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GENESIS AND GEOGRAPHY OF SOILS

Properties of Solonetzes on Terraces of Salt Lakes Bulukhta and Khaki in the Caspian Lowland

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Abstract—A comparative assessment of pedogenetic processes in solonetzes (Calcic Gypsic Salic Solonetzes (Siltic, Albic, Cutanic, Differentic)) developing on terraces of lake depressions within the Volga–Ural interfluve of the Caspian Lowland has been performed on the basis of data on their macro- and micromorphological features and chemical, physicochemical, and physical properties. The studied soils have number of common characteristics shaped by the humus-accumulative, solonetzic, eluvial–illuvial, calcification, and gypsification processes. However, it is shown that macro- and micromorphological indicators of solonetzic processes (the development of clay–humus coatings and the character of structural units in the solonetzic (B) horizon) do not always agree with the modern physicochemical conditions of the development of this process. This is explained by differences in the degree and chemistry of the soil salinization and the depth and salinity of the groundwater. Solonetzes developing on the second terrace of Playa Khaki are distinguished by the highest water content and maximum thickness of the horizons depleted of soluble salts. They are characterized by the well-pronounced humus-accumulative process leading to the development of the light-humus (AJ) horizon. In other solonetzes, the accumulation of humus is weaker, and their topsoil part can be diagnosed as the solonetzic-eluvial (SEL) horizon. Active solodic process and illuviation of organomineral substances with the development of thick coatings and infillings in the B horizon are also typical of solonetzes on the second terrace of Playa Khaki. Micromorphological data indicate that, at present, layered clayey coatings in these soils are subjected to destruction and in situ humification owing to the active penetration of plant roots into the coatings with their further biogenic processing by the soil microfauna. The process of gleyzation (as judged from the number of Fe–Mn concentrations) is most active in solonetzes developing on the first terrace of Playa Khaki. These soils are also characterized by the highest degree of salinization with participation of toxic salts. The maximum accumulation of gypsum is typical of the heavy-textured horizons.

Keywords: genesis, solonetzes, solonetzic process, micro- and macromorphological properties, comparative analysis

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INTRODUCTION

The soil cover of the Volga–Ural interfluve within the Caspian Lowland has a long history of studies. Many characteristic soil properties in this region are clearly described in literature [3–5, 13–17, 29, 31]. The territory of the Dzhanybek Research Station of the Institute of Forestry of the Russian Academy of Sciences is one of the best studied areas in this region [9, 18–23, 26–28, 30, 34, 35, 40]. However, information on the soil cover of lake depressions within the Volga–Ural interfluve is relatively scarce. There are few works describing the chemical composition of soils, parent materials, and groundwater of different terraces of these lakes [1, 8, 17, 38, 39, 41]. Data on the microfabric of soils developing on terraces of numerous closed depressions within the Volga–Ural interfluve are absent.

There are many studies devoted to the particular properties and genesis of solonetzes [42–45, 47–50]. However, a comparative analysis of the properties and geneses of solonetzes developing on terraces of different ages, hypsometric levels, groundwater levels, and microtopographic features has not been performed. There are virtually no works, in which the morphologies of solonetzes at different levels of their organization are studied in relation to the chemical, physical, and physicochemical properties of these soils and to the physicochemical conditions for the development of solonetzic process.

The aim of our work was to compare the genetic features of solonetzes developing on different terraces of Bulukhta and Khaki lake depressions.

OBJECTS AND METHODS

Lakes Bulukhta and Khaki represent relict drying water bodies formed in the erosional depressions within the Caspian Lowland. Their geomorphological history is somewhat different: Lake Bulukhta was formed during the Early Khvalyn Transgression of the Caspian Sea, whereas Playa Khaki was formed during the Late Khvalyn period. According to the geomorphological division of the Caspian Lowland [10], they belong to different geomorphological regions: the northwestern endorheic Early Khvalyn plain with clearly pronounced microdepressions (Lake Bulukhta) and the Batkul–Khaki depression composed of the Late Khvalyn and Holocene sediments of the marine and lacustrine origins.

Lake Bulukhta is found in the west of the Volga–Ural interfluve (Fig. 1). It is ellipse-shaped, with the long axis stretching from the northwest to the southeast. The length of the lake is 12.4 km; its width is 6.7 km; and its area is 77 km^2. The lake is filled with water immediately after the snowmelt season. By the beginning of summer, its larger part is dried and represents a wet solonchak with some water bodies inside. Three terrace levels are distinguished in the basin of Lake Bulukhta. The first terrace is composed of layered clayey and sandy deposits and has an absolute height of 15–17.5 m a.s.l. The second terrace is found at the heights of 20–21 m a.s.l. The surface of the terraces is complicated by numerous microlows [17].

The hydrochemical regime of the territory is characterized by considerable variations: during the snowmelt season, the water of the lake is subjected to desalination. The water salinity varies from 19 to 200‰. The major component of dissolved salts is NaCl; it is followed by Na_2SO_4. The portions of $MgSO_4$ and $CaSO_4$ in the chemical composition of lake water are significant [32].

Playa Khaki is found in the central part of the Volga–Ural interfluve. At present, it represents the final stage of lake drying under arid climatic conditions: the stage of salt mud periodically covered with a thin layer of strongly saline water. Playa Khaki is one of the largest playa solonchaks of the world with a total area of more than 1000 km^2. Its length is about 80 km; its width varies from 15 to 25 km; and the depth of the lake depression filled with salt mud reaches 15 m [8].

The surface of the lake is covered with a thin (0.3–3 cm) salt crust underlain by saline clay. A thin layer of brine appears on the surface in spring; in summer, it only remains in microdepressions [8]. Sodium and magnesium chlorides are the major dissolved salts [11].

The shoreline of Playa Khaki is sinuous. The first terrace is clearly elevated above the main surface in the west [1]. In the east, only some fragments of this terrace are pronounced. The absolute height of this terrace is within –7 to –10 m (below sea level). The second terrace is better expressed and, in some places, directly borders the playa forming steep slopes. Its absolute height is –5(6) to 0 m a.s.l. The 0-m contour line serves as the boundary of the depression of Playa Khaki and its two terraces. The third terrace is distinguished at absolute heights of 0–10 m a.s.l. It extends to about 30–45 km from the playa. To the east, it borders the Urda Sands [17].

Three soil profiles located on the first and second terraces of Playa Khaki and on the second terrace of Lake Bulukhta were examined. The age of the first terrace of Playa Khaki is estimated at 10.5 ka [37]. The groundwater table is found at the depth of 1.6 m. The surface is virtually flat with some zoogenic (casts of susliks) microhighs. The soil cover is relatively homogeneous and consists of light-humus solonchakous quasigleyed solonetzes (Calcic Gypsic Salic Solonetzes (Siltic, Albic, Cutanic, Differentic, Oxyaquic,)) under saltbush–wormwood vegetation [39].

The age of the second terrace of Playa Khaki is estimated at 11 ka [37]. The groundwater table is found deeper (2.2 m), and the microtopography is more pronounced with distinct microhighs (up to 8 m in diameter) and shallow open microlows. The soil cover is represented by the complex of predominating light-humus solonchakous solonetzes (Calcic Gypsic Salic Solonetzes (Siltic, Albic, Cutanic, Differentic)) under wormwood and light chestnut soils of the microlows under grassy vegetation [38].

The age of the second terrace of Lake Bulukhta is about 16 ka [37]. The groundwater level is at the depth of 4 m. The terraces of Lake Bulukhta are characterized by distinct microtopography with well-shaped deep microlows. The soil cover is represented by the predominating solonchakous solonetzes (Calcic Gypsic Salic Solonetzes (Siltic, Albic, Cutanic, Differentic)) and light chestnut soils in combination with meadow chestnut soils in the microlows.

The parent materials at the three studies sites are represented by the layered lacustrine deposits.

In the field, we studied the morphology and horizonation of the soils; undisturbed soil samples for micromorphological studies were collected from the major genetic horizons. Thin sections were prepared by M.A. Lebedev in the Laboratory of Mineralogy and Micromorphology of Soils of the Dokuchaev Soil Science Institute with the use of polysynthetic resins and vacuum soil impregnation, which made it possible to preserve intact salt concentrations for their microscopic study. Micromorphological features were described in agreement with the international handbook [46].

Boreholes down to the groundwater were drilled near the soil pits. The soil water content was measured by the gravimetric method in 10-cm-deep soil layers down to the groundwater level [25]. The analysis of soil water extracts was additionally performed din auger samples taken on terraces of Playa Khaki. In the soil of Lake Bulukhta terrace, all the analysis were performed in the samples taken from the studied pit. We determined the contents of soil organic carbon, gypsum, and

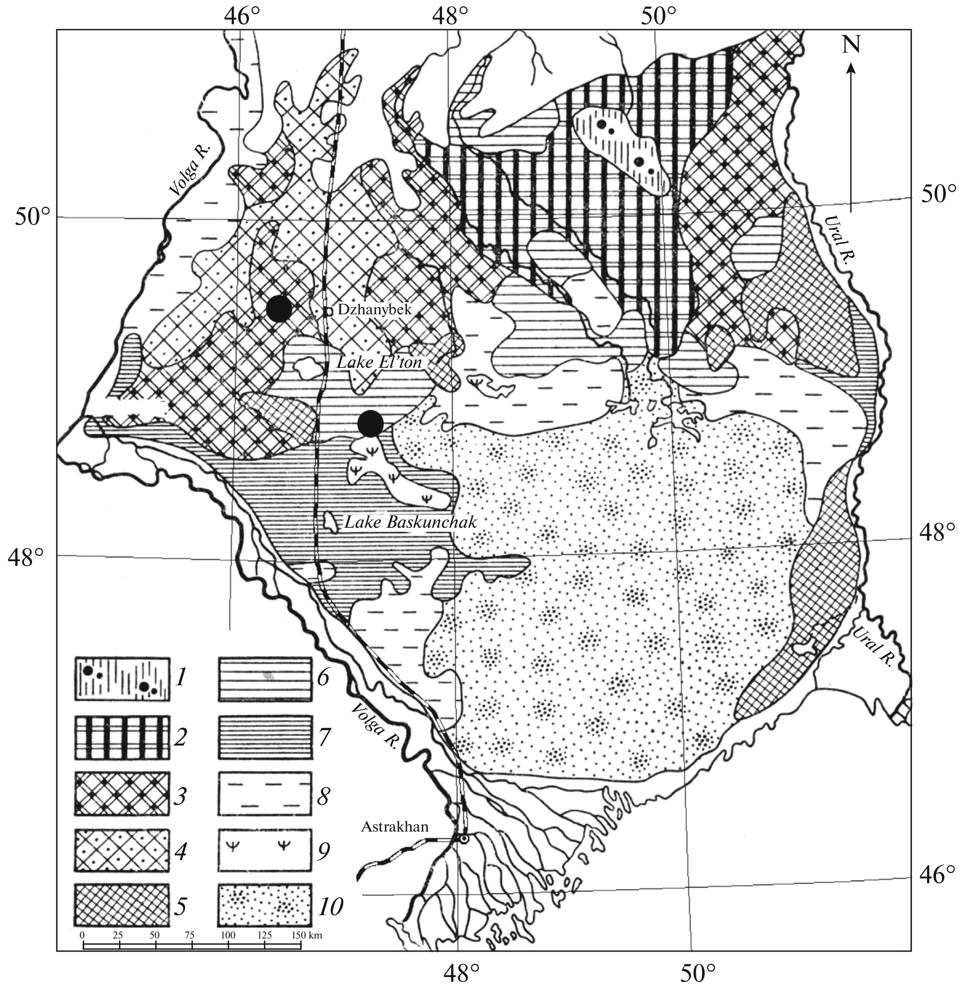

Fig. 1. Distribution of the types of solonetzic soil complexes within the Volga–Ural interfluve (according to [4]): (*1*) meadow complexes, (*2*) meadow-steppe complexes with flat-bottomed microdepressions, (*3*) meadow-steppe complexes with microlows and microhighs, (*4*) steppe to meadow-steppe complexes with a smoothed microtopography, (*5*) meadow-steppe complexes without distinct microtopography, (*6*) typical steppe complexes, (*7*) paleohydrogenic steppe complexes, (*8*) areas without soil complexes, (*9*) solonchaks, and (*10*) sands. Black circles indicate studied sites.

carbonates; the pH of soil water extracts (1 : 2.5); the composition of exchangeable cations; and the composition of soil water extracts (1 : 5). The total content of dissolved solids and the composition of salts were also determined in the groundwater samples.

The analyses of the groundwater and water extracts from soils were performed by routine methods [2, 6], except for the concentration of SO_4^{2-} ions in the water extracts, which was determined by the Komarovskii method [7]. Exchangeable cations were determined by the Pfeffer method in modification by Molodtsov and Ignatova [6]. The content of carbonates was determined by the acidimetric method according to Kozlovskki; and the total content of sulfate ions was determined by the gravimetric method according to Khitrov [36]. The organic carbon content was determined by the wet combustion method of Tyurin. The soil salinity was estimated using criteria suggested in the monograph of salt-affected soils of Russia [12]. The field guide for soil correlation was used to determine the classification position of studied soils and the symbols used in designation of genetic horizons [24].

RESULTS AND DISCUSSION

Soil morphology. All the studied soils were classified as solonetzes: a light medium-deep solonchakous quasigleyed solonetz was described on the first terrace of Playa Khaki; a light-humus medium deep solonchakous solonetz, on the second terrace of Playa Khaki; and a light shallow solonchakous solonetz, on the second terrace of Lake Bulukhta. The thickness of soil horizons above the solonetzic horizon was approximately the same: 10–12 cm on the terraces of Playa Khaki and 8–10 cm on the terrace of Lake Bulukhta. Thus, according to this criterion (depth of the upper

Table 1. Morphological properties of solonetzes on terraces of Lake Bulukhta and Playa Khaki

Characteristic	Playa Khaki		Lake Bulukhta
Location	First terrace	Second terrace	Second terrace
Soil	Light medium-deep solonchakous quasigleyed solonetz	Light-humus medium-deep solonchakous solonetz	Light shallow solonchakous solonetz
Suprasolonetzic horizon			
Depth, cm	SEL 0–11(12)	AJ 0–6/SEL 6–10(12)	SEL 0–8 (10)
Color	Pale yellow	Light gray to pale yellow	Light pale yellow
Structure	Thin platy	Platy to very thin platy	Loose crumble–platy
Texture	Silty loamy sand	Silty–sandy loam	Silty sandy loam
Pedofeatures	Iron and manganic punctuations	Biotubules	Absent
Solonetzic BSN horizon			
Depth/thickness, cm	11(12)–18/7(6)	10(12)–20/10(8)	8(10)–23/15(13)
Color	Dark reddish brown	Reddish brown	Brownish red-brown
Structure	Angular blocky to fine prismatic	Columnar	Coarse prismatic
Texture	Sandy–clayey heavy loam	Sandy–clayey heavy loam	Sandy–clayey heavy loam
Pedofeatures	Thick clay–humus coatings	Thick chocolate-colored coatings	Glossy coatings on ped faces
Solonetzic BSNdc horizon			
Depth, cm	18–28	20–25(27)	23–32
Color	Dark brown mottles against the background brown color	Light brown	Reddish brown
Structure	Prismatic	Fine to coarse crumbly	Prismatic
Texture	Sandy–clayey heavy loam	Coarse silty–clayey heavy loam	Sandy–clayey heavy loam
Pedofeatures	Fragmentary thin chocolate-colored coatings	Thick chocolate-colored coatings	Absent
Depth of effervescence, cm	18	20	26
Subsolonetzic BCA horizon			
Depth, cm	28–35	25(27)–57	32–55
Color	Heterogeneous, with pale mottles against the brown background color	Brown	Yellowish brown
Structure	Crumble to coarse blocky	Weakly aggregated	Loose coarse blocky
Texture	Clayey–sandy heavy loam	Clayey–coarse silty heavy loam	Silty–sandy heavy loam
Pedofeatures	Single coatings; small salt concentrations	Abundant salt efflorescence (mottles, veins)	Whitish veins of salts; concentrations of dispersed carbonates in the form of whitish yellow mottles of 5 mm in diameter
Subsolonetzic BCAcs horizon			
Depth, cm	37–70	57–66	
Color	Brown	Light brown	
Structure	Coarse blocky	Structureless	
Texture	Sandy–silty loam	Sandy–silty loam	
Pedofeatures	Abundant salt veins and punctuations	Salt concentrations and veins in a smaller amount that in the overlying layer	

Table 1. (Contd.)

Characteristic	Playa Khaki		Lake Bulukhta
Horizon	Transitional BCs horizon		
Depth, cm	70–105	66–80	55–80
Color	Brown with olive tint	Brown	Brownish yellow
Structure	Structureless	Structureless	Loose blocky
Texture	Coarse silty heavy loam	Silty–sandy loam	Clayey–sandy heavy loam
Pedofeatures	Few salt concentrations	Salt punctuations and veins	Whitish salt veins concentrated in "nests" of 3–5 cm in diameter
	Parent material (Cs horizon)		
Depth, cm	105–...	80–100	80–100
Color	Yellowish brown	Brownish red-brown	Pale yellow
Structure	Structureless	Structureless	Crumble
Texture	Sandy (field determination)	Sandy light loam	Fine sandy loamy sand
Pedofeatures	Absent	Salts in the form of punctuations and veins	Gypsum veins

boundary of solonetzic horizon), all of them belong to the medium-deep (10–12 cm) or shallow (8–10 cm) species of solonetzes [24].

However, a detailed study of soil morphology showed a number of significant differences between the soil profiles.

The topsoil horizons are characterized by the platy structure, light color, and relatively coarse texture (Fig. 2, Table 1). Some difference in the color may be due to the difference in the thickness of clayey coatings on the surface of sand and silt particles.

On the first terrace of Playa Khaki, these horizons are characterized by the coarsest texture, which may be related to the eolian transfer of sand particles from the adjacent massif of Urda sands. In this soil profile, evident features of hydromorphism were described: Fe

I II III

(a) (b) (c)

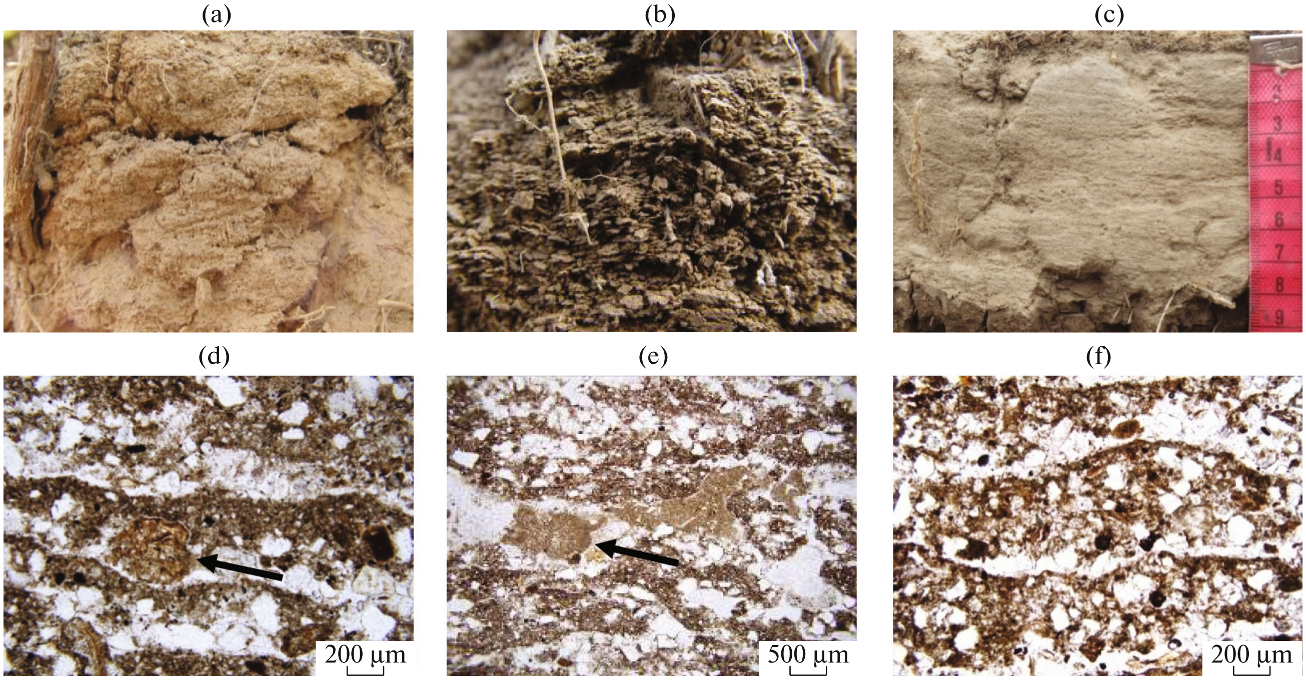

Fig. 2. Meso- and microfabrics of suprasolonetzic horizons (II N): I—first terrace of Playa Khaki; II—second terrace of Playa Khaki; III—second terrace of Lake Bulukhta; Structure of suprasolonetzic horizons: (a) loose platy, (b) thin platy, and (c) crumble–platy; (d, e) biogenic infillings (microbiota activity) between fine silty and sandy interlayers; and (f) thin platy aggregates coated by films.

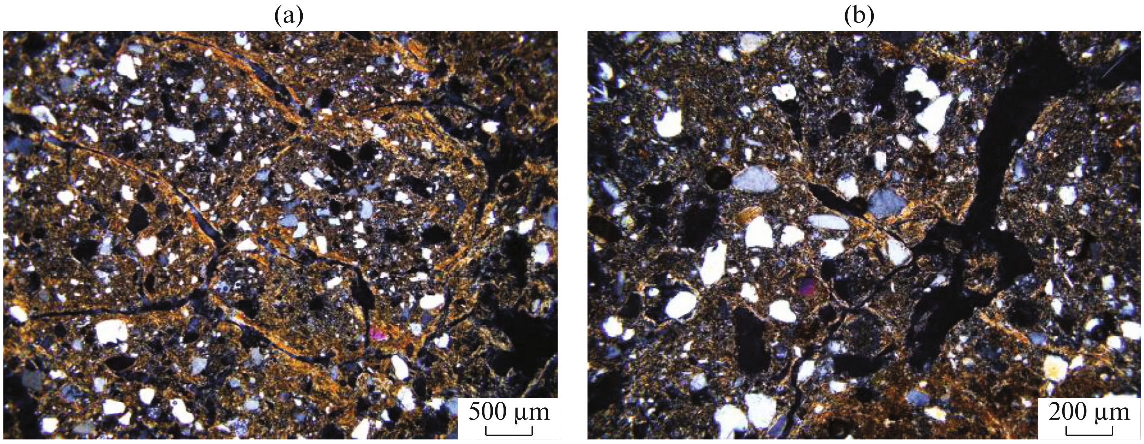

Fig. 3. Micromorphological diversity of clayey coatings in the solonetzic horizons (XN): (a) thin continuous coatings on ped faces of the solonetz on the first terrace of Playa Khaki, (b) thin fragmentary clayey coatings in intraped voids of the solonetz in the second terrace of Lake Bulukhta.

and Mn concentrations at the boundary between the topsoil and the solonetzic horizon and the olive color of the transitional BC horizon. In the solonetz on the second terrace of Playa Khaki, a thin light-humus AJ horizon is clearly shaped under a relatively rich vegetation cover. We suppose that a higher projection cover of vegetation at this site is related to the leaching of salts from the topmost horizons of the solonetz on the second terrace of Playa Khaki.

The topsoil horizons of both solonetzes described on the terraces of Playa Khaki are characterized by the clear differentiation of clayey and sandy material at the microlevel (Figs. 2d and 2e). In the solonetz on the second terrace of Lake Bulukhta, the differentiation between fine silty and sandy interlayers is less distinct (Fig. 2f).

The differences in morphology of the solonetzic horizons are seen in their color, structure, and depth. The maximum thickness of the solonetzic horizon was found in the solonetz on the second terrace of Lake Bulukhta, whereas the minimum thickness of this horizon was observed in the solonetz on the first terrace of Playa Khaki. The solonetz on the second terrace of Playa Khaki occupied a transitional position.

In the solonetz on the first terrace of Playa Khaki, the solonetzic BSN horizon had an angular blocky to small prismatic structure; in the underlying BSNdc horizon, a prismatic structure was developed. In the solonetz on the second terrace of Playa Khaki, the BSN horizon has a columnar structure with rounded solodized column heads. The BSN horizon of the solonetz on the second terrace of Lake Bulukhta had a coarse prismatic structure.

The major differences between the compared solonetzic horizons are seen in the color and thickness of coatings. In the solonetzes on terraces of Playa Khaki, clay–humus gray-brown coatings on ped faces have a considerable thickness and clearly differ in their color from the intraped mass. These horizons are also characterized by silty infillings in the pores. The migration of clay and silt with the formation of coatings and infillings is clearly seen in thin sections (Fig. 3a). In the solonetz on the second terrace of Lake Bulukhta, the coatings in the BSN horizon are thinner and are fragmentarily distributed on ped faces (Fig. 3b).

The underlying solonetzic horizons with carbonate concentrations (BSNdc) in the studied soils have a somewhat lighter (light brown) color and clearly effervesce with HCl. The structure is less distinct, and the illuviation clayey coatings are less pronounced. In the solonetzes on terraces of Playa Khaki, some chocolate-colored coatings can be found in the BSNdc horizon, but their amount is smaller than that in the BSN horizon. In the solonetz on the second terrace of Lake Bulukhta, illuviation coatings in the BSNdc horizon are absent.

The subsolonetzic horizons of the studies soils are generally similar in their morphological characteristics. These are poorly structured horizons with loose coarse blocky structure, yellow-brown color, and abundant salt concentrations in the form of punctuations, filaments, threads, etc.

Physical properties. The compared solonetzes are characterized by the eluvial–illuvial distribution pattern of clay; their textural characteristics are similar and are characterized by the predominance of fine sand, coarse silt, and clay fractions (Fig. 4). Solonetzes on the terraces of Playa Khaki are richer in coarse and medium sand particles, which may be related to the eolian input of sand from the Urda sand massif.

At the depth of about 1 m, the soil texture becomes coarser in all the three pits. This attests to the inhomogeneity of the parent materials represented by layered lacustrine sediments.

The solonetz on the second terrace of Lake Bulukhta is the driest soil (Fig. 5). The field water con-

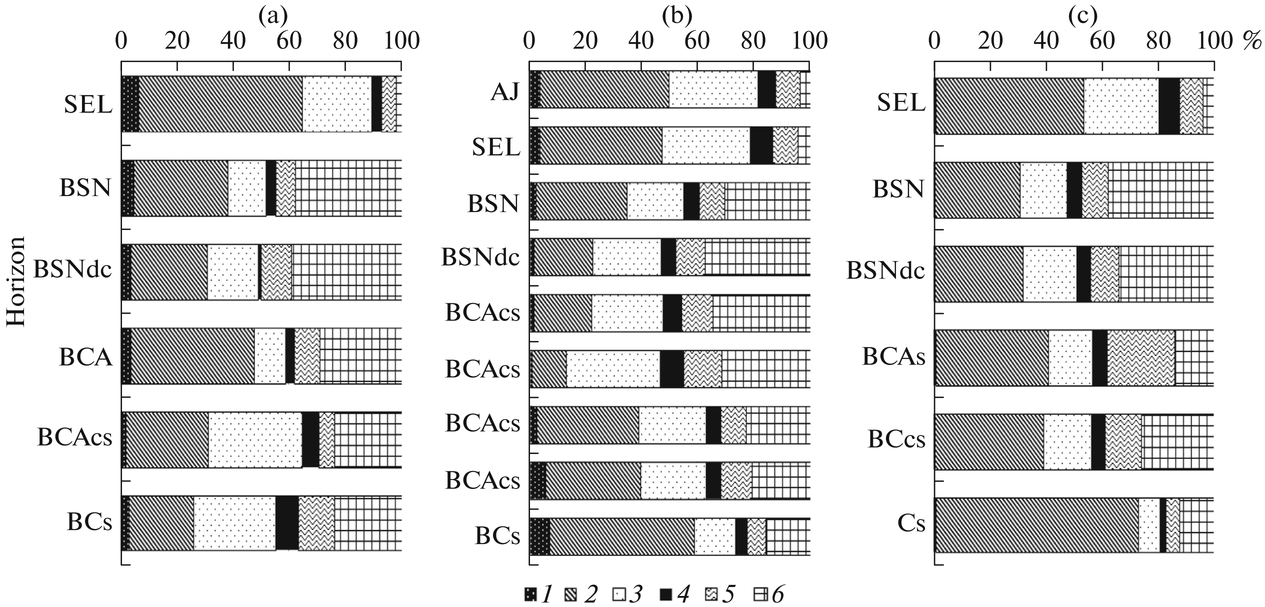

Fig. 4. Particle-size distribution in solonetzes on the first (a) and second (b) terraces of Playa Khaki and on the second (c) terrace of Lake Bulukhta; fraction size (mm): *1*—1.0–0.25, *2*—0.25–0.05, *3*—0.05–0.01, *4*—0.01–0.005, *5*—0.005–0.001, and *6*— <0.001.

tent in solonetzes on the terraces of Playa Khaki was considerably higher, and the water content of the solonetz on the first terrace of this salt lake was higher than that of the solonetz in the second terrace. In the solonetz on the first terrace, the water content above the solonetzic horizon was about 8%; in the solonetzic horizons, it increased up to 16–17%. In the solonetz on the second terrace, the corresponding values were about 4 and 6–8%, respectively. In the deeper horizons, the gravimetric water content sharply increased down the soil profile (up to 17%). At the depth of about 1 m, it decreased in all the soils because of the coarser texture (Fig. 5). Finally, increased values of the water content in the deepest horizons of solonetzes on the terraces of Playa Khaki are related to the shallow position of the groundwater table.

Chemical properties. The solonetz on the first terrace of Playa Khaki is the most saline of the studied soils. Salts are only absent in the above-solonetzic (solonetz-eluvial SEL) horizon; the solonetzic horizons are strongly saline with a predominance of sodium chlorides (Fig. 6a). The maximum salinization is reached in the underlying horizons: the sum of toxic salts is 1.52%. The chemistry of salts changes: sulfates and chlorides of calcium and magnesium predominate; gypsum is present. Below, the degree of salinity gradually decreases to a minimum in the sandy interlayer at the depth of 110–120 cm. The soil salinity gradually increases again in the deeper layers.

The solonetz on the second terrace of Playa Khaki is characterized by the low salinity in the upper 40 cm. In the deeper horizons, the content of soluble salts increases and becomes comparable with that in the solonetz on the second terrace of Lake Bulukhta. The AJ and SEL horizons are nonsaline. The upper solonetzic horizon is slightly saline with a predominance of sodium chlorides (Fig. 6b); in the second solonetzic horizon (BSNdc), the salinity increases to the strong level. In the underlying horizons, sodium sulfates and chlorides predominate; gypsum is present. In the transitional (BC) horizons, the chemistry of salts changes again: they are characterized by the predominance of sodium chlorides. At the depth of about 1 m, the amount of toxic salts decreases to 0.17%, which is related to the coarser texture of the soil. The salinity increases again in the layers deeper than 130 cm; sodium chlorides predominate in the composition of soluble salts in the deep soil layers.

The solonetz developed on the second terrace of Lake Bulukhta is characterized by the predominantly sulfate sodium salinization (Fig. 6c) replaced by the chloride–magnesium salinization in the subsolonetzic horizons. The SEL horizon is slightly saline (in contrast to the nonsaline SEL horizon in the solonetzes on terraces of Playa Khaki). The solonetzic (BSN) horizon is moderately saline. Sodium sulfates predominate in the chemical composition of salts in these horizons. In the BSNdc horizon, the amount of salts increases; they are characterized by a predominance of sodium sulfates and chlorides.

Thus, the solonetzes developing on the terraces of Playa Khaki have the sodium chloride salinization in their solonetzic horizons on the first terrace and the sulfate–chloride sodium salinization on the second terrace. The solonetz on the second terrace of Lake Bulukhta with a deeper groundwater level has the sul-

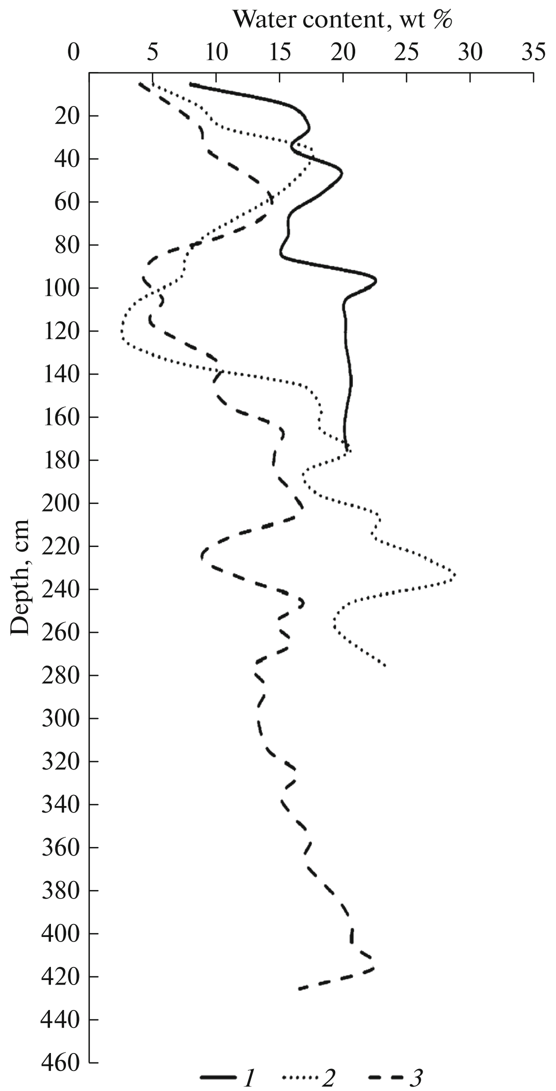

Fig. 5. Water contents in the profiles of solonetzes on the (*1*) first and (*2*) second terraces of Playa Khaki and on the (*3*) second terrace of Lake Bulukhta.

fate sodium salinization typical of the territories with a long period of continental development in the Caspian Lowland [29].

The most active salinization takes place in the solonetz on the first terrace of Playa Khaki. The content of toxic salts in this soil reaches its maximum (Fig. 7). The high degree of salinity is specified by the shallow occurrence of strongly saline groundwater. In the solonetz on the second terrace of Playa Khaki with a deeper groundwater level, the accumulation of salts is less pronounced. In the solonetz on the second terrace of Lake Bulukhta, the amount of toxic salts is smaller. The distribution of soluble salts in the soil profiles is uneven and is characterized by several peaks, which is related to the layered character of parent materials. The concentration of soluble salts decreases in the coarser layers.

The differences in the degree and chemistry of salinization of the compared solonetzes depend on the chemical composition and depth of the groundwater (Table 2). On the first terrace of Playa Khaki, the groundwater is strongly saline (37 g/L) with a predominance of sodium chlorides. On the second terraces of Playa Khaki and Lake Bulukhta, the groundwater salinity reaches 16 and 13 g/L, respectively; magnesium and sodium chlorides predominate in the composition of dissolved salts. Deep position of the groundwater table on the second terrace of Lake Bulukhta specifies its relatively low impact on the soil profile.

The compared soils differ in the composition of exchangeable cations. Magnesium predominates among them in solonetzes on the terraces of Playa Khaki, whereas sodium predominates in the solonetz on the second terrace of Lake Bulukhta (Table 3). The portion of exchangeable magnesium is the highest in the solonetz on the first terrace of Playa Khaki. The predominance of exchangeable magnesium is explained by its stronger sorption in the exchange complex in comparison with sodium. It can be supposed that exchangeable magnesium predominates in the deeper layers of solonetz on the second terrace of Lake Bulukhta. The content of exchangeable sodium reaches its maximum in the solonetzic horizons. According to this criterion, solonetzes of the terraces of Playa Khaki belong to the medium-sodium solonetzes, and solonetz of the second terrace of Lake Bulukhta belongs to the high-sodium solonetzes (Table 3).

The effective cation exchange capacity (ECEC) in topsoil horizons of solonetzes on terraces of Playa Khaki reaches 3.52–4.89 cmol(equiv.)/kg soil; in the solonetz on the second terrace of Lake Bulukhta, it is as high as 9.79 cmol(equiv.)/kg soil. Maximum ECEC values are typical of the solonetzic horizons enriched in clay and in organic matter (Table 4). They reach 12.43–15.03 cmol(equiv.) in the solonetzes on terraces of Playa Khaki and 26.52 cmol(equiv.) in the solonetz on the second terrace of Lake Bulukhta with a heavier texture.

According to other chemical properties, the studied soils do not differ much from one another. Thus, their reaction changes from the slightly alkaline values in the topsoil horizons to alkaline and strongly alkaline values in the solonetzic and subsolonetzic horizons. The content of carbonates reaches 11–16%. The gypsum content in solonetzes on the terraces of Playa Khaki is somewhat higher than that in the solonetz on the second terrace of Lake Bulukhta. The maximum accumulation of carbonates and gypsum takes place in the subsolonetzic horizons. In the parent material, their contents somewhat decrease.

The criteria suggested by Khitrov [33] were used to judge the degree of the development of solonetzic process in the studied soils. The morphological indicators

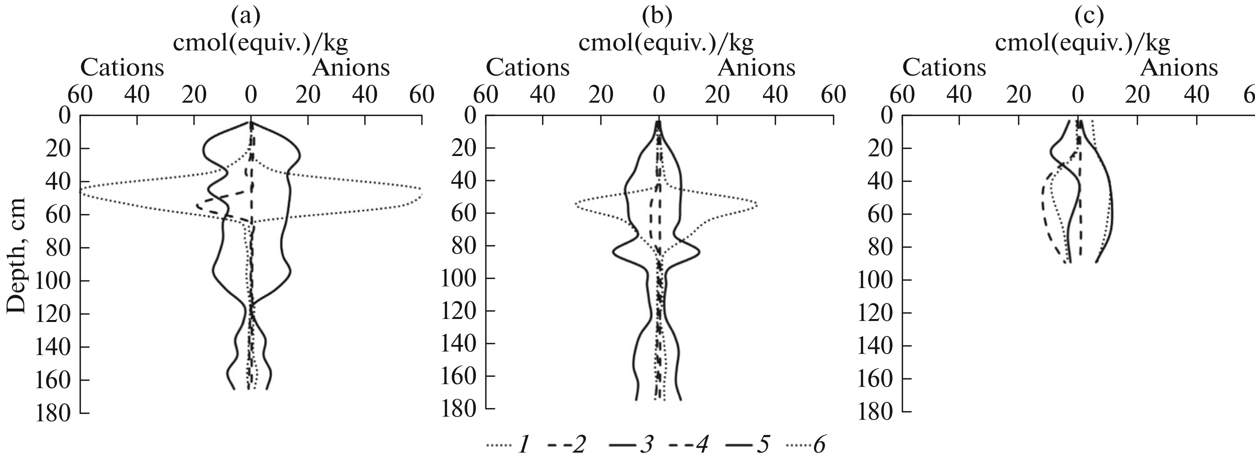

Fig. 6. Salt profiles of solonetzes on the (a) first and (b) second terraces of Playa Khaki and on the (c) second terrace of Lake Bulukhta: *1*—Ca^{2+}, *2*—Mg^{2+}, *3*—Na^{2+}, *4*—HCO_3^-;, *5*—Cl^-, and *6*—SO_4^{2-}.

of the solonetzic process include (a) the prismatic structure of the solonetzic horizon (the height of prismatic peds should exceed their width by more than 1.5–2 times, and the horizontal size of peds should be no more than 8–12 cm) and (b) the presence of humus–clay coatings on lateral sides of peds in the solonetzic horizon. In addition, the physicochemical conditions of the solonetzic process are judged from the B value; it should exceed 0 in the horizon with the morphological criteria of the solonetzic horizon and/or in the overlying horizon. The values of $B < 4$ indicate the low degree of the development of solonetzic process, and the values of $B > 4$ indicate the strong degree of the development of solonetzic process.

As seen from Table 5, the solonetzic process is clearly diagnosed according to its morphological manifestation and physicochemical conditions ($B > 0$) in the solonetz on the second terrace of Playa Khaki. Thus solonetz has a columnar structure in the solonetzic horizon with thick organomineral coatings; the content of toxic salts in it is relatively low, and B value equals 1 in the topsoil horizon and 3 in the solonetzic horizon.

In the solonetz on the first terrace of Playa Khaki, the morphological features (prismatic structure and clay–humus coatings) satisfy the criteria for the active development of solonetzic process. However, the physicochemical conditions in the solonetzic (BSN) horizon do not meet the requirement ($B = 0$). It can be concluded that the modern development of solonetzic process in this soil is hampered by the strong salinization of the solonetzic horizon (Table 5).

In the solonetz on the second terrace of Lake Bulukhta, the morphological and physicochemical properties generally meet the criteria of the active development of solonetzic process, though the clay–humus coatings in the BSN horizon are weakly developed. This may attest to the insufficient soil moistening and, hence, relatively weak illuviation process in this soil; data on the soil water content confirm this conclusion.

In general, the modern physicochemical conditions in the studied soils do not meet the criterion of the active development of solonetzic process ($B < 4$), whereas the morphological manifestation of this process (prismatic or columnar structure of the BSN hori-

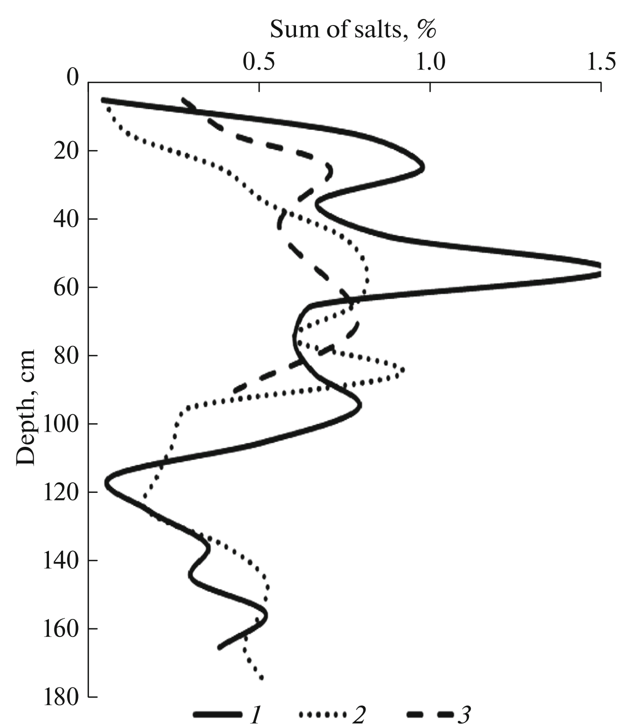

Fig. 7. Distribution of toxic salts in the profiles of solonetzes on the (*1*) first and (*2*) second terraces of Playa Khaki and on the (*3*) second terrace of Lake Bulukhta.

Table 2. Salinity and chemical composition of salts in the groundwater under solonetzes on terraces of Playa Khaki and Lake Bulukhta

Groundwater table, m	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	Na^+	TDS, g/L
	mmol(equiv.)/L							
Light medium-deep solonchakous quasigleyed solonetz (1st terrace of Playa Khaki)								
1.58	12	47.4	435.4	118	58.5	120	434.3	36.97
Light-humus medium-deep solonchakous solonetz (2nd terrace of Playa Khaki)								
2.19	0	3	250.5	47	71	93.5	136	17
Light shallow solonchakous solonetz (2nd terrace of Lake Bulukhta)								
4.5	0.8	4.8	231.6	9	31	97	118	13.47

Table 3. Composition of exchangeable cations in solonetzes on the terraces of Lake Bulukhta and Playa Khaki

Horizon	Depth, cm	Ca^{2+}	Mg^{2+}	Na^+	K^+	Sum	Ca^{2+}	Mg^{2+}	Na^+	K^+
		cmol(equiv.)/kg					%			
Light shallow solonchakous solonetz (2nd terrace of Lake Bulukhta)										
SEL	2–10	5.63	2.67	1	0.49	9.79	58	27	10	5
BSN	12–20	6.82	8.77	10.62	0.31	26.52	26	33	40	1
BSNdc	20–30	6.83	2.48	10.09	0.73	20.13	34	12	50	4
Light medium-deep solonchakous quasigleyed solonetz (1st terrace of Playa Khaki)										
SEL	1.5–12	1	1.07	0.27	1.18	3.52	28	30	8	34
BSN	12–18	2.07	6.1	4.62	2.24	15.03	14	41	31	15
BSNdc	18–27	1.94	7.13	5.49	2.06	16.62	12	43	33	12
BCA	27–39	1.61	5.83	2.54	1.33	11.31	14	52	22	12
Light-humus medium-deep solonchakous solonetz (2nd terrace of Playa Khaki)										
AJ	1.5–6	1.51	1.5	0.13	1.75	4.89	31	31	3	36
SEL	6–10(12)	1.28	1.08	0.49	1.36	4.21	30	26	12	32
BSN	12–20	2.55	4.65	3.04	2.19	12.43	21	37	24	18
BSNdc	20–25(27)	1.79	5.41	4.66	2.01	13.87	13	39	34	14
BCAs,cs	25(27)–42.5	0.97	4.93	4.94	1.38	12.22	8	40	40	11

zon and the presence of clay–humus coatings) is clearly pronounced in the solonetzes on the first terrace of Playa Khaki and on the second terrace of Lake Bulukhta. The solonetz on the second terrace of Playa Khaki is characterized by the well-shaped morphological features (columnar structure) and by the relatively high *B* value characterizing the physicochemical conditions for the development of solonetzic process. In the solonetz on the second terrace of Lake Bulukhta, the structural features and the physicochemical conditions satisfy the criteria for the active development of solonetzic process, though the clay–humus coatings in the BSN horizon are weakly developed. In the solonetz on the first terrace of Playa Khaki, the structure of the solonetzic horizon and the physicochemical conditions of solonetzic process are poorly developed, though the illuviation coatings in the BSN horizon are very distinct. We suppose that the modern development of solonetzic process in this soil is hampered by the high amount of soluble salts.

We tried to estimate the intensity of elementary pedogenetic processes in the studied soils (Table 6). Humus accumulation is most active in the solonetz on the second terrace of Playa Khaki, in which a distinct light humus horizon (AJ) with the humus content of 1.1% is formed. This process is weakly developed in the solonetz on the first terrace of Playa Khaki, where the humus content in the topsoil horizon is low.

Cryogenic structuring and eluviation processes in the studied solonetzes are manifested in the form of platy aggregates in the topsoil horizons with clear differentiation of the fine silt and sand material inside platy peds. The solonetzes on the terraces of Playa Khaki are characterized by the more pronounced differentiation in comparison with the solonetz on the second terrace of Lake Bulukhta.

The salinization and gleyzation processes are most active in the solonetz on the first terrace of Playa Khaki, which is related to the shallow depth of strongly saline groundwater. In the solonetzes on the second terraces of

Table 4. Chemical properties of solonetzes on the terraces of Lake Bulukhta and Playa Khaki

Horizon	Depth, cm	pH H_2O (1 : 2.5)	Corg	$CaCO_3$	Gypsum
			%		
Light medium-deep solonchakous quasigleyed solonetz (1st terrace of Playa Khaki)					
SEL	1.5–12	7.31	0.56	Not det.	
BSN	12–18	8.23	1.22	″	
BSNdc	18–27	8.49	1.24	8.32	0.31
BCAcs	27–39	8.57	0.36	16.87	0.925
BCAs	39–70	8.33	0.14	11.98	10.89
BCq	70–80	8.73	0.08	11.92	0.2
Light-humus medium-deep solonchakous solonetz (2nd terrace of Playa Khaki)					
AJ	1.5–6	6.84	1.11	Not det.	
SEL	6–10(12)	7.97	0.58	″	
BSN	12–20	8.44	0.57	″	
BSNdc	20–25(27)	9.02	0.69	5.34	Not det.
BCAcs	25(27)–42.5	9.1	0.41	15.94	″
	42.5–57	8.51	0.18	14.44	6.2
	57–66	8.57	0.27	12.89	1.3
	66–80	8.45	0.2	10	3.36
BCs	80–100	8.34	0.14	7.34	3.52
Light shallow solonchakous solonetz (2nd terrace of Lake Bulukhta)					
SEL	2–10	7.37	0.80	Not det.	
BSN	12–20	8.57	1.05	″	
BSNdc	20–30	8.68	0.91	″	
BCAcs	35–50	8.91	0.30	13.17	5.00
BCs	60–80	8.91	Not det.	17.66	1.43
C	80–100	8.98	″	7.40	Not det.

Table 5. Diagnostic criteria of the development of solonetzic process

Index	Playa Khaki		Lake Bulukhta
Location	First terrace	Second terrace	Second terrace
Structure, BSN horizon	Angular blocky to small prismatic	Columnar	Coarse prismatic
Exchangeable Na percentage in the BSN horizon	31	24	40
Exchangeable Mg percentage in the BSN horizon	41	37	33
Sum of toxic salts in the BSN horizon	0.78	0.123	0.42
Predominant salts in the BSN horizon	NaCl	NaCl	$NaSO_4$
Salinity of the BSN horizon	Very strong	Weak	Moderate
Morphology of coatings	Thick clay–humus	Thick chocolate colored	Glossy
Micromorphology of coatings	Thick recent clayey coatings and stress-cutans	Thick recent clayey coatings	Stress-cutans
Index *B* in the SEL horizon (according to [33])	1	1	0
Index *B* in the BSN horizon	0	3	3

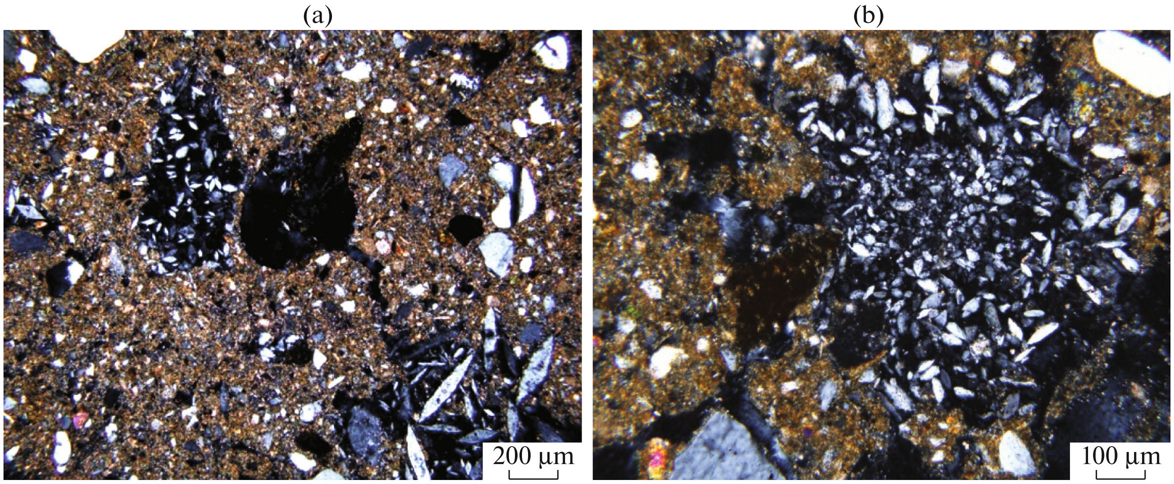

Fig. 8. Modern gypsum pedofeatures in the subsolonetzic horizons (XN) of solonetzes on the (a) first terrace of Playa Khaki (small and large lens-shaped crystals) and (b) second terrace of Playa Khaki (dense microcrystalline infillings).

Playa Khaki and Lake Bulukhta, the hydrogenic accumulation of soluble salts is weaker because of the greater depth and lower salinity of the groundwater.

The modern solonetzic process is most active on the second terrace of Playa Khaki; it is manifested by the clearly pronounced columnar structure and thick illuviation coatings in the BSN horizon. Favorable physicochemical conditions for the development of solonetzic process exist in the BSN horizon and in the overlying horizon. The accumulation of carbonates is clearly pronounced in all the studied soils; fine calcium crystals impregnating the soil mass predominate.

The accumulation of gypsum is most active in the solonetz on the first terrace of Playa Khaki, where the gypsum content reaches 11%. Micromorphological data confirm the results of chemical analyses. In this soil, well-shaped gypsum crystals of different sizes are present in the pores (Fig. 8). It is known that large gypsum crystals are formed in the zone affected by the groundwater with the high concentration of Ca^{2+} and SO_4^{2-} ions [21].

CONCLUSIONS

Macro-, meso-, and micromorphological features in the studied solonetzes attest to the development of several elementary pedogenetic processes common of all these soils; the specificity of particular soils is seen in the development of some additional elementary pedogenetic processes and in different intensities of these processes.

Common features of the studied solonetzes are as follows: (1) morphologically distinct diagnostic *suprasolonetzic horizons* with thin platy structure developed due to active eluviation processes and soil aggregation under conditions of winter freezing of water-saturated soil material and *solonetzic horizons* shaped by the solonetzic process; (2) the high portion of exchangeable sodium and magnesium in the soil adsorption complex, (3) the uneven distribution of particle-size fractions and soluble salts in the soil profile, and (4) the accumulation of humus in the solonetzic horizons owing to its illuviation under alkaline conditions.

The specificity of particular soils is seen in their morphological characteristics and chemical properties. The studied soils differ in the (1) thickness of clayey coatings and amount of pore infillings with clay–humus substances that gain their maximums in the solonetzes on the terraces of Playa Khaki, (2) thickness of the solonetzic horizons related to different durations of pedogenesis with the maximum thickness in the solonetz on the second terrace of Lake Bulukhta developed from more ancient deposits and the minimum thickness in the solonetz on the first terrace of Playa Khaki, (3) contents of iron and manganic concentrations indicative of the degree of soil hydromorphism with their maximum in the solonetz on the first terrace of Playa Khaki and their virtual absence in the solonetz on the second terrace of Lake Bulukhta.

The differences in the chemical properties are as follows: (1) the highest content of toxic salts is found in the solonetzes on the terraces of Playa Khaki, which is related to the shallow depth of highly saline groundwater; (2) the predominance of magnesium in the exchange complex of solonetzes on the terraces of Playa Khaki and the predominance of sodium in the exchange complex of solonetz on the second terrace of Lake Bulukhta, which may be related to differences in the salt composition of soil solutions and to different durations of the continental stage of pedogenesis; (3) a stronger leaching of soluble salts from the suprasolonetzic horizons of the solonetzes on terraces of Playa Khaki in comparison with the solonetz on the second terrace of Lake Bulukhta, despite the

Table 6. The major elementary pedogenetic processes in solonetzes on terraces of Playa Khaki and Lake Bulukhta

Index	Playa Khaki		Lake Bulukhta
	first terrace	second terrace	second terrace
Humus accumulation			
Corg in the upper horizon, %	0.56	1.1	0.8
Color of surface horizon	Pale	Light grayish pale	Light pale
Salinization			
∑toxic salts in the BCAcs horizon, %	1.52	0.82	0.79
∑salts in the BCAcs horizon, %	4.27	2.8	1.17
Solonetzic process			
Exchangeable Na percentage in the BSN horizon, %	31	24	40
Structure of the BSN horizon	Angular blocky to fine prismatic	Columnar	Prismatic
Index *B* in the BSN horizon (according to [33])	0	3	3
Index *B* in the SEL horizon	1	1	0
Lessivage			
Morphological manifestation of coatings	Thick clay–humus coatings	Thick chocolate-colored coatings	Glossy coatings
Micromorphological features of coatings	Recent continuous clayey coatings and stress-cutans	Recent thick clayey coatings	Thin fragmentary clayey coatings and stress-cutans
Cryogenic structuring			
Structure in the SEL horizon	Thin platy	Platy to very thin platy	Crumble–platy; loose in the lower part
Differentiation of the fine silt and sand material	Distinct	Distinct	Indistinct
Calcification			
$CaCO_3$ content in the BCAcs/BCs horizons, %	17/12	16/13	13/17
Macro- and micropedofeatures	Dispersed forms of calcite	Dispersed forms of calcite	Dispersed forms of calcite
Gypsum accumulation			
Gypsum content in the BcaCs horizon, %	10.89	3.3–6.2	5–1.4
Pedofeatures	Abundant veins and punctuations	Veins, filaments, punctuations	Nests, veins,
Microfeatures	Numerous infillings of microcrystalline gypsum in pores	Numerous infillings of well-shaped gypsum crystals of different sizes in pores	Single loose infillings of microcrystalline gypsum in the pores
Gleyzation			
Color	Brown with olive tint	Absent	Absent
Macro- and micropedofeatures	Fe and Mn concentrations (punctuations and mottles)	Few Fe and Mn punctuations	Absent

higher total content of soluble salts in the former soils; and (4) the different chemistry of salinization with a predominance of sodium chlorides (with participation of gypsum in the deep horizons) of in the solonetzes on terraces of Playa Khaki and with a predominance of sodium sulfates in the upper horizons and magnesium chlorides in the deep horizons of the solonetz on the second terrace of Lake Bulukhta.

With respect to their physical properties, solonetzes on the terraces of Playa Khaki are characterized by the higher water content in comparison with the solonetz on the second terrace of Lake Bulukhta. We suppose that this difference specifies a more active modern migration of clay and organomineral particles with the development of thick coatings and pore infillings in the solonetzes on the terraces of Playa Khaki.

With respect to the physicochemical conditions for the development of solonetzic process estimated on the basis of *B* index, the solonetz on the first terrace of Playa Khaki has unfavorable conditions for the modern development of solonetzic process ($B = 0$) because of the higher content of soluble salts; in the other two solonetzes, $B = 3$ (moderately favorable conditions for the development of solonetzic process).

In the topsoil horizon of the solonetz on the first terrace of Playa Khaki, $B = 1$, which attests to the possibility of the migration of organomineral particles. This is proved by the micromorphological observations attesting to the formation of clayey coatings in the solonetzic (BSN) horizon. In the solonetz on the second terrace of Playa Khaki, $B > 0$ both in the suprasolonetzic and solonetzic horizons. This is indicative of the higher activity of modern solonetzic process in comparison with solonetzes on the first terrace of Playa Khaki.

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