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## GENESIS AND GEOGRAPHY OF SOILS

# Micromorphological and Microbiological Diagnostics of Initial Pedogenesis on the Bottom of an Artificial Mesodepression in the Northern Caspian Semidesert

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**Abstract**—The results of micromorphological and microbiological studies of the initial pedogenesis on the gypsum-bearing calcareous heavy loams exposed within an artificially created mesodepression in the northern Caspian semidesert are discussed. Under conditions of an increased moistening and dense cover of trees and shrubs, the initial soil profile developed in 30 years has specific microfeatures related to the high activity of macro-, meso-, and microbiota. Micromorphological studies of large (5.5 × 8 cm) thin sections allowed us to trace the direction of humification processes, the degree of the biological decomposition of plant residues, and the character of structural changes under the impact of seasonal soil freezing against the background of the layered character of parent materials. Microbiological investigations demonstrated certain changes in the distribution patterns of different ecotrophic groups of soil microorganisms related to the input of fresh leave litter onto the soil surface and the decay of the roots of arboreal and herbaceous plants in the mineral soil profile. The layered distribution of plant residues in the soil profile predetermined specific functioning patterns of these groups.

*Keywords*: clayey semidesert, elementary pedogenetic processes, microfeatures of soil horizons, weakly developed humus soils, differentiation of the ecotrophic groups of microorganisms

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## INTRODUCTION

Studies of the geochemical role of microorganisms and their impact on the initial pedogenesis were initiated in the Dokuchaev Soil Science Institute by Polynov in 1947 [21]. Considerable attention to this problem was paid by Glazovskaya in her study of desert varnish in arid environments [10]. She demonstrated that desert varnish is developed as a result of several stages of mineral weathering with active participation of living microorganisms, including thin films of microorganisms on rock faces and iron–manganic crusts with participation of green and blue-green algae. The studies of initial pedogenesis and weathering by micromorphological and mineralogical methods were mainly performed for hard igneous rocks [34, 39–41]. The studies of initial pedogenesis on loose loamy substrates are relatively few in number [1, 23, 31]. In recent years, the first results attesting to the transformation of clay and silt fractions of mantle loams under the impact of various cenoses (including forest cenoses) have been obtained in special experiments with large lysimeters [4, 37].

The study of initial pedogenesis on dated surfaces is a widespread methodological approach allowing us to obtain information on the rates of temporal changes in separate soil properties and to predict their further evolution [25, 35].

Abakumov [1] investigated initial pedogenesis in different natural zones and concluded that the processes of organic matter accumulation play the major role in it. The thickness of the developing organomineral horizons and their macro- and micromorphological features depend on many factors, including the character and duration of the soil moistening, the pH, the contents of nutrients, and the activity of the soil fauna and microorganisms [9, 12, 14, 22, 38, 44–46, 48, 49].

The results of the study of initial pedogenesis on heavy-textured calcareous loam presented in this paper continue an earlier study of one of the soil profiles on the territory of the Dzhanybek Research Station of the Institute of Forest Science. Mineralogical, chemical, and physicochemical properties of these profiles were discussed in the paper by Sokolova with coauthors [33]. As noted in that work, the soil that had been formed in 30 years on the bottom of an artificially created mesodepression with a depth of about 3 m had a thin but distinctly differentiated profile composed of the litter (0.5–1 cm), the weakly developed humus horizon W depleted of carbonates (2–2.5 cm), and the underlying C1ca horizon with the high content of dis-

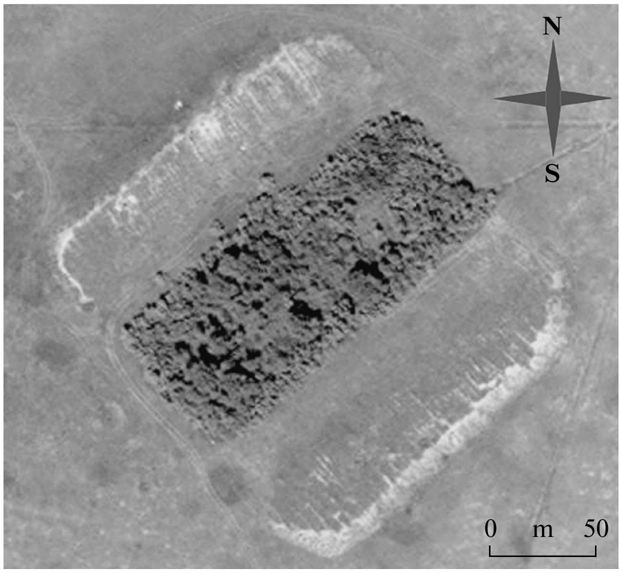

**Fig. 1.** Artificial mesodepression on a Bing image.

persed carbonates. The total thickness of these horizons reached 7–10 cm.

The goal of our study was to examine specific features of the microfabric and microbiological activity in this soil profile and, on this basis, to characterize the direction of elementary pedogenetic processes (EPPs). Integrated micromorphological and microbiological investigations allow us to obtain better estimates of the amounts of plant residues and the character and intensity of their transformation, to reveal tendencies of the organic matter transformation in the soil profile and the interaction between organic and mineral substances, and to describe microfabrics of plasmic material and its composition [44, 26]. The theoretical and applied significance of such studies is beyond doubt.

## SPECIFIC FEATURES OF SOIL FORMATION IN THE ARTIFICIAL MESODEPRESSION

The environmental conditions of the Dzhanybek Research Station are typical of large areas in the northern part of the Caspian Lowland. They have been described in detail in numerous publications [3, 5, 26]. The soil cover of the territory, where the studied mesodepression was created, is composed of solonetzic soil complexes with solonchakous solonetzes on the microhighs, meadow-chestnut soils in the microlows, and light chestnut soils on the slopes of microlows.

The conditions of pedogenesis in the studied artificial mesodepression were characterized in detail by Sokolova with coauthors [33]. This depression (pond) was excavated in 1979. It has a rectangular shape elongated in the northeastern direction; its depth is about 3 m. The excavated soil was used to shape two surfaces along both sides of the depression sloping toward it. The area of each of these slopes was approximately equal to the area of the depression itself. Thus, the catchment area of the depression was increased by almost three times. The size of the depression is 113 × 45 m (5085 $m^2$). The length of the left-hand and right-hand slopes toward the depression reaches 30 and 38 m, respectively. The total catchment area is 13899 $m^2$ (123 × 113 m). These morphometric measurements were performed using the Bing satellite image of Microsoft Company.

It was supposed that a pond should be created in the depression. To fill it with water, a special channel was dug from the main irrigation canal. However, this pond was filled with water only once in 1980.

At present, the bottom of the depression represents a flat surface overgrown with arboreal vegetation (Fig. 1). In its central part, there are some areas devoid of the trees.

The soil water regime at the bottom of the mesodepression and the proximity of the arboretum of the Dzhanybek Research Station with more than 120 species of acclimated trees and shrubs favor the development of arboreal vegetation. In two years after the construction of this mesodepression, its bottom was colonized not only by reed (*Phragmites australis* Trin. ex Steud.) but also by some species of trees and shrubs [30]. Silverberry (*Elaeagnus oxycarpa* Schlecht.), poplars (*Populus nigra* L. and *P. alba* L.), willow (*Salix caspica* Pall.), and other arboreal species appeared in the mesodepression.

The specificity of the environmental conditions in the bottom of the mesodepression is dictated by its regular ponding in the spring and considerable fluctuations of the groundwater level. The species tolerant to relatively long ponding and the species that settled on less ponded microelevations are typical of this area [31].

By 2011, about 20 species existed in the depression, including *Populus alba*, *Elaeagnus oxycarpa*, *Populus nigra*, and *Salix caspica*. Currant (*Ribes aureum* Pursh), berberis (*Berberis vulgaris* L.), and honeysuckle (*Lonicera tatarica* L.) predominated on its slopes. A wet meadow association with participation of reed grass (*Calamagrostis epigeios* L.), common reed (*Phragmites australis* Trin. ex Steud), and lycopus (*Lycopus exaltatus* L. fil.) predominated at the bottom. In general, the developed biogeocenosis preserved its intrazonal “quasimagrove” character [30, 31].

In the studied area, natural or anthropogenic mesodepressions serve as accumulators of snow and snowmelt, which increases the reserves of productive moisture in the soil and favors the leaching of soluble salts. In some cases, lenses of fresh groundwater are formed under such mesodepressions. These factors are favorable for the development of trees and shrubs, including fruit crops. In the semidesert with dry climate and widespread development of soil salinization, the appearance of arboreal vegetation in the mesodepressions signifies a higher biodiversity and is generally favorable for humans; it does not cause any significant adverse ecological effects.

## OBJECTS AND METHODS

The horizons of a weakly developed soil in the depression (Fig. 2) were the main objects for our micromorphological and microbiological studies. The samples for preparation of thin sections were taken from the upper 5 cm in June 2011 and 2012. These thin sections were used for a comparative analysis of the main features of the soil microfabric in order separate them into the groups of stable features and dynamic features directly related to the character of elementary pedogenetic processes.

Large (5.5 × 7 cm) thin sections from the undisturbed oriented soil samples were prepared by M.A. Lebedev in the Laboratory of Mineralogy and Micromorphology of Soils of the Dokuchaev Soil Science Institute. The soil impregnation with synthetic resins was performed without the soil heating, which made it possible to preserve salt pedofeatures intact. The description of the thin sections generally followed international recommendations [19].

The microbiological studies were performed by classical methods of soil microbiology, including inoculation onto solid nutrient media (beef-extract agar, starch-and-ammonium agar, starvation agar, and Czapek medium for cultivating micromycetes [36]), serial dilution [24], cultivation of anaerobic nitrogen fixers on the Winogradsky medium, and cultivation of microorganisms of the group of nitrogen respiration on the GND medium [13]). The inoculations were performed from the soil water suspension (1 : 10); the incubation at 20–25°C lasted for 3–14 days in dependence on the particular medium. The activity of *Azotobacter* was estimated from data on fouling of soil particles in Ashby medium [36]. Confidence intervals were calculated for $P = 0.92–0.99$. The Rybalkina–Kononenko method [28] of direct observation of the microbial community was applied to visualize active forms of microorganism, their distribution patterns in the soil, and their relationships with one another and with the environment. The photographs of the microorganisms were taken with the help of a Biomed-6 microscope equipped with a Webbers camera at magnification ×400. The exposure of the undisturbed soil samples on fouling glasses lasted for 5 and 10 days; the samples were moistened with sterile water. In this paper, we present generalized visual appearance of six agarized glasses.

## RESULTS

In 30 years, thin soils with distinctly differentiated profiles developed on the bottom of the artificial mesodepression.

The studied soil pit was dug on a flat surface under dense vegetation cover with poplars (*P. nigra* and *P. alba*), willow (*S. caspica*), and silverberry (*Elaeagnus oxycarpa*) in the tree story; *P. alba* in the undergrowth; and reed grass, melilot, lycopus, and other grasses and forbs in the ground cover. In general, the ground cover can be referred to as a herbaceous wet-meadow community. The groundwater level was found at the depth of 3.88 m.

**Morphological features of the weakly developed soil.** The soil profile had the following morphology.

O, 0– +1(1.5) cm. Thin litter with weakly decomposed leaves and twigs of poplar; in the lower part, the degree of decomposition is higher (about 60%); dry; the upper part is whitish gray, and the lower part is brown-gray; abrupt boundary.

W, 0–1(1.5) cm. Dry, brownish dark gray; fine crumb to powdery structure; sandy loam with the high amount of silt particles; does not effervesce; densely penetrated by fine roots; highly porous; distinct wavy boundary.

WC1. 1(1.5)–3 cm. Slightly dry, grayish light brown with gray mottles of irregular shapes along the paths of decayed roots and burrowing animals (about 10% of the section); these mottles may have both diffuse and abrupt boundaries; fine crumb–powdery structure; strong effervescence; rather compact; contains whitish "dots" (<0.2 mm) resembling diffuse carbonates; porous; distinct wavy boundary.

WC2, 3–5(7) cm. Pale brown moist horizon with platy–angular blocky structure; silt loam, more compact; strongly porous; strongly effervescent; contains few poorly shaped gypsum druses and their fragments; the transition is seen in the amount and the degree of preservation of these druses; wavy boundary.

CWca,m, 5(7)–15 cm. Pale brown moist horizon with platy–small angular blocky–granular structure; silt loam to clay loam; strongly effervescent; compact; single coarse tree roots; abundant fine roots; porous; few black manganic punctuations. Gypsum druses are arranged into layers of coarse-crystalline gypsum that occupy up to 30% of the section; the distance between the layers if about 10–15 cm, and the size of the druses is 3–5 cm; some druses are hard, whereas other druses are soft; there are also small (<1 mm) snowy white gypsum concentrations that are traced to the depth of 200 cm (according to the examination of auger samples). The transition is seen in color and structure; diffuse boundary.

Cca,cs, 15–54 cm. Wet brown silt loam to clay loam; platy–angular blocky; compact; strongly effervescent; many fine roots; porous. Few black manganic punctuations; gypsum layers and snowy white small gypsum concentrations.

In general, according to the new Russian soil classification system, the morphology of this profile fits the definition of the type of humic pelozems from the order of weakly developed soils in the trunk of initial pedogenesis [20]. The most distinct horizons in this profile are the thin litter horizon and the weakly developed humus horizon (W).

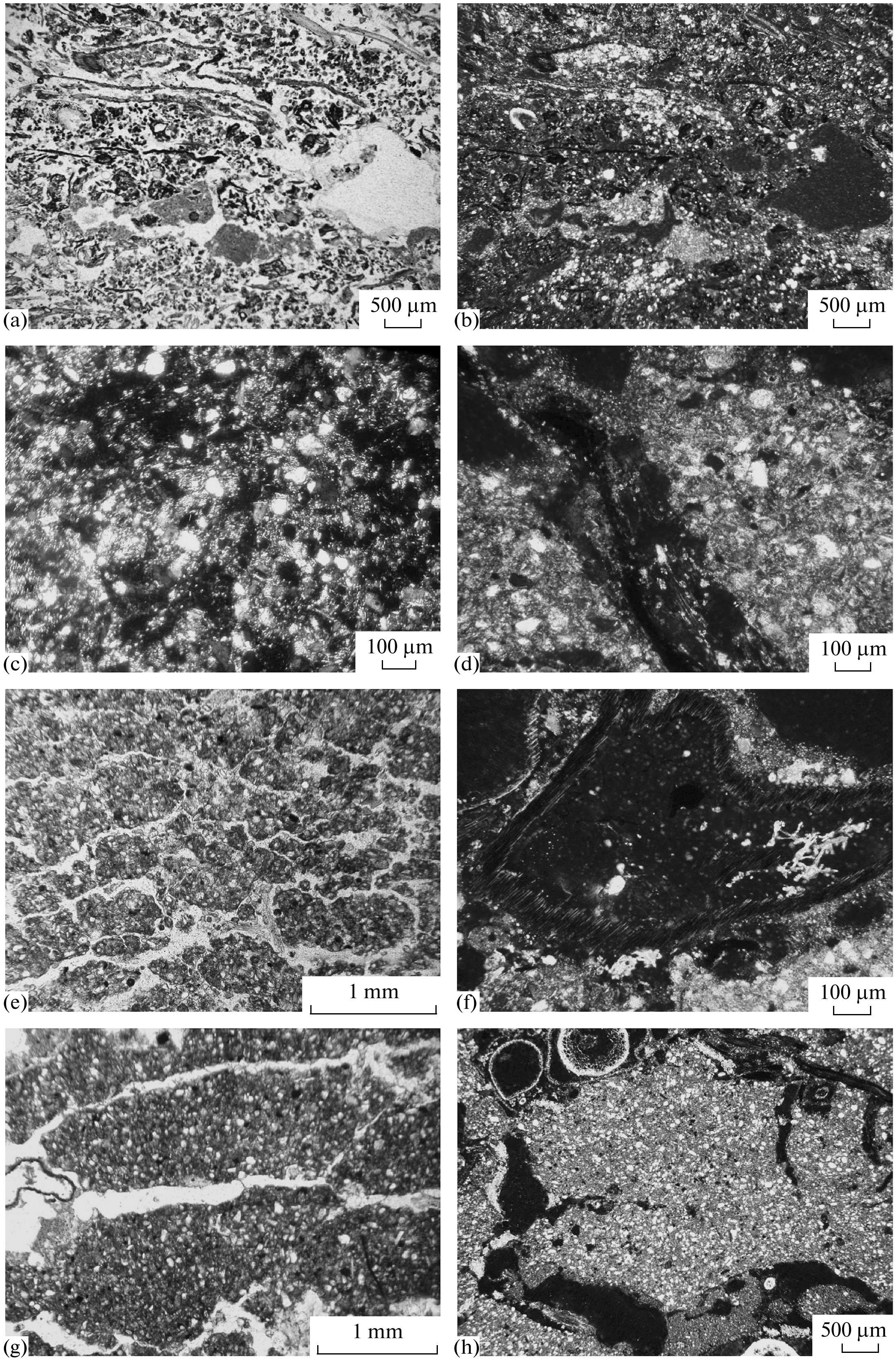
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**Fig. 2.** Vertical differentiation of microfeautures in the upper 5 cm of the weakly developed humic soil. W1 (0–1.5 cm): (a, b) layered distribution of weakly developed fine roots, abundant excrements of enchytraeids, single excrements of Diptera larvae, small angular aggregates of silty–clayey or silty–calcareous–clay material, and silt-size quartz grains (a—IIN and b—XN); (c) high intraaggregate porosity in the aggregate devoid of micrite (XN); and (d) ferruginated root in a pore with loose silty–micritic infilling between the aggregates of compact microfabric of the silty–clay matter (XN). WC1 (1.5–3 cm): (e) crumb aggregates rearranged into platy structure with subparallel porosity (IIN) and (f) biogenic growths of calcite microcrystals inside the root (XN); WC2, 3–5 cm: (g) thin platy microstructure with subparallel planar voids and loose infillings in the pores (IIN) and (h) the section with cut roots (preserving birefringence of cellulose), silty infillings, and carbonate nodules with elongated calcite microcrystals around an angular platy aggregate (XN).

The humus content sharply decreases down the soil profile: from 4.8% at the depth of 0–3 cm to 0.9% at the depth of 3–10 cm and 0.4% at the depth of 15–20 cm. Such a distribution of humus is typical of many initial weakly developed soils [1]. In the field, the texture of all the horizons (except for the W horizon) was determined as heavy loam.

Gypsum crystals in the druses display the features of dissolution: some of them have indistinct "fused" faces, whereas other crystals are well shaped.

The study of chemical properties in the profiles examined within the flat bottom of the mesodepression shown that soluble salts are generally leached off from the upper 80 cm; calcium sulfates predominate in the composition of salts; the content of toxic salts is less than 0.3%; the content of $Cl^-$ ion is insignificant, and the content of exchangeable $Na^+$ is less than 1 cmol/kg. The groundwater of the sulfate–calcium type is fresh. These characteristics, in combination with additional moistening of the soils with snowmelt, ensure favorable conditions for the development of herbs, shrubs, and trees at the bottoms of the artificial depressions [33].

**Micromorphological characteristics** of the weakly developed initial soil are summarized in the table. The following characteristics are typical of all the horizons.

(1) In the entire profile, the intraped mass has a compact fabric with "nests" of fine sand grains amidst silt and clay material (Figs. 2a and 2b). These features of the c/f related distribution were earlier describe by use for the parent material of the soils of solonetzic complexes of the Dzhanybek research station [17].

(2) Carbonate concentrations (in the form of nodules or concretions) are absent in the studied profile. Crypto- and micrograined carbonates are dispersed in fine silty–clay material. At large magnification, it is seen that many medium-silt particles of the primary calcite grains are recrystallized inside.

(3) Minerals of the coarse fractions are mainly represented by the sharp-angled quartz and feldspar grains; there are many light-colored mica grains; glauconite, amphiboles, epidote, zoisite, and ore minerals have also been identified.

The differentiation of the profile into the weakly developed humus (W) horizon and two WC subhorizons is seen in their micromorphological characteristics. These horizons (subhorizons) differ from one another in the amount of plant residues and the intensity of their biogenic transformation and in the character of structural changes in the mineral matter, including microstructures. It is important that the thin sections prepared from the upper 7 cm of the soil sampled in different years have similar distribution patterns of microfabrics and microstructures of the soil mass (table).

The W horizon (0–1.5 cm) is marked by the high amount of fine dark brown tissues of plant origin with a tendency for their subparallel orientation to the soil surface; the content of the fine material is generally low (Figs. 2a and 2v). Between plant residues, there are many excrements of primary decomposers (Enchytraeidae and Diptera larvae), though there are also few coprolites of secondary decomposers (supposedly, earthworms) and aggregates with the high amount of fine intraped pores in the silty–clay material with granostriated b-fabric; micrite is absent in this material (Fig. 2c). Some "nests" of coarse silt particles virtually devoid of clay bridges between them are seen amidst plant tissues. Complex packing voids (according to Stoops [50]) between plant residues and between silty–clay aggregates and sand particles predominate in this horizon. Rounded aggregates with granostriated b-fabric are analogous to the intraped mass of solonetzic horizons (Fig. 2d) [17].

In this horizon, against the background of active biogenic structuring, the processes of leaching of carbonates and local destruction and/or eluviation of the fine material take place. The transition to the underlying horizon is marked by a decrease in the amount of dark brown plant tissues and an increase in the amount of mineral aggregates.

In the upper part of the transitional horizons WC1 (1.5–3 cm), the predominant type of plant residues is represented by brown root residues in pores–channels and by large fresh plant tissues with birefringence. There are also small aggregates impregnated with dark brown amorphous humus and coprogenic aggregates assimilated by the soil mass. In chamber with brown root residues, excrements of mites are present.

This horizon is specified by the well-developed crumb microstructure with a tendency for it reorganization into lenticular microstructure (Fig. 3e). Another specific feature is the presence of fine calcite growths in the interaggregate pores; such calcite grains of micritic size are mainly located near fresh or weakly decomposed plant residues (Fig. 2f). In the biogenic pores with roots, loose fine silty carbonate–silicate infillings are present.

In the lower part of the transitional horizon (WC2, 3–5 cm), the amount of plant residues drastically decreases, and some microzonality in the character of

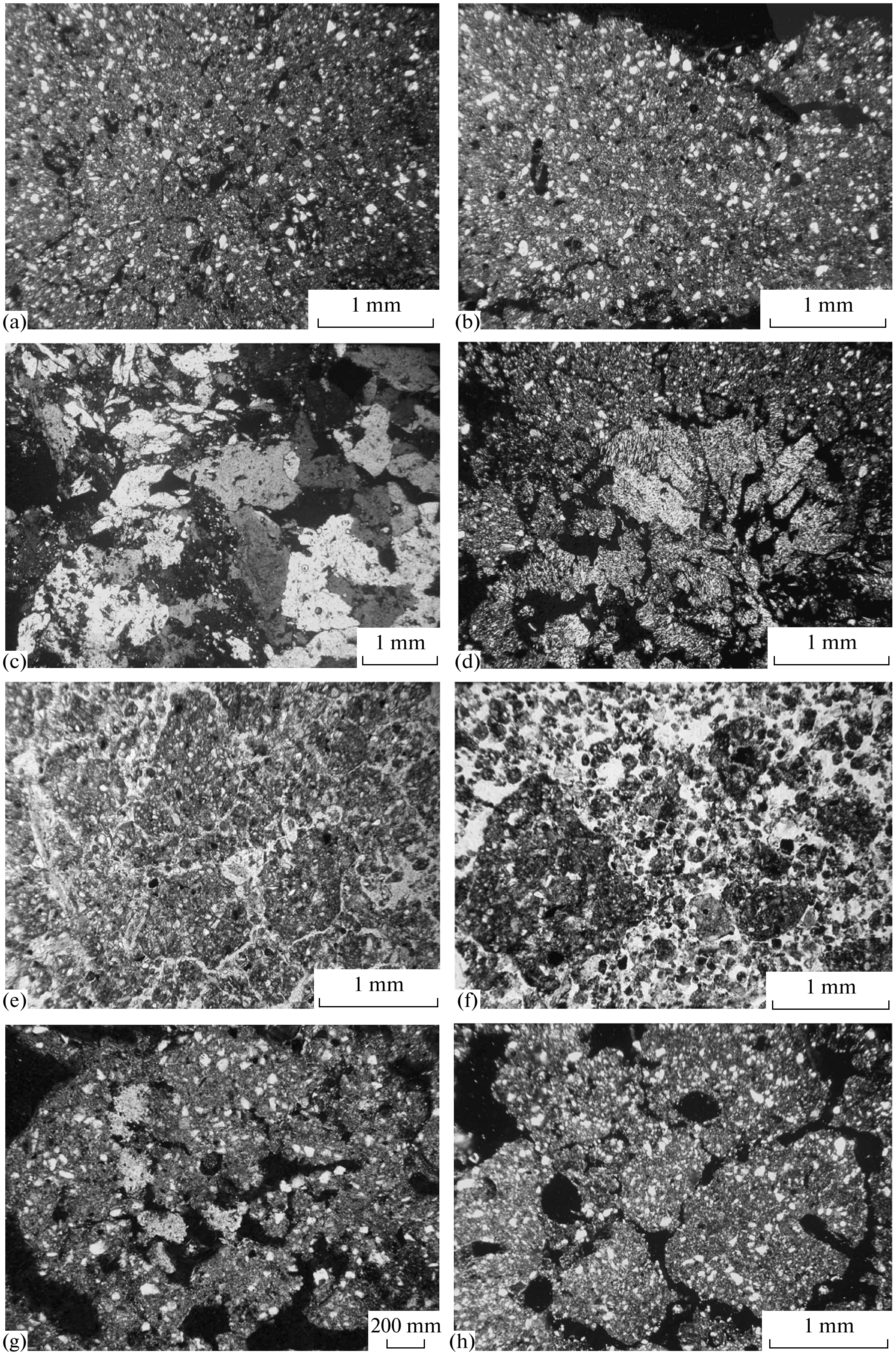
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**Fig. 3.** Vertical differentiation of microfeatures in the weakly developed humic soil (WH) below 5 cm and their comparison with the microfeatures in the virgin quasigleyed chestnut soil (K) [16] and reclaimed solonetz (SN) [18]: (a) crumb and angular blocky types of microstructure with silty infillings in pores (WH, 10–15 cm; XN); (b) compact microfabric inside platy aggregates of the silty–calcareous–clayey material with "nests" and laminae of fine sand (WH, 30–40 cm; XN); (c) compact growth of large xenomorphic crystals of relic gypsum and newly formed small rhombohedral gypsum crystals of the peripheral zone inside the enclosing silty–clayey–calcareous material (WH, 30–40 cm; XN); (d) fissuring of gypsum druse composed of large xenomorphic relic gypsum crystals with their transformation into bassanite (SN, 120–140 cm; XN); (e) subangular blocky microstructure with silty infillings and separate excrements of soil mesofauna in the interaggregate pores (WH, 30–40 cm; IIN); (f) crumb, subangular blocky, and coprogenic types of microstructure (K, 30–40 cm; IIN); (g) crumb microstructure with abundant biogenic carbonate micronodules in the intraped mass (WH, 1.5–3 cm; XN); and (h) crumb microstructure with abundant biogenic pores (K, 40–45 cm; XN).

aggregates appears. The soil microstructure is of the platy type (table; Figs. 2g and 2h). Near root residues, there are zones with crumb aggregates; some of them represent earthworm coprolites. The earthworms could appear in the depression from the nearby arboretum, in which special introduction of the earthworms was performed 50 years ago. Under the forest canopy of the arboretum, the diversity of the soil mesofauna considerably increased [6, 7, 16]. The intraped mass in this microhorizon is very compact in all the types of aggregates; it has a crystallitic b-fabric. Coarse silt and fine sand particles are arranged in "nests."

The development of the platy microstructure can be related to the seasonal freezing of moist soils. An increase in the amount of fine silty silicate–carbonate infilling in comparison with the overlying horizon is specific of the WC2 horizon. Such infilling are dense, though they are also found in the biogenic pores with roots (Figs. 2 and 3).

The CWca,m (10–15 cm) horizon is specified by the very high porosity and good aggregation of the material. There are many rounded or subangular aggregates and biogenic aggregates assimilated by the soil mass; packing voids predominate (Figs. 3a and 3e).

In the main channel pores, in loci with the preserved root residues, there are many excrements of mites. Near the roots, the soil material is more compact. The character and intensity of its biogenic transformation allow us to consider this horizon as a humus horizon transitional to the parent material. It has a pedogenic structure shaped due to the high activity of the soil mesofauna. In separate zones, there are angular blocky aggregates. In the pores of the most compact zones, there are infillings of microcrystalline gypsum of xenomorphic shape. The amount of silt-size carbonate infillings is lower than in the overlying horizon. These infillings are seen in pores–channels with the remains of fine roots.

The Cca,cs (15–54 cm) horizon is characterized by the thick platy structure (Fig. 3b). These thick plates are subdivided into thinner plates by the subparallel planar voids. It can be supposed that thick platy aggregates are inherited from the initial structure of the parent material, whereas the development of planar voids in them is related to the cryogenic structuring processes during seasonal freezing. Pores–channels and biogenic chambers with fine root residues are not numerous.

A specific feature of this horizon is the abundance of coarse gypsum growths (gypsum nests or druses). These druses are different with respect to their inner porosity, the size of the crystals, and the shape of their sides. We suppose that all these features depend on the age of the particular gypsum crystals and on the degree of their dissolution. Gypsum druses are composed of the largest crystals that have no distinct faces (xenomorphic gypsum crystals) and have "fused" edges; often, they include calcite grains (Fig. 3c).

Inside such gypsum "nests," fragments of the enclosing clayey calcareous material may be enclosed. There are also inner voids within the druses, though gypsum crystals are tightly bound to one another. A specific morphological feature is the presence of fine idiomorphic rhombohedral gypsum crystals in the silt–clayey carbonate material (Fig. 3c), which allows us to assume their modern genesis.

**Assessment of the microbiological activity** of the horizon of this weakly developed soils made it possible to identify several elementary pedogenetic processes.

The appearance of woody thickets on the slopes and bottom of the mesodepression and the rich wet meadow herbaceous vegetation in the ground cover are the main factors of the soil profile differentiation with the corresponding differentiation of the microbial communities.

Let us analyze data on the activity of microorganisms participating in the carbon and nitrogen cycles under aerobic and anaerobic conditions.

Microbiological inoculates and microbial patterns on agarized fouling glasses attest the high microbiological activity (Figs. 4 and 5) typical of the soils of arid territories [2, 11, 15]. Virtually all the ecotrophic groups of microorganisms are present in the soil profile; they are differentiated by the soil horizons.

Ammonifying microorganisms utilizing the organic forms of nitrogen participate in the decomposition of proteins of different origins. Data on the numbers of these microorganisms in separate horizons are shown in Fig. 5a.

In the upper 5 cm, this number is an order of magnitude higher than in the underlying horizons, which is explained by the partial assimilation of the lower part of litter and the decomposition of the roots of herbs, trees, and shrubs. At the depth of 10–15 cm, the leaching of nutrients into the lower horizons may take place. As a result, at the depth of 30–40 cm, where the calcareous soil material is arranged into platy aggregates, the amount of nutrients is sufficient for the development of ammonifying microorganisms. Their

Microfabric of the weakly developed soil

| Horizon | Depth, cm | Organic matter | | | | Fine material | | | Microstructure | | | | Pores | | | | Optical orientation | | | Pedofeatures | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | fr | db | b | a | ch | cl | cc | e | cr | sb | pl | pv | cv | bc | p | c | sp | gr | carb | gyps | inf |
| W | 0–1.5 | + | +++ | + | + | – | +++ | + | +++ | +++ | – | – | + | +++ | – | – | – | ++ | ++ | + | – | – |
| WC1 | 1.5–3 | ++ | + | +++ | ++ | + | – | +++ | + | + | ++ | ++ | +++ | – | +++ | ++ | +++ | – | – | ++ | – | + |
| WC2 | 3–5 | + | + | ++ | + | – | – | +++ | + | + | + | +++ | ++ | – | ++ | +++ | +++ | – | – | + | – | +++ |
| CWca,m | 10–15 | + | – | ++ | – | – | – | +++ | ++ | ++ | + | + | ++ | – | ++ | +++ | +++ | – | – | – | – | +++ |
| Cca,cs | 30–40 | – | – | + | – | – | – | +++ | – | – | – | +++ | | – | + | +++ | +++ | – | – | – | +++ | + |

The occurrence frequency of the microfeatures is as follows: (–) absent, (+) few, (++) moderate, and (+++) high.

Microfabric of the organic matter: (fr) fresh roots preserving birefringence of cellulose, (db) dark brown moderately decomposed tissues, (b) brown fine and highly decomposed tissues, and (a) amorphous brown humus. Composition of the micromass: (ch) clayey–humus, and (cl) calcareous–clayey. Type of microstructure: (e) excrements, (cr) crumb, (sb) subangular blocky, and (pl) platy. Porosity: (pv) compound (interaggregate) packing voids, (cv) complex packing voids (between aggregates, coarse silt grains, and plant residues), (bc) biogenic chambers and channels, and (p) planes. Optical orientation (b-fabric): (c) crystallitic, (sp) speckled, and (gr) granostriated. Pedofeatures: (carb) micritic micronodules in pores, (gyps) growths of small gypsum crystals, and (inf) fine silty silicate infillings.

number in this horizon is only slightly smaller than that in the upper 5 cm.

Microorganisms utilizing mineral forms of nitrogen can be attributed to zymogenic microorganisms, because they participate in the decomposition of the organic matter of plant origin and simpler organic compounds. These microorganisms are considered active immobilizers of available carbon; as the source of nitrogen, they utilize its mineral forms directly from the soil.

Data on the numbers of amylolytic organisms in separate soil horizons are presented in Fig. 4b. In general, the number of microorganisms utilizing mineral nitrogen is high. As for their distribution pattern, it resembles that of the ammonifying microorganism: the high activity of amylolytics is determined in the upper 5 cm; the low activity, at the depth of 10–15 cm; and the moderate activity, at the depth of 30–40 cm. This is explained by the high content of nondecomposed organic residues.

Actinomycetes have hydrolytic enzymes that serve as destroyers of difficultly available polymers and hydrocarbons in the composition of plant residues and other organic substances entering the soil. Actinomycetes can also participate in the mineralization of humic substances. They are tolerant to long droughty periods and are sensitive to the increased moistening of the soil. The distribution of actinomycetes in the soil profile is shown in Fig. 4c.

In the upper 5 cm, actinomycetes participate in the decomposition of plant litter, and their number in this horizon is by an order of magnitude higher than that in the underlying horizons. At the depths of 10–15 and 30–40 cm, the numbers of actinomycetes are also significant and reach 4.2 log CFU/g soil.

The development of oligotrophic microorganisms with a low demand for nutrients is characteristic of the final stages of microbial successions. Oligotrophs decompose the products of the organic matter decomposition dispersed in the soil mass in relatively low concentrations.

Data on the distribution of oligotrophs in the soil profile are shown in Fig. 4d. Their distribution is similar to the distribution of most of the other ecotrophic groups: the maximum (6.1 log CFU/g soil) in the uppermost soil (0–5 cm), the minimum (4.9 log CFU/g soil) at the depth of 10–15 cm, and the intermediate amount (5.8 log CFU/g soil) at the depth of 30–40 cm.

Microscopic soil fungi are the main decomposers of complex organic substances, such as lignin, chitin, tannins, and cellulose, which ensures possibility for the use of these substances by other organisms.

Data on the numbers of fungal primordia in the soil profile are presented in Fig. 4e.

Microscopic fungi were only detected in the uppermost horizon, which may be due to the presence of litter with weakly decomposed twigs of leaves on the soil surface and to the high moistening of the lower horizons.

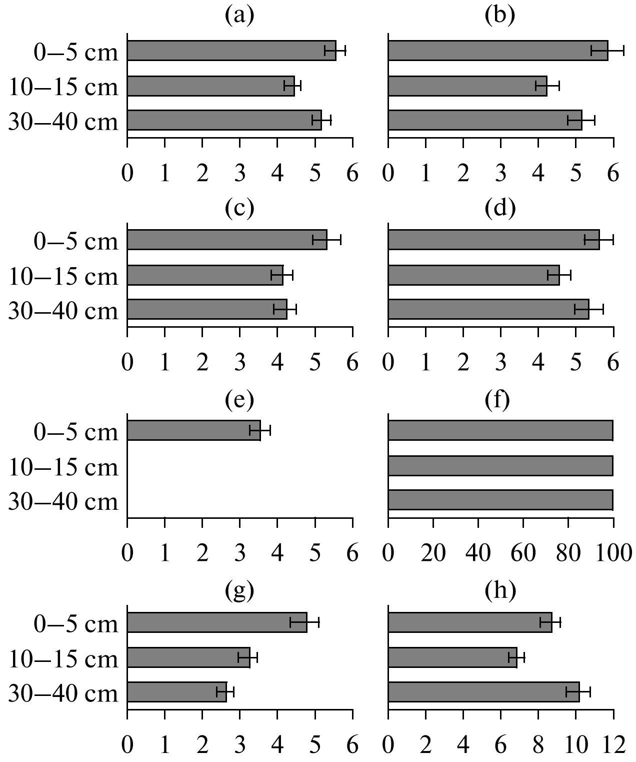

**Fig. 4.** Numbers of major ecotrophic groups of microorganisms (log CFU/g soil; for aerobic N-fixing organisms (f), % of fouling) in the horizons of the weakly developed humic soil (confidence interval $P = 0.92–0.99$): (a) ammonifiers, (b) amylolytic microorganisms, (c) actinomycetes, (d) oligotrophic microorganisms, (e) micromycetes, (f) aerobic N-fixing microorganisms, (g) anaerobic N-fixing microorganism (Clostridia), and (h) denitrifiers.

One of the main factors affecting the productivity of biocenoses is the level of nitrogen supply in the soil, because this element is of crucial importance for producing plant and animal food. The processes of the nitrogen cycle affect the development of microflora and plant growth. We analyzed the groups of microorganisms participating in the accumulation of nitrogen and its loss from the soil.

The assimilation of atmospheric nitrogen is a biological process ensured by the soil microorganisms. Free-living bacteria can fix nitrogen under both aerobic and anaerobic conditions. Microorganisms cultivated on the nitrogen-free Ashby medium are typical oligonitrophiles. These are representatives of the *Azotobacter* genus.

If there are available mineral forms of nitrogen in the soil, the nitrogen-fixing activity of *Azotobacter* is suppressed. Data on the activity of nitrogen-fixing bacteria are shown in Fig. 4f.

The high activity of *Azotobacter* in all the horizons of the studied soil can be explained by the low reserves of mineral nitrogen in the soil. In turn, this factor can limit the development of other ecotrophic groups of the soil microorganisms. The assimilated atmospheric

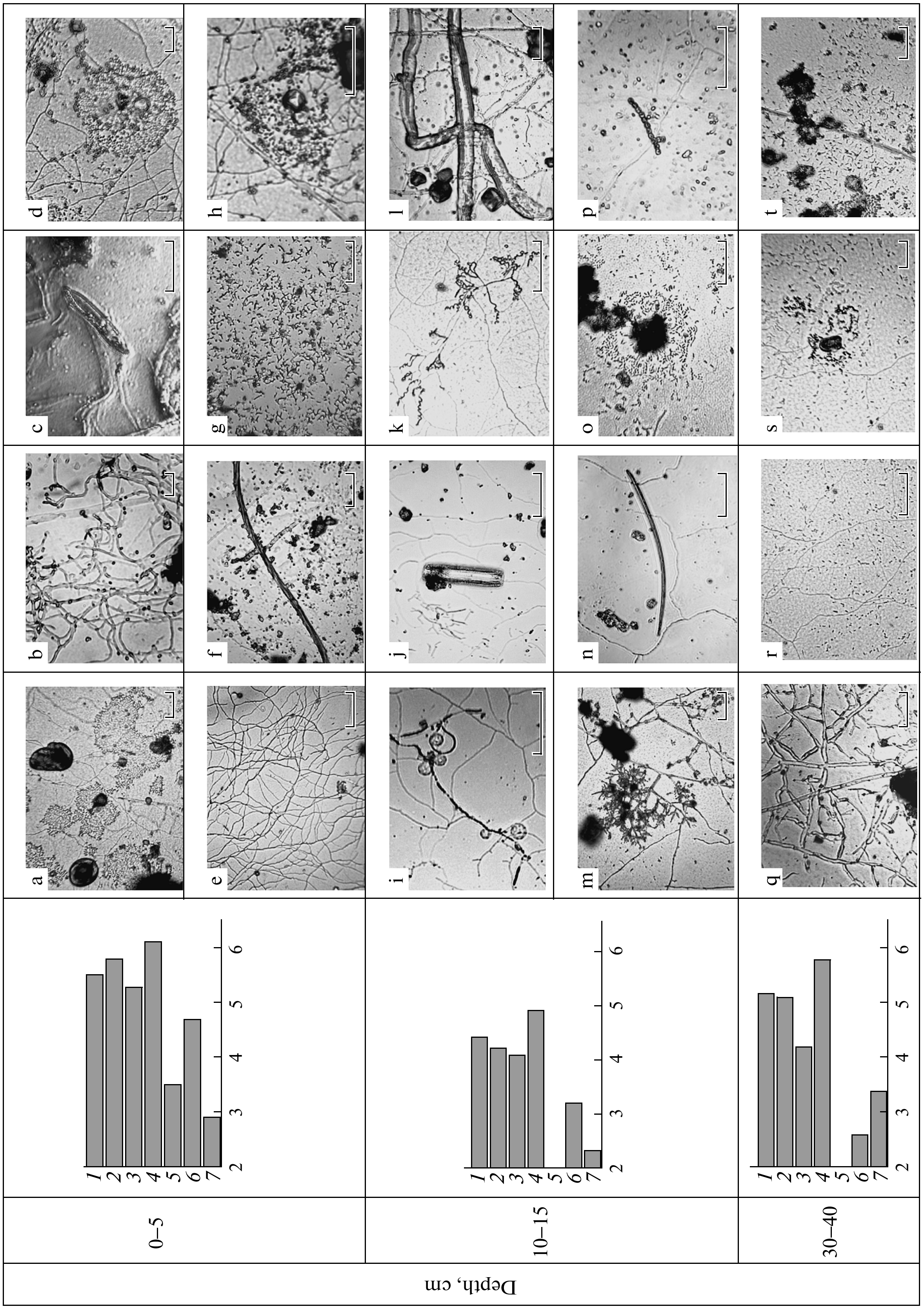
Depth, cm
0–5
10–15
30–40
1
2
3
4
5
6
7
2
3
4
5
6
a
b
c
d
e
f
g
h
i
j
k
l
m
n
o
p
q
r
s
t

**Fig. 5.** Total biological activity (log CFU/g soil) in the horizons of the weakly developed humic soil (plots), contribution of different groups of microorganisms (*1*—ammonifiers, *2*—amylolytics, *3*—oligotrophs, *4*—micromycetes, *5*—anaerobic N-fixing, and (*7*—denitrifiers), and corresponding biological diversity: (a, d, g, h, p, r, s, t) general patterns on agarized glass; (b, i, m) micromycetes and their sporulation; (c, j) diatoms; (d, h, o, s) soil bacteria concentrated around mineral and organic particles; (e, k) actinomycetes; (f, l, p, q) soil algae and cyanobacteria; and (n) nematode.

nitrogen is utilized not only for the development of the *Azotobacter* population; the assimilated nitrogen can be stored in the soil. After the decomposition of microbial biomass, it can be involved in the trophic chain of the entire microbial community.

Bacteria belonging to the *Clostridium* genus are capable of nitrogen fixation under the anaerobic conditions. Their distribution in the soil profile is shown in Fig. 4g.

The highest number (4.7 log CFU/g soil) is typical of the uppermost horizon (0–5 cm), which is explained by the high activity of the microbiological community and by the deficit of mineral nitrogen in this horizon. Down the soil profile, the activity and anaerobic nitrogen-fixing microorganisms gradually decreases to 2.6 log CFU/g soil at the depth of 30–40 cm.

Microorganisms-denitrifiers are facultative anaerobes. They oxidize organic matter at the expense of nitrates that become reduced and are lost from the soil into the air in the form of molecular nitrogen $N_2$. The denitrification develops under conditions of the deficit of atmospheric oxygen.

Data on the activity of microorganisms with nitrate respiration are shown in Fig. 4h. The numbers of denitrifiers cultivated on the GND medium are affected by changes in the color of the medium owing to changes in its pH, gas emissions, and changes in the transparence of the medium at the expense of the growth of the microbial biomass.

In general, the activity of denitrifiers in the soil is low. This can be explained by the low content of the oxidized forms of nitrogen (nitrates and nitrites) in the soil and the high aeration of the topmost horizons. The development of anaerobic conditions and anaerobic niches in the topsoil is insufficient for the active development of denitrifiers. In the lower horizons, the activity of denitrification processes increases, which can be due to their higher moistening.

## DISCUSSION

In the studied profile, the heavy calcareous loam—parent material for the soils developing in the area of the Dzhanybek Research Station—has all the features typical of this material. From the depth of 2 m and more, this loam has a compact microfabric, platy structure, carbonate–clayey fine material, and clustered distribution of fine sandy skeletal grains [17]. In 30 years of pedogenesis under the canopy of trees and shrubs with the dense herbaceous ground cover, the soil profile with a distinctly different microfabric of the upper horizons has been developed from this material (table).

**Microfabrics of the organic matter and microstructure.** In 30 years of the development of this soil from the calcareous and gypsum-containing heavy loams under the forest cenosis in the subarid climatic conditions, certain differentiation of plant residues by their size, shape, and degree of decomposition has taken place. The soil is also differentiated by the types of microstructure and by the character of excrements of the soil meso- and microfauna. The microfabric of the upper horizons characterizes a weakly developed humus profile.

In the uppermost 3 cm of the mineral soil, the biogenic transformation of plant residues by the primary decomposers is distinctly pronounced. In the lower layer, the number of excrements of the larvae of Diptera and other species of the soil mesofauna significantly increases. These data are in agreement with the earlier published results of the study of initial pedogenesis on the calcareous loesslike loams under forest vegetation in Belgorod oblast [8]. In the latter case, a weakly developed humus horizon was formed under the canopy of oak trees; the character of the parent material, as well as the character of the litter horizon, in both soils are relatively similar. However, because of the higher bioclimatic potential and higher activity of the earthworms in Belgorod oblast, the time required for the development of the humus horizon was three times shorter than that in the soil studied by us.

Clear indications of the biogenic structuring of the soil are seen in the upper 15 cm. The presence of the pedogenic structure in the CWca,m horizon (10–15 cm) is indicated by the lower-case "m." Such a deep penetration of the soil biota can be explained by the seasonal migration of the organisms into the lower horizons with an increased water content, whereas the upper 10 cm of the profile become very dry in the summer period. Excrements of mites are seen in the pores with plant residues down to the depth of 30 cm. Thus, the biogenic transformation of plant residues in the biogenic channels penetrates deep into the soil profile and parent material. Among the microforms of humus, brown amorphous humic substances predominate. They impregnate some clayey calcareous aggregates in the upper horizons (W and WC1), though their amount is insufficient to mask the crystallite orientation of the clayey–calcareous material.

On the basis of the classical work of Kubiena [47] and numerous other studies devoted to the micromorphological diagnostics of humus formation in different soil types [41], we argue that the accumulation of coarse and weakly decomposed plant resides has taken place in this soil in the 30 years of its development. At present, these residues are subjected to the biogenic destruction with the formation of the coprolites of micro- and mesofauna. This allows to state that the moder type of humus is being formed in this soil. The most significant accumulation of humus takes place in the uppermost 1.3 cm. The conditions of the decomposition of plant residues are rather specific. In the spring, their decomposition and mineralization are retarded because of the long-term ponding of the soil. A sharp activation of the biological and microbiological activities may take place during a relatively short period of the optimum soil moistening after its ponding and before its strong drying in the summer. Despite the abundance of plant litter under the forest with the dense herbaceous ground cover, the development of the mull type of humus does not take place. In general, within the upper 15 cm of the profile, some vertical "zonality" in the distribution of soil mesofauna is observed; it is also seen from the character of decomposition of plant residues. As the number of secondary decomposers (earthworms) in the soil is not great, a more significant role in the decomposition of plant litter belongs to the larvae of Diptera, enchytraeids, mites, and collembolans.

It is interesting to note that the high interaggregate porosity and the presence of rounded and subangular blocky aggregates and small coprolites at the depth of 10–15 cm (in the CW horizon, Figs. 2e and 2g) in the studied weakly developed soil were earlier observed by us in the virgin hydrometamorphized (meadow, quasigleyed) chestnut soil in the microlow of the solonetzic complex (Figs. 3f and 3h) [16]. This allows us to suppose that the studied weakly developed soil evolves in the direction of the quasigleyed chestnut soils, the most fertile soils of the solonetzic soil complexes in the semidesert. This assumption in agreement with data on the high content of humus, low content of toxic salts, and other characteristics of the soils of the artificial depression obtained by Sokolova with coauthors [33].

**Microfabric of the micromass.** Most of the aggregates in the studied soils are composed of the calcareous clayey material with the crystallite orientation of the clay matter and are rather compact (low-porous). It can be supposed that the formation of aggregates with the high intraggregate porosity in the W and WC1 horizon, as well as aggregates with fragmentary granostriated b-fabric and low birefringence of the clay particles (Fig. 2c), is ensured by the local processes of the removal and/or destruction of clay material with a predominant loss of minerals of the smectitic group. Sokolova with coauthors [33] showed that the W horizon is depleted of the clay fraction with the loss of smectitic minerals.

A characteristic feature of the studied profile is the presence of silicate–calcitic infillings in channels containing the remains of the roots (Figs. 3d, 3f, and 3h). The number and thickness of the infillings increase from the W horizon to the WC1 horizon. Their maximum content is seen in the CWca,m horizon at the depth of 10–15 cm. This allows us to suppose the eluvial–illuvial redistribution of the clay material in suspensions within the microprofile of the weakly developed soil.

**Distribution of carbonates** in the soil profile also has a number of specific features. Carbonates in the parent material are represented by micritic calcite grains bound with the clayey material. Carbonate concentrations in the intraped mass have not been detected. The formation of carbonate pedofeatures in the form of compact growths of cryptograined calcite crystals in the pores is probably related to the process of biogenic calcification, which is most pronounced at the depth of 1.5–3 cm. Such carbonate concentrations are only found in the pores, which also contain the remains of the roots of different sizes and different degrees of decomposition. In some cases, they are formed inside the roots (Fig. 2f). A comparison of thin sections prepared from the samples taken in different years attests to quantitative rather than qualitative changes in the formation of calcitic growths in the pores with root residues. In the samples taken in 2012, the content of such growths is two times lower than that in the samples take in 2011. We suppose that this difference is related to the annual precipitation patterns. In 2011, annual precipitation reached 317 mm, which is higher than the mean annual precipitation (calculated for 50 years) in the area of the station (291 mm). In 2012, annual precipitation was considerably smaller (252 mm). The differences in the amounts of winter precipitation are much smaller: 157 mm in 2011, 142 mm in 2012, and 134 mm as the mean winter precipitation in the past 50 years. Thus, the year of 2012 was drier than the year of 2011, which could affect the intensity of synthesis of secondary calcite. This allows us to state that the described carbonate pedofeatures belong to the group of labile microforms sensitive to the regime of the soil moistening.

The presence of separate silty–clay aggregates without micrite in the upper 3 cm of the profile (Figs. 2c and 2d) attests to the local decalcification of the initially calcareous heavy loam. It is interesting that in the study of initial pedogenesis performed by Gagarina and Tsyplenkov [8] the authors also noted the presence of aggregates devoid of the micro- and cryptograined carbonates typical of the parent material in some microzones of the weakly developed humus horizon. In that study, the local loss of carbonates was observed on the tenth year of the soil development.

**Gypsum pedofeatures and their microfabric.** The "nests" and druses of gypsum (in the form of spherulites with radiant arrangement of the crystals) were earlier described in the lower horizons of the solonchakous solonetzes at the Dzhanybek Research Station. They were considered to be inherited from the parent materials [18, 32]. Special methods of the preparation of thin sections from such gypsum growths (to minimize their destruction) used in our study made it possible to examine them more carefully. It was found that they contain both relic (large xenomorphic) and modern (fine idiomorphic rhombohedral) gypsum crystals. The formation of modern gypsum crystals points to the partial recrystallization of the lithogenic gypsum growths. At the same time, the good degree of preservation of the large relic crystals attests to their relative stability despite the more pronounced percolative soil water regime in the artificial mesodepression in the past 30 years (Figs. 3c and 3d).

Few small concentrations of platy gypsum crystals in the pores of upper soil horizons attest to a slightly pronounced ascending migration of the soil solutions saturated with gypsum.

Thus, the results of the micromorphological study allow to state that some elements of the microfabric inherited from the initial parent material (platy microstructure, high density of the calcareous clay material with crystallitic b-fabric) have been transformed by frontal and localized pedogenetic processes. The frontal processes include the accumulation of moder humus and the zoogenic structuring of the mineral matter in the upper 3 cm of the weakly developed humic soil. Localized pedogenetic processes are responsible for the creation of microzonal features shaped by different combinations of these processes.

Thus, at the depth of 0–3 cm, we can see the features attesting to the (a) leaching of lithogenic cryptograined carbonates and (b) transformation of clay minerals and/or their destruction is separate aggregates, which is diagnosed by the lower birefringence of clay domains and by the fragmentation of clay coatings on mineral grains of the coarse fractions.

At the depth of 3–5 cm, we observe the features attesting to the (a) relatively active illuvial accumulation of the fine silty silicate–calcareous material with the formation of infillings and a very weak accumulation of the humus–iron–clayey material with the formation of thin iron–clayey coatings; (b) biogenic accumulation of elongated calcite crystals in the pores containing plant (root) residues and inside the tissues of these residues, (c) zoogenic and phytogenic (by roots) transformation of the thin platy cryogenic aggregates. In general, humus-accumulative processes and metamorphic (transformational) processes of the biogenic and cryogenic structuring of the soil mass are the most well-manifested processes in the studied soil.

**Microbiological data** indicate that the profile of this weakly developed soil has a high biogeneity, especially in the uppermost horizon (Fig. 5). Microbial patterns on fouling glasses are very distinct and dense. They attest to the great diversity of microorganisms, including bacteria, fungi, actinomycetes, diatoms and other soil algae, and cyanobacteria. The upper horizon is also rich in nematodes and some Protista. The diversity of the microbial community is obviously related to the input of litter from woody and herbaceous plants and active transformation of plant residues by the soil macro-, meso-, and microfauna. In the upper part of the profile (0–5 cm), active transformation of the raw organic matter takes place with participation of the soil microfauna, such as heterotrophic free-living nematodes.

One of the remarkable features of the distribution of microorganisms in the soil profile is a considerable decrease in their numbers at the depth of 10–15 cm. The density of microbial patterns on agarized glasses exposed in this horizon (Figs. 5i–5p) is much lower than that in the upper 5 cm (Figs. 5a–5h). The structure of the microbial community is also changed: the portion of eukaryotes is higher, and the portion of bacteria is smaller. The experiments with fouling glasses attest to the presence of micromycetes at this depth, though the inoculation of the soil suspensions onto the selective medium gave a negative result. It is probable that noncultivated forms of microscopic fungi were developed and even sporulated (Fig. 5m) on the fouling glasses. The biological components of soils are highly dynamic, and the structure of the biotic and, particularly, microbiotic complexes is subjected to considerable changes in response to the environmental impacts. So, we may conclude that at the moment of our studies, the prokaryotic activity in the layer of 10–15 cm was reduced. At the same time, the results of the micromorphological study attest to a relatively high porosity and biogenic aggregation of this layer, which may be related to the activity of micromycetes (Fig. 5i), algae (Fig. 5l), and microfauna (Fig. 5n). One of the reasons for the observed decrease in the biological (microbiological) activity in this layer may be related to the depletion of nutrients available for the microorganisms.

The increased biological activity of the lower horizon (30–40 cm) is due to the functional development of prokaryotic organisms. Mainly bacterial forms colonized fouling glasses (Figs. 5r–5t), and their sizes are much lower than those in the upper humus horizon. This is generally typical of the impoverished substrates, such as the lower horizons of the weakly developed soils.

The biogenic transformation of the mineral mass is observed in the entire profile; this process is clearly manifested in the deep (30–40 cm) horizon. All the horizons display the concentration of microorganisms around mineral, organic, or organomineral soil particles (Figs. 5a, 5d, 5h, 5o). In the lower part of the profile, the concentration of microorganisms around mineral particles is especially pronounced, because, because of the absence of available organic matter entering the soil with plant falloff, mineral serve as the only source of nutrients. The high biogeneity of the entire soil profile is indicative of the favorable properties of the parent material for the development of microorganisms. The parent material is also characterize by the high adsorptive properties. As a result, the number of microorganisms in the lower soil horizons remains significant and reaches 5.8–6.1 log CFU/g soil. These microorganisms are represented by oligotrophs and ammonifiers.

The activity of humus-accumulative and biogenic transformation processes that was noted during the micromorphological study of the soil profile is also confirmed by the data on the numbers and activity of microorganisms.

## CONCLUSIONS

(1) In 30 years of pedogenesis under forest vegetation on calcareous gypsum-containing heavy loams exposed to the surface with an artificial mesodepression in the semidesert zone, a weakly developed initial soil with specific sets of micromorphological and biological characteristics has been shaped.

(2) In the topmost 3 cm of the soil profile, humus-accumulative processes of the moder type and active zoogenic aggregation of the mineral matter take place. The microfeatures of the initial pedogenesis are clearly differentiated in the profile. The leaching of the crypto- and micrograined calcite inherited from the parent material and the transformation and/or partial destruction of clay minerals in separate aggregates take place in the uppermost 3 cm. Below (3–5 cm), active illuvial accumulation of the fine silty silicate–calcareous materials and weak accumulation of the humus–iron–clayey material take place. This horizon is also characterized by the biogenic accumulation of micrite crystals in the pores containing plant residues and the zoogenic and phytogenic (by roots) transformation of the thin platy cryogenic aggregates.

(3) The growths of large gypsum crystals inherited by the soil from the parent material have been subjected to some dissolution with the development of small idiomorphic rhombohedral gypsum crystals in the enclosing material. No new horizons with pedogenic gypsum concentrations have been shaped.

(4) The biological processes in the horizons of the weakly developed soil are sufficiently active, except for the denitrification process because of the deficit of the mineral forms of nitrogen.

(5) Micromorphological and microbiological studies indicate that the evolution of the weakly developed soil is directed toward the formation of the quasigleyed chestnut soil typical of the microlows in the surrounding semidesert soil complexes. The microbiological transformation of the mineral and organomineral phases has somewhat different patterns in separate soil horizons within the upper 15 cm of the profile. The highest intensity of the microbiological processes is typical of the weakly developed humus (W) horizon.

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