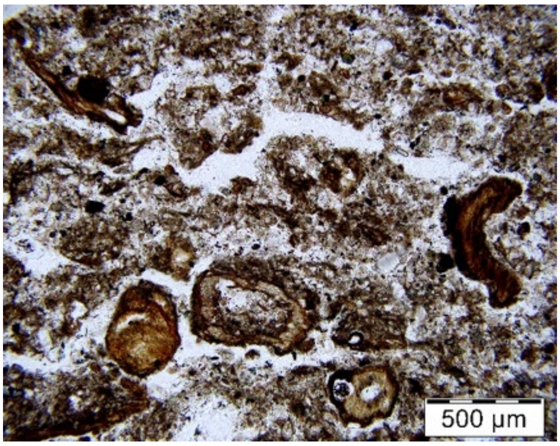
Between 2002 and 2013, the studied Solonetz generally retained the same elements of the soil fabric within the eluvial and natric horizons, but deeper, within the saline horizons down to the

Table 5. Semiquantitative comparative estimate of the changes in micromorphological features of the Amphi-Salic Solonetz

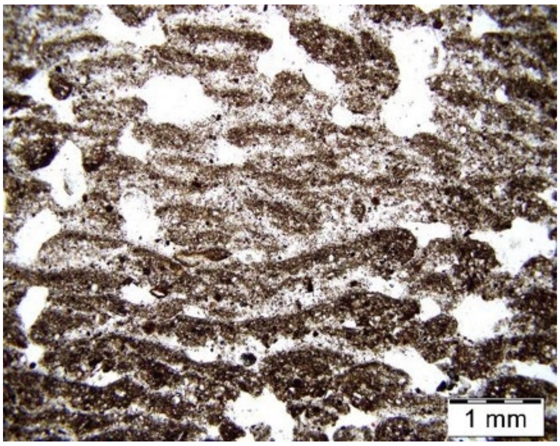
Depth (cm)	Year	Organic matter					Coarse/fine related distribution			Pedofeatures							
		Organ residue	Tissue residue	Punctua-tions	Organic pigment	Organic fine material	Porphyric			Carbonate depletion	Micrite in ground-mass	Carbonate coatings	Gypsum crystal in-tergrowth	Gypsum infillings	Humus infillings	Fe/Mn dendritic nodules	Chambers
							Close	Single spaced	Double spaced								
0-7	2002	++	++	+	+	+	-	+++	++	+	-	-	-	-	+	+++	+
	2013	+++	+++	+++	+++	+++	+	+++	++	+++	-	-	++	-	+	+	++
7-14	2002	+	+	+	++	+++	+++	+	++	+	-	-	-	++	+	+	-
	2013	+++	++	++	++	+++	+++	+	++	+	-	-	-	-	+++	++	++
14-24	2002	+	+	-	-	+	+++	+	++		-	-	-	-	+	-	-
	2013	++	++	+	+	++		+	++		-	-	-	-	++	+	++
24-33	2002	-	+	-	-	-	+++	+	++		-	-	-	-	-	+	+
	2013	-	+	-	-	-	++	+	++		+	-	+	++	+	+	+
33-57	2002	-	-	-	-	-	+	+++	+		+	-	-	+	-	+	+++
	2013	-	-	-	-	-	+++	+	+		++	-	-	-	-	++	+
57-100	2002	-	-	-	-	-	+	++	+		+	-	-	-	-	+	++
	2013	-	-	-	-	-	+++	+	+		++	+++	-	-	-	++	-
100-141	2002	-	-	-	-	-	+++	++	++		+	-	-	+	-	-	+++
	2013	-	-	-	-	-	+	+	+++		+++	++	-	++	-	+++	+
141-160	2002	-	-	-	-	-	+++	+	++		+	-	-	-	-	+	-+
	2013	-	-	-	-	-	++	+	+++		++	+	+++	-	-	+++	-

Note: -, +, ++, +++ Indicate the increasing frequency of pedogenic features: - = absent; + = rare (locally in separate zones); ++ = common; +++ = abundant.
Degree of micrite impregnation in groundmass: + = weakly; ++ = moderately; +++ = strongly.

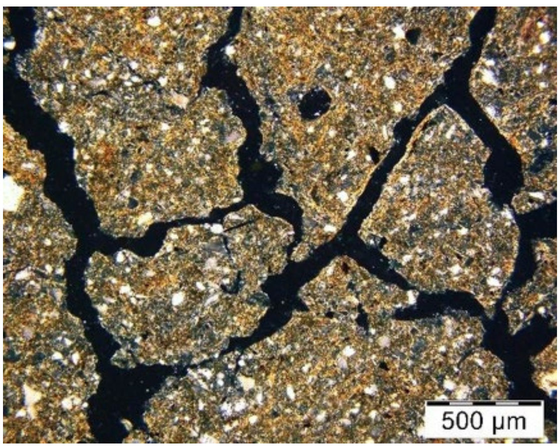
parent material, there were three new elements of soil fabric: compaction of subsoil (which is also evident from the data on soil bulk density at **Figure 5B**), micrite coatings and dendroid Fe-Mn pedofeatures in biopores. We believe that these changes in soil fabric are connected with the development of new natural processes over the past 11 years at the study site, as described below.



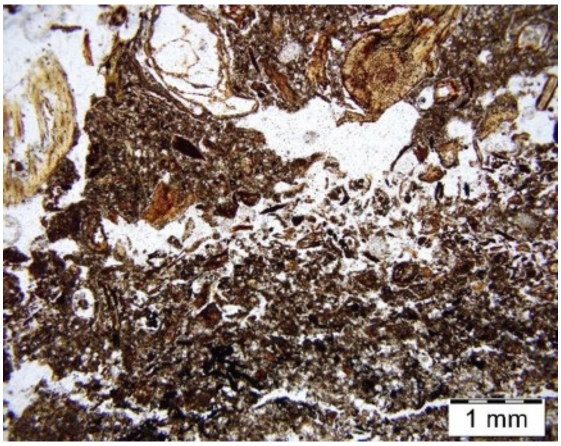
(A)



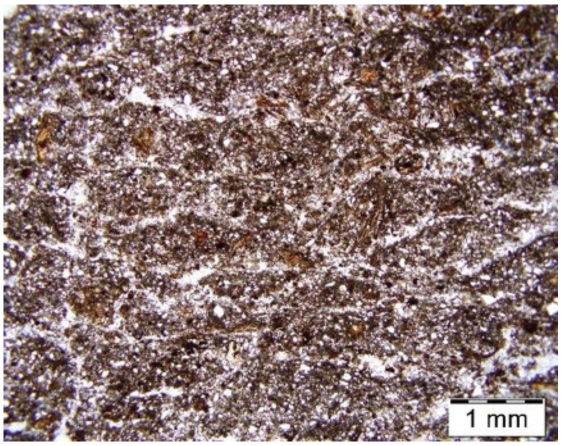
(B)



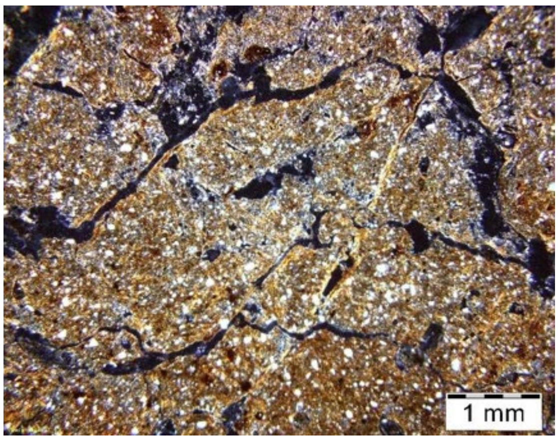
(C)



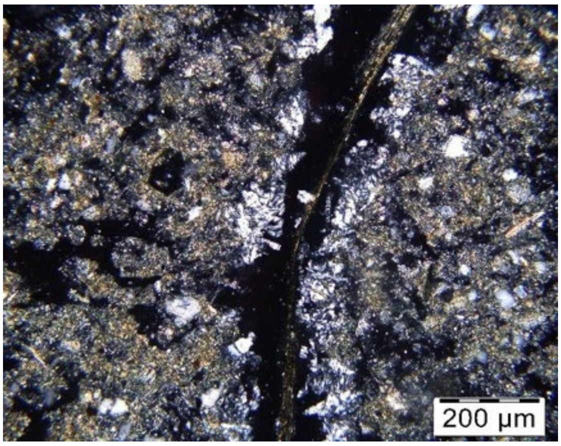
(E)



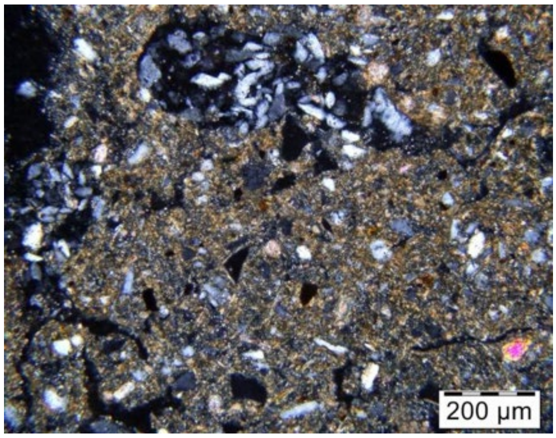
(F)



(G)



(D)

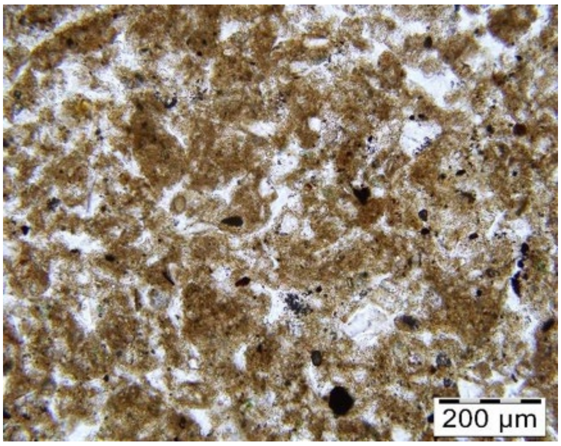


(H)

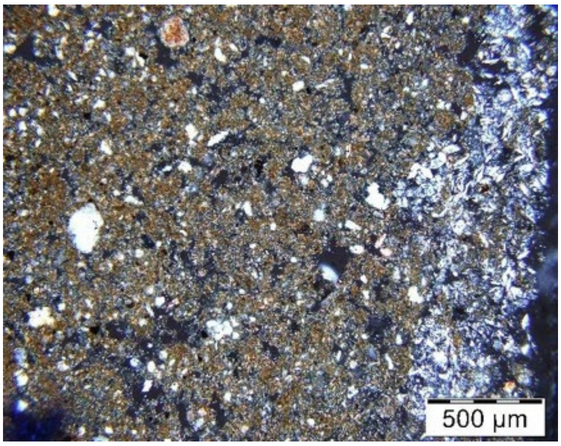
Figure 6. Soil fabric of solonetzic eluvial (E) and illuvial (Bn,t and Bn,y,z) horizons in the Solonetz sampled in different years (2002: A-D; 2013: E-H): A – numerous cross-sections through weakly decomposed large roots in a silty-clayey-humic material, which has initial microfeatures of its structural reorganisation into small crumbs (E; 0-3 cm) (PPL); B – a fine lenticular microstructure, where the upper parts of the lenses are enriched with finely dispersed particles (E; 3-7 cm) (PPL); C – an angular blocky microstructure, striated and porostriated b-fabric, thin clay coatings (Bn,t, 7-14 cm) (XPL); D – gypsum coatings on pore walls with remains of plants roots, loose material, crystallitic b-fabric (Bn,y,z; 24-33 cm) (PPL); E – thin organic fibers of residues of large roots that covers numerous fragmented (biogenically reworked) tissues (E; 0-3 cm) (PPL); F – a lenticular-crumb microstructure in a weakly compacted silty-clayey-humic material, with abundant small residues of plants (E; 3-7 cm) (PPL); G –angular blocky aggregates, striated and porostriated b-fabric, thin clay coatings, numerous small Fe nodules (Bn,t, 7-14 cm) (XPL); H – dense infillings and coating of lenticular gypsum microcrystals inside channel voids in a weakly compacted material with crystallitic b-fabric (Bn,y,z; 24-33 cm) (XPL).

- In the *eluvial* horizon, features of vertical differentiation of humus-accumulative process were observed (**Figures 6A, B, E, F**): 1) in the upper part – an increased accumulation of organic residues coming mostly from mosses and lichens and partly from *Poa bulbosa, Cardaria draba, Artemisia austriaca* and *Kochia prostrata* (**Figure 6A, E**); in the lower part – an increased amount of finely dispersed organic matter and the reorganization of thin dense lenticular (lens-like) peds (**Figure 6B**) into loosened crumb-lenticular peds (**Figure 6F**).
- In the *upper part of the natric* (*solonetzic*) horizon, an increased eluviation of silty clay-humus particles and solodization (dealkalization) resulted in the formation of thick fine-textured silicate-humus infillings inside the main cracks running all through this solonetzic horizon and partially through the subsolonetzic horizon. These infillings contained a large amount of plant roots, including humified dead roots. These pedeofeatures indicate on the one hand a more intensive accumulation of root organic matter, on the other hand, on the mobility of fine humic particles.
- In the *lower part of the natric* (*solonetzic*) horizon, there was an increased amount of clay coatings that underwent re-organization into the micromass of b-fabric due to swelling and shrinking; the clay coatings were very thin and fragmentary (**Figures 6C, G**).
- In the *solonetzic* and *subsolonetzic* horizons, both (a) general and (b) specific microfeatures appeared (**Figures 6D, H; 7**). (a) The general microfeatures included gypsum pedofeatures of different types and localizations. For example, microfeatures of current accumulation of gypsum found just under the solonetzic horizon at the depth of 25-30 cm were represented by labile forms of gypsum pedofeatures (coatings) in biopores containing plant roots (**Figure 6D**), loose infillings within narrow channel pores and thin coatings on ped faces (**Figures 6H, 7B**). The diversity of gypsum pedofeatures in size and genesis increased with depth in the subsolonetzic horizon: there were dense gypsum infillings in large pores (**Figures 7C, D**) and aggregates of large gypsum crystals (**Figure 7G**).

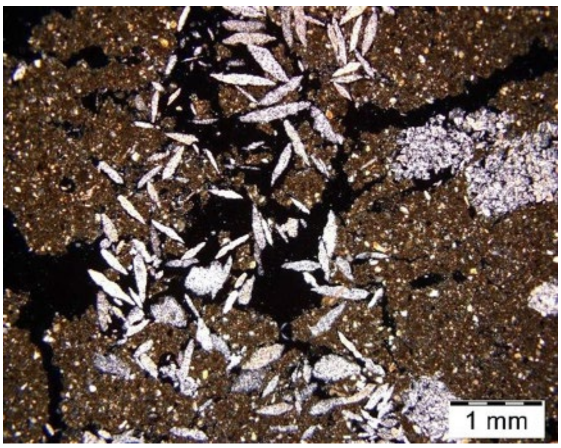
The latter are known to be formed under conditions of complete saturation with water (Verba and Yamnova 1997). (b) The specific microfeatures of solonetzic and subsolonetzic horizons were related to the adhesion of pseudosand microaggregates due to the dissolution of salts in more moist conditions and consequent compaction of soil mass (**Figures 7A, E**) and different rates of gleyzation and carbonatization processes manifested by the formation of numerous dendroid ferromanganese pedofeatures (**Figure 7H**) and carbonate coatings (**Figure 7F**).



(A)



(B)



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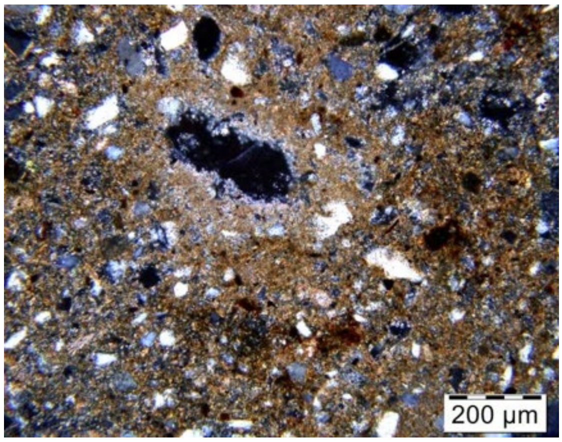
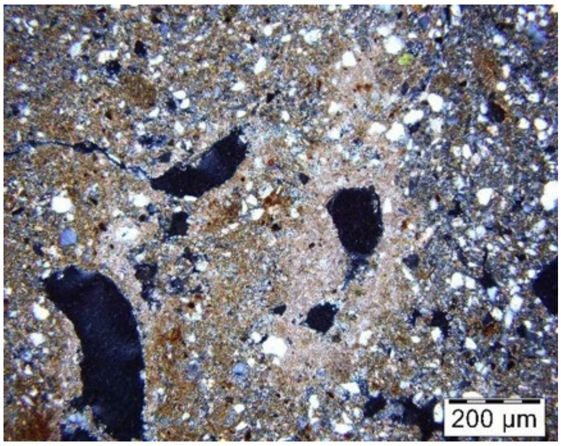
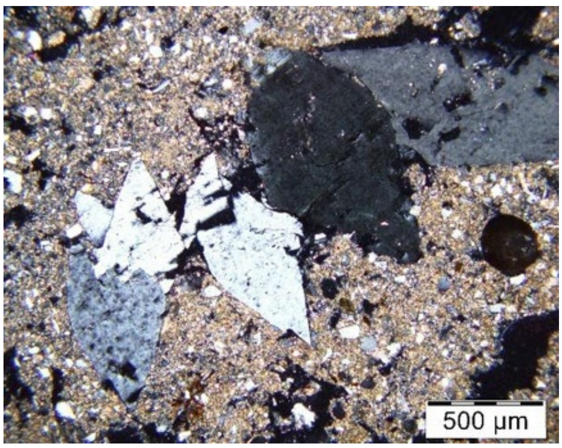


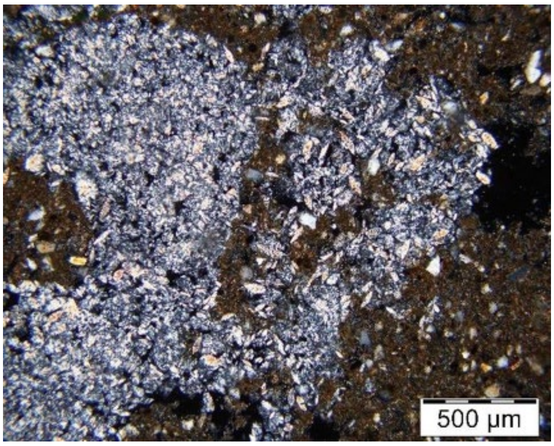
(E)



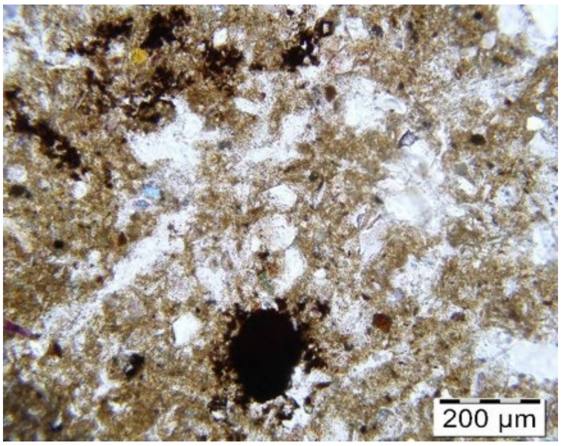
(F)



(G)



(D)



(H)

Figure 7. Soil fabric of salt-affected illuvial and saline horizons of the Solonetz (2002: A-D; 2013: E-H): A – a loose cloddy-crumbly clayey-calcareous material (BCk,y,z; 50-55 cm) (PPL); B gypsum coating on the wall of a biopore (BCk,y,z; 50-55 cm) (XPL); C – dense infilling of small gypsum crystals and intergrown large lenticular gypsum crystals, which loosen the soil material in the course of their growth (BCy,z1; 65-100 cm) (XPL); D – dense infilling of small tabular gypsum crystals (141-160 cm) (XPL); E – a compacted clayey-calcareous material with small ferruginous mottles and patterns and a micrite coating around an oval-shaped pore (BCk,y,z; 50-55 cm) (XPL); F – a strongly compacted silty-clayey-calcareous material with micrite coatings and small Fe-Mn concentrations of various types (BCk,y,z; 50–55 cm) (XPL): G – an intergrowth of large rhomboidal gypsum crystals (141-160 cm) (XPL); H – dendroidal Fe-Mn pedofeatures in a silty-clayey-calcareous material (141-160 cm) (PPL).

3.4. Temporal changes in micromorphological characteristics of Solonetzs in 1950s-1982

The comparison of the thin sections given at the published works (Polskii 1958; Yarilova 1966; Bazykina 1978) with the ones sampled at 1982 showed their similarity in terms of structure, type of porosity, the content of finely dispersed matter, b-fabrics and pedofeatures. Thus, in the hor. E of Solonetzs sampled in 1950s-1982, the low content of finely dispersed clay-organic matter, platy structure and the presence of minute plant residues can be observed (**Figures 8A, B**). In the subsolonetzic (salic) horizon Bk,y,z, high porosity and the predominance of loess aggregates (50-100 µm) forming the loose coarser soil aggregates (about 500 µm) are observed (**Figures 8C, D**). As was mentioned above, in the Solonetzs of 2002 and 2013, the content of organic matter and plant residues in the topsoil is much higher and the significant compaction of subsolonetzic (salic) horizons due to the decrease of inter-aggregate porosity is observed.

Therefore, it can be concluded, the main changes in soil micromorphological features took place during the last decades. The trends of soil-forming processes identified from changes in macro- and microstructure of the virgin Solonetz over the past 11 years (2002-2013) followed a generally similar direction as those of the previous 20 years (1982 – 2002). In general, changes within the last 30 years of the Solonetz evolution were connected with the recent changes in soil-forming factors – raised groundwater table and increased amount of rainfall during spring-summer seasons in the north of the Caspian Lowland (Sapanov and Sizemskaya 2016). The recorded changes in macro- and micromorphological features over the last 11 years were different at different depths within the profile of the Solonetz studied. In the eluvial horizons, most prominent features resulted from increased rates of humus accumulation accompanied by biogenic and cryogenic structuring and eluviation of finely dispersed clayey-organic particles. In different parts of the solonetzic horizons (with macrofeatures of strong solodization in the upper part and salinization in the lower part), specific solonetzic structures and illuvial clay coatings underwent degradation due to strengthening of the following processes: swelling and shrinking of silt-clay material accompanied by an active assimilation of fresh clay coatings into the intraped mass as well as a deeper biogenic transformation of humic substances.

Leaching of soluble salts from the saline (subsolonetzic) horizon was caused mostly by the atmospheric water flow through the main chan-

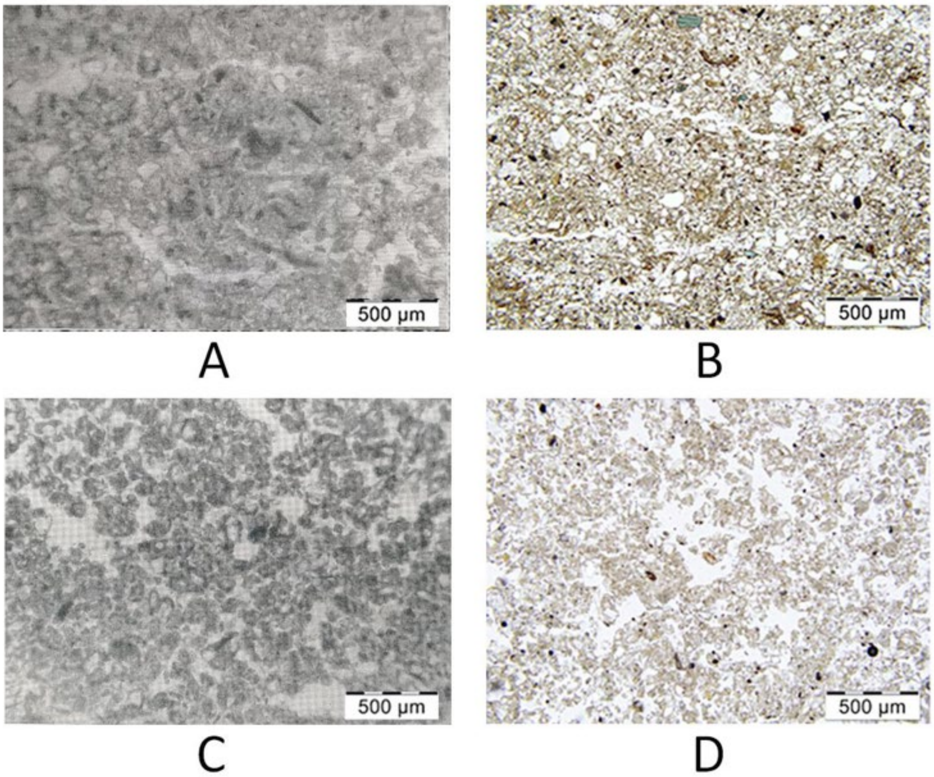


Figure 8. Similar elements of microfabrics of the Solonetz horizons in 1958 (A and C) and 1982 (B and D). Horizons: A, B - Albic (E) (0-7 cm) platy aggregates, low content of finely dispersed clay-organic matter, separate minute fragments of plant tissues. C, D - BCk,y,z horizon (33-57 cm) coarser (about 500 µm) silty-clay-carbonate aggregates consisting of loosely packed loess aggregates (50-100 µm).

nel pores of this horizon as well as by the raised groundwater seeping up through the capillary fringe in the period from 1982 to 2002. This was likely to be the cause of the decomposition and merging of pseudosandy peds and compaction of fine silty-calcareous material observed particularly clearly at a micro-scale. An increase in numbers of dead roots and channel pores within the compacted subsolonetzic horizon resulted in the appearance of labile forms of gypsum (just under the solonetzic horizon) and carbonates (in the lower part of the saline horizon). The abundance of Fe-Mn accumulations around channel pores, which appeared mostly during the last 11 years, could serve as a microfeature of the longer period of moistening of the deep horizons of the Solonetz studied. These ferromanganese accumulations were specific for soils and, therefore, could be considered as pedofeatures related to increased rates of gleyzation due to the observed raised groundwater table.

4. Conclusions

The changes observed in the microfabric of the Solonetz studied serve as a basis for identifying the trends of pedogenic processes related to the recent increase in precipitation and rise of the groundwater table. These trends over the period of two decades include an acceleration of the following pedogenic processes: humus formation, biogenic structuring, eluviation of silty-clay-humus substances, solodization, gleyization and accumulation of a large amount of plant roots, including humified dead roots. There is also a re-organization of clay coatings with their inclusion into the intraped mass observed within the solonetzic B horizons of the studied soils. The compaction of pseudosandy salt-bearing mass, the accumulation of fine-grained calcite (micrite) and a decrease in the amount of gypsum crystals in pores occurred within the subsolonetzic horizons. The identified changes in soil micromorphology were concordant with changes in soil-forming factors recorded within the last decades.

5. Acknowledgements

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REFERENCIAS

- Alexander EB, Nettleton WD. 1977. Post-Mazama Natrargids in Dixie Valley, Nevada. Soil Sci Soc Am J. 41:1210-1212.
- Bazykina GS. 1978. The change in agrophysical properties of solonchakous Solonetzes in the northern Caspian Lowland due to amelioration. In: Kovda VA, editor. Issues of Soil Hydrology and Genesis. Moscow: Nauka. p. 5-31.
- FAO. 2006. Guidelines for Soil Description. Rome: Food and Agriculture Organization of the United Nations. 97 p.
- Fedoroff N, Courty MA. 1986. Micromorphology of natric horizons. In: Transactions of the 13th Congress International Society Soil Science, vol. 5. p. 1551-1552.
- Field Guide to Soils of Russia. 2008. Moscow: V.V. Dokuchaev Soil Science Institute. 182 p.
- Gerasimova MI, Gubin SV, Shoba SA. 1996. Soils of Russia and adjacent countries: Geography and micromorphology. Wageningen: Van Gils Graphic Centre. 204 p.
- IUSS Working Group WRB. 2015. World Reference Base for Soil Resources 2014, update 2015. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. Rome: FAO.
- Ivanova EN, editor. 1964. Soils of the Complex Northern Caspian Plain and their Characteristics for Reclamation purposes. Moscow: Nauka. 292 p.
- Konyushkova MV. 2014. Digital Soil Mapping of Solonetzic Regions in the Northern Caspian Lowland. Moscow: KMK Scientific Press. 316 p.
- Kühn P, Aguilar J, Miedema R. 2010. Textural features and their related horizons. In: Stoops G, Marcelino V, Mees F, editors. Micromorphological Features of Soils and Regoliths. Their Relevance for Pedogenic Studies and Classifications. Amsterdam: Elsevier. p. 217-250.
- Lebedeva (Verba) MP, Gerasimova MI. 2009. Macro- and micromorphological features of genetic horizons in a Solonetzic soil complex at the Dzanybek Research Station. Eurasian Soil Science 42(3):239-252.
- Lebedeva (Verba) MP, Gerasimova MI, Konyushkova MV. 2009. Micromorphology of Solonetzic horizons as related to environmental events in the Caspian Lowland. Journal of Mountain Science 6(2):132-138.
- Lebedeva MP, Konyushkova MV. 2010. Changes in micromorphological features of semidesert soils in the southeast of European Russia upon the recent increase in climate moistening [conference presentation on the internet]. In: Proceedings of the 19th World Congress of

Soil Science. Soil Solutions for a Changing World; 2010 Aug 1-6; Brisbane, Australia. p. 12-15. Available from: http://iuss.org/19th WCSS/Symposium/pdf/1202.pdf.

• Lebedeva MP, Konyushkova MV. 2011. Temporal changes in the microfabric of virgin and reclaimed Solonetzs at the Dzhanybek Reseach Station. Eurasian Soil Sci. 44(7):753-765.

• Lebedeva (Verba) MP, Sizemskaya ML. 2011. Analysis of the microfabrics of reclaimed Solonetzs at the Dzhanybek research station for evaluation of their ecological status. Biology Bulletin 38(10):1001-1007.

• Oliveira LB, Ferreira MGVX, Marques AF. 2004a. Characterization and classification of two soils derived from basic rocks in Pernambuco State Coast, northeast Brazil. Scientia Agricola 61:615-625.

• Oliveira LB, Ribeiro MR, Ferraz FB, Ferreira MGVX, Mermut AR. 2004b. Mineralogia, Micromorfologia e Gênese de Solos Planossólicos do Sertao do Araripe, Estado de Pernambuco. Revista Brasileira de Ciência Solo 28:665-678.

• Pol'sky MN. 1958. Agrophysical properties of solonchakous Solonetzes as the target of amelioration. The Proceedings of the Forest Institute of AS USSR. Scientific Bases for Land Improvement in Semideserts of Northwestern Caspian Lowland 38:58-73.

• Rode AA. 1974. Biogeocenotic basics for the land management of the Northern Caspian semidesert. Moscow: Nauka. 360 p.

• Rode AA. 1976. The Principles of Organization and the Methods of the Stationary Soil Study. Moscow: Nauka. 412 p.

• Rode AA, Pol'sky MN. 1961. The soils of the Dzhanybek research station, their morphology, particle-size distribution, chemical and physical properties. Proceedings of V.V. Dokuchaev Soil Science Institute 56:3-214.

• Rode AA, Pol'sky MN. 1963. The water regime and balance in the virgin soils of semidesert complex. In: Tyurin IV, editor. The Water Regime of Semidesert Soils. Moscow: Izdatelstvo Akademii Nauk SSSR. p. 5-83.

• Sapanov MK. 2007. Synchronism of changes of Caspian sea level and ground waters in northern near-Caspian sea area at the second part of the XX Century. Izvestiya RAN. Geographical Series 5:82-87.

• Sapanov MK, Sizemskaya ML. 2016. Climate changes and virgin vegetation dynamics in the Northern Caspian lowland. Biol. Bull. 43(10):1393-1400.

• Sotneva NI. 2004. The dynamics of climatic conditions at the Dzhanybek Research Station in the northern Caspian Lowland in the second half of the XXth century. Izvestiya RAN. Geographical Series 5:74-83.

• Stoops G. 2003. Guidelines for analysis and description of soil and regolith thin section. Madison, Wisconsin: Soil Science Society of America. 184 p.

• Titkova TB. 2003. Climate changes of Near-Caspian and Tyrgaya semideserts in the XX Century. Izvestiya RAN. Geographical Series 1:106-112.

• Verba MP, Yamnova IA. 1997. Gypsum neoformation in non–irrigated and irrigated soils of the serozem zone. In: Shoba SA, Gerasimova MI, Miedema R, editors. Proceedings of X International Workshop Meeting on Micromorphology. Soil Micromorphology: Studies on Soil Diversity, Diagnostics, Dynamics. Moscow, Wageningen. p. 187-195.

• Vorob'eva LA. 2006. The Theory and Practice in Chemical Analysis of Soils. Moscow: GEOS. 400 p.

• Yarilova EA. 1966. The peculiarities of micromorphological features of Solonetzes in the chernozemic and chestnut zones. In: Zonn SV, editor. The Micromorphological Method in the Research into Soil Genesis. Moscow: Nauka. p. 58-75.