Byulleten Pochvennogo instituta im. V.V. Dokuchaeva. 2016. Vol. 86.

УДК 631.4

HIERARCHICAL MORPHOGENETIC ANALYSIS OF KURSK CHERNOZEM

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Each of four hierarchical levels in the morphogenetic research is characterized in terms of technical and information facilities. A detailed hierarchical study was performed for the first time for chernozems and may be qualified for a basic one. Its results comprise confirmation of occurrence and details in manifestations of pedogenetic processes well-known in chernozems, as well as additional information on the pedofauna contribution to chernozem formation, variability and dynamics of carbonate pedofeatures, stability of the mineral soil ingredients.

Key words: typical chernozem, hierarchical levels of soil mass arrangement, coprolites, calcite pedofeatures, elementary mineral particles.

DOI: 10.19047/0136-1694-2016-86-64-76

The method of hierarchical morphogenetic analysis was first implemented by Roy Brewer, the first micromorphologist who formalized the description of thin sections and proposed the idea to study the structural arrangement of soil material (1964). The most complete implementation of this approach was performed by a research group headed by Victor Targulian with the example of a soddy-(pale)-podzolic soil (Retisol according to WRB-2014) near Moscow; genesis of this soil was actively discussed during the Xth International Congress of Soil Scientists in 1974 by the outstanding representatives of national pedological schools. It was possible partly owing to the new data obtained by the hierarchical method. The next study objects were saline soils: the last stage of hierarchical investigation performed by Sergey Shoba, Irina Yamnova, and Tatiana Tursina was the submicroscopic diagnostic of salt minerals (1980). Some elements of the hierarchical approach are recorded in a number of publications, where soil components were examined at 2–3 levels (Pustovoitov, Targulian, 1996; Bronnikova, Targulian, 2006). Commonly, combinations of macro- and meso-features, or macro- and micro-features are described, hence, the morphological sequence appears incomplete. Examples of full-set hierarchical research are the studies of Andrey Gogolev for the texturally differentiated soils (1986), Sviatoslav Inozemtsev and Victor Targulian for Permian paleosols (2010), Ilya Shorkunov for the Pleistocene pedolithocomplexes of the East-European Plain and Mexico (2013). In the set of levels composing the hierarchical system, the least elaborated is the submicroscopical one because of insufficiency of expensive devices, technical difficulties of the method, as well as absence of common terminology and approaches for interpreting soil components at submicroscopic level. The same is true for mesomorphology making its first steps towards designing concepts and terminology: a first guide appeared quite recently (Field training…, 2013).

The field (*macro*)*morphology* describes objects visible without any devices. The resolution of human eye is about 0.n mm, the field of vision is not limited. At the macro-level, the profile horizonation is analyzed, the morphogenetic description of horizons is afforded with indication of their heterogeneity in commonly identified features, which size exceeds the resolution of the human eye. The advantage of macro-level is the possibility to obtain a general impression of the soil profile as of a paragenetic association of horizons, as well as the three-dimensional hierarchical arrangement, so to say "architecture" of the soil body.

When using the magnifying devices at meso-, micro- and submicro-levels, study objects are samples with undisturbed fabric: fragments of genetic horizons, individual fabric elements (aggregates, pedofeatures). The size of sample investigated is limited by non-optical technical parameters: length of extension pole handling the optical system, diameter of the microscope stage (Table). A comprehensive morphological picture may be observed with the help of magnifying tools only within the field of vision. To obtain a broad morphological image of a horizon or morphon, a procedure of expert synthesis of the vision fields observed is necessary, similar to assembling a puzzle.

Investigations at meso- (low-magnification digital microscope), micro- (polarizing microscope) and submicro- (scanning electron microscope) levels may be performed in a broad range of magnifications

Magnifications and corresponding fields of vision

Magnification	×6.3	×10	×40	×100	×400	×20 000
Field of vision area, mm^2	960	415	22	3.5	0.9	0.02
Levels	Meso		Micro		Submicro	

providing the instrumental overlapping, which means conjugation of information obtained by neighboring levels. For example, the polarizing microscope enables working in the range of magnifications from 8 to 400×, whereas the scanning electron microscope magnifications range from +100 до 20 000–30 000 are common.

At the *mesomorphological level* samples with undisturbed fabric are studied in reflected light: small morphons, medium-size (10 cm and smaller) aggregates and their arrangement in the soil mass, other fabric elements tenth parts of millimeter in size. Kursk chernozem was studied in the magnification interval: +6.3 to +40 with Leica microscope, its resolution is centesimal fractions of a millimeter permitting to discern coarse silt particles, individual crystals, their spatial patterns within the pedofeatures, for example, the internal arrangement of ingredients in coatings.

The main distinction of *micromorphological level* of other hierarchical levels of morphogenetic research is the object – fine section of the soil material i.e. a two-dimensional instead of the three-dimensional one, as well as optical properties of the object. The limit of the optical microscope resolution is 0.2 µm. The objects of investigation are aggregates and voids, organic matter and its bonds with the mineral soil ingredients, details of pedofeatures fabric, mobility of the fine disperse part of the soil (Bullock et al., 1985).

Scanning electron microscope JEOL JSM-6610LV used in the *submicroscopic* research, has a gentle regulation of magnifications in the interval ×35…×300 000. Particularities of soil objects: heterogeneity of material, occurrence of low-density components, such as organic matter, high-porosity loci, permit to obtain a distinct image in a stable regime at magnifications below +20000–30000. At these magnifications, it is possible to identify objects about 2×10^{-2} µm in size. As a rule, the undisturbed samples for electron microscopy are chosen at the meso-level. Technologies of scanning electron microscopy and sample preparation provide the possibility to observe either the surfaces of different objects (aggregates, voids, grains, pedofeatures related to the surfaces), or internal arrangement of the groundmass and pedofeatures. Moreover, the electron microscopes are usually supplied with microanalyzers enabling to accompany the submicroscopic observations by point and areal semi-quantitative microanalysis of the elemental substance composition. Thus, surfaces of mineral grains are studied, pore walls and their covers, shape, perfection and/or distortion of monocrystals or crystal aggregates, mutual arrangement of crystals and patterns of amorphous substances.

Despite the abundance of publications on chernozems, their micromorphology and aggregation, in particular (Chernozems of the USSR, 1974), a complete morphogenetic hierarchical investigation has been performed for the first time. As in case with soddy-podzolic soil, it was made by a team of specialists guided by the Institute of Geography RAS when preparing the International workshop on paleopedology (Guidebook..., 2013).

The object of the hierarchical morphological study – typical medium-thick chernozem from Kursk oblast; its full name in the classification system of soils of Russia (Classification…, 2004) is the following: migrational-mycellary zooturbated chernozem (post-agrogenic?) medium-thick, medium-humus, heavy loamy on loess-like loam. The pit is located 10 km to the south of Kursk on an interstream surface under grass-forb pasture. Absolute altitude (GPS) 244 m, coordinates: N 51°32’23.4”; E 36°05’11.8”.

Macromorphology. The chernozem profile has the following sequence of horizons: humus-accumulative AU gradually merging into the strongly reworked AUb,zoo and carbonate-accumulative BCA to the depth of 170 cm (Fig. 1). The main properties of the profile are typical of the central image of a chernozem of the southern forest-steppe (Chernozems..., 1974), and fully correspond to the given name.

For this profile, most characteristic features are the following: (1) several types of coprogenic aggregates in all parts of AU horizon predominating among all other aggregates; (2) structure homogeneity only in the uppermost part of AU horizon – up to 20–30 cm; (3) extremely strong and heterochronous reworking of transitional horizons by diverse soil animals; (4) indistinct boundary of carbonate appearance in the profile and considerable thickness along with varying degree of effervescence in krotovinas and morphones; (5) diversity of

Fig. 1. Morphological profile of Kursk chernozem.

migrational carbonate pedofeatures in carbonate-accumulative horizons: punctuations, fine tubes, efflorescences. Features (1) and (2) may testify to the arable past of the soil; dynamics of pedogenic carbonates is reflected by the features (4) и (5).

Thus, information at the macro-level permits to reveal the diagnostic indices of the main profile-forming processes, define the taxonomic position of the soil, record its probable agrogenic elements, manifest the contribution of pedofauna, and the character of the carbonate profile, which is diagnostic for chernozem subtypes (Classification…, 2004).

Mesomorphology. A detailed characteristic of the multi-level structural organization of chernozem and its pore space, additional information on the heterogeneity within horizons and morphons, description of biogenic fabric elements, diversity of carbonate pedofeatures and their distribution as along the profile, so in individual horizons. More information is given here about this level, since it is weakly known.

The upper part of the dark-humus horizon is homogeneous in terms of consistence, structure and color. The whole mass is aggregated. Homogeneity indicates the post-agrogenic nature of this part of the horizon and is in good agreement with the status of soil under a rather simple phytocenosis as compared to the initial one. There are loci abounding in plant detritus. The abundance of coprolites produces the effect of a porous sponge. Coprolites are dark, of similar size (3–5 mm). Fresh coprolites are both single and clustered and have intricate internal porosity. Old coprolites are incorporated into the multi-level structure forming its background – primary peds (Fig. 2a). The structural levels comprise: coarse blocks- clods → blocks → rounded and angular crumbs → angular aggregates → isometric coprogenic aggregates. The supposed former arable land use may be confirmed by the above sequence of peds comprising angular ones. Many light-colored sand and silt grains, which may be interpreted (accounting also for the color of pedfaces) either as "podzolization" inherent to forest-steppe chernozems, or, as a rather common property of the upper parts of arable horizons resulting of their surficial position, the so-called splash effect (Fedoroff, 2009). It means breaking down the aggregates by rain drops and removal of fine material downward within the first few centimeters of the upper horizon. Sometimes pedfaces are more light in color than ped interiors.

The parent material' property – prismatic elements – appears below 30–40 cm, first in combination with blocky peds of lower level;

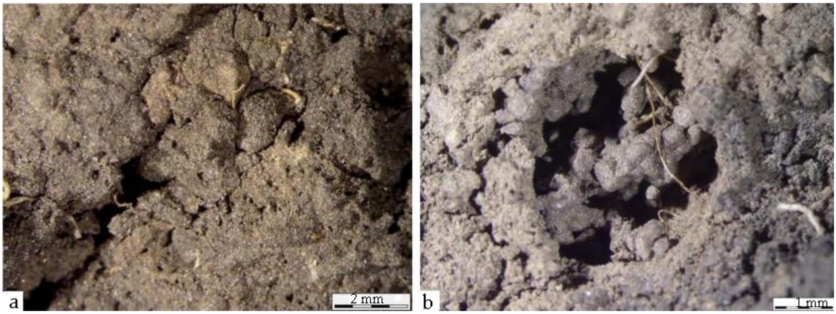

Fig. 2. Coprolites: a – in the upper part of AU horizon, partly degrading, brownish – assimilated from the lower horizons, porous, with whitish sandy grains; b – in the lower part of AU horizon – pedotubule composed of fresh copropiltes in the centre and older ones at the periphery.

deeper than 0.5 m, the peds resemble triangle pyramids, and this structural motive is preserved to the end of the profile. In the lower part of the AU horizon, the coprolites become slightly different although they are still numerous; they are larger in size, more intricate and compact, some of them are interlaced by fine roots; old brown coalescent coprolites occur (Fig. 2b).

The horizon with the most prominent zoogenic reworking (up to 1 m) is peculiar by old and new krotovionas distinctly separated of the brown groundmass; pedotubules are composed of brown and dark gray coprolites, and roots are confined to them. Vesicles may be related to the appearance of carbonates: needle-shaped calcite crystals are found in some places.

Carbonate pedofeatures have common manifestations in BCA subhorizons. These are impregnation mottles, fine soft nodules, coatings and quasicoatings, including those composed of fibrous and acicular (needle-shaped) calcite, vermiform infillings of microsparite in fine tubular voids that are found only in the carbonate-accumulative horizon. In its upper part, mold-like efflorescence on pedfaces prevail among carbonate pedofeatures, in some of them needles are clearly discerned, they are not oriented and intermingled and about tenths of a millimeter in size (Fig. 3a). Impregnation mottles are identified only by lighter color (Fig. 3b). Punctuations (up to 1 mm) are filling the voids: their outer layer is composed of fine weakly separated needles and re-

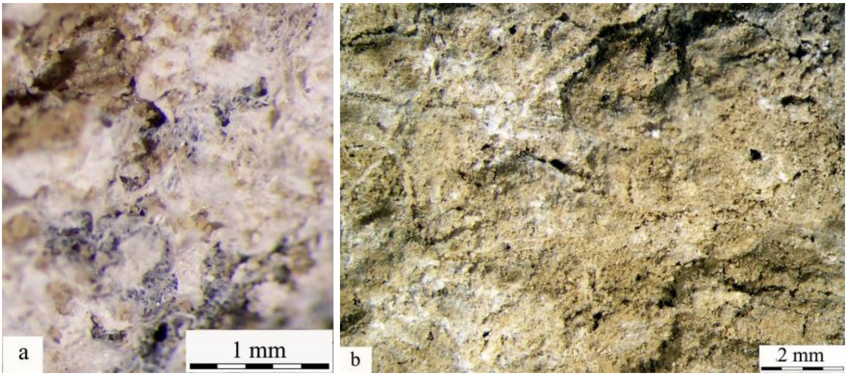

Fig. 3. Carbonate pedofeatures: a — in the upper part of BCA horizon, mold-like efflorescence; b – in the upper part of AU horizon, in the lower part of BCA horizon, impregnation forms.

sembles felt, the inner part is more compact and composed of fine rounded crystals.

In the lower part of the horizon there are many carbonate phytomorphoses: grains of coarse-grained calcite, limpid with a glass shining, elongated or cylindrical, 0.2 mm in diameter and 1 mm long, they are confined to voids – remnants of root channels (Fig. 4a). Acicular calcite occurs as a continuous cover over the pedfaces and displays different limpidity: bright white multi-layer covers of acicular calcite, pale one-layer of disordered fibrous calcite. Dark coprolites have sometimes fine coatings of needle-shaped calcite (Fig. 4b) and display a weaker effervescence than the brown groundmass. Coprolites are confined to coarse voids, chambers and passage ways; they vary in shape, degree of preservation, and color – black, dark gray and brown. The passage ways are filled with rounded coprolites interlaced by very fine roots (root hairs).

In this way, the information from the macro-level is confirmed by the data obtained at meso-level; moreover, additional information is generated, in particular, that concerning the set of elementary soil-forming processes – ESP, and patterns of their diagnostic features within horizons.

At *micro-level*, some characteristics responsible for the formation of the dark-humus horizon are added. They comprise the results of soils fauna activity, details of carbonate pedofeatures composition and size, orientation of crystals in them, the ratio of various fabric types in a horizon. Micromorphological features confirm the stability of the profile, since there is no optically oriented clays in the micromass.

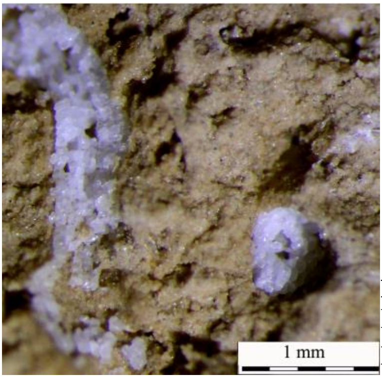

Fig. 4. Carbonate pedofeatures in the lower part of BCA horizon: sparite phytomorphoses.

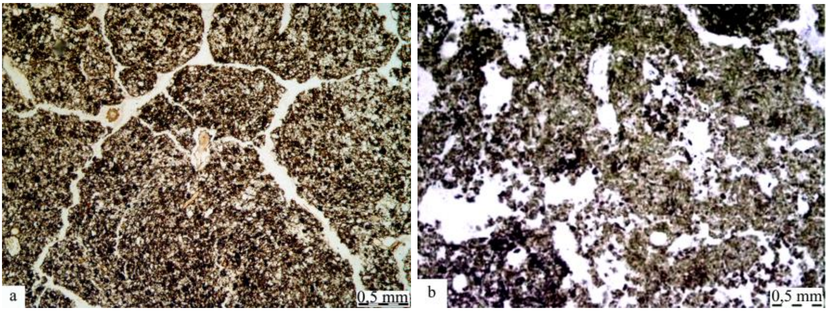

Fig. 5. Pedality of the AU horizon, NII: a – medium in the postagrogenic part; b – active reworking by pedofauna, inclusions of brown coprolites.

Micromorphology of the upper part of the AU horizon confirms its post-agrogenic nature: the material of coprolites is weakly aggregated (Fig. 5a). The process of coprolites assimilation in the groundmass is obvious in deeper layers, and concerns either dark coprolites (their "own" horizon), or the brown ones, translocated from the carbonate-accumulative horizon by active zooturbation (Fig. 5b), and later leached.

Carbonate pedofeatures are abundant and diverse, they are composed by crystals differing in size: from cryptocrystalline forms to medium-grained isometric and acicular crystals; carbonates impregnate plasma, coarse crystals and aggregates of crystals are included in the micromass, coatings, quasicoatings, infillings, nodules. Basically, the microforms of calcite are in good agreement with those observed at the meso-level (Figs. 6a, 6b and 7a, 7b) and testify to high mobility of carbonates in the lower part of the dark-humus and zooturbated horizons. However, the spatial distribution of pedogenic calcite pedofeatures does not indicate any distinct sequence of their accumulation. It is not impossible that the diversity of secondary carbonates derives from the spatial variability of the conditions of their formation and/or seasonal dynamics of their accumulation and redistribution.

At the *submicroscopic level*, the packing of mineral components of the groundmass is described, as well as surfaces of mineral grains: percussion-pits, fracturing features, etching pits etc., and coatings. Additional knowledge was gained for understanding the internal fabric of carbonate pedofeatures: for describing their cryptocrystalline varieties,

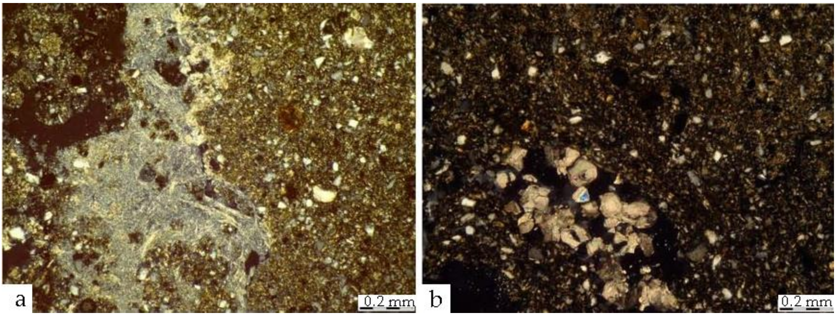

Fig. 6. Carbonate pedofeatures, NX: a – infilling composed of acicular calcite; b – sparite in the void.

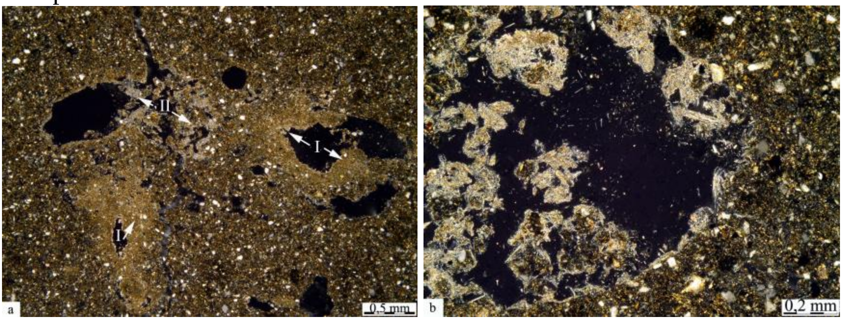

Fig. 7. Carbonate pedofeatures, NX:a – micritic hypocoatings (I); acicular calcite calcite (II); b - acicular calcite over pedofauna castings.

differentiated characteristics of single crystals and aggregates of crystals. Investigations manifested the speckled b-fabric of clay plasma domains (Fig. 8), its submicro-granularity in some places, which may be attributed to the inclusion of organomineral glaebules, rather common occurrence of organomineral films on silicate grains and complete absence of chemical damages on grain surfaces (Fig. 9). It is shown that the stable status of clay plasma does not exclude its short-distance migration~~s~~: some crystals of pedogenic carbonates are partly covered by clay plasma. Part of coarse-needle (cylindrical) calcite crystals (ca. 1µm thick, 10–50 µm long) are crystal intergrowth rather than monocrystals, aggregates of finer ribby cylindrical crystals (decimal ractions of micron thick). Such coarse-needle intergrown crystals are frequently arranged in interlaced fibers up to 10 µm thick (Fig. 10). Cryptocrystalline forms of pedogenic calcite were discovered as dense coatings over

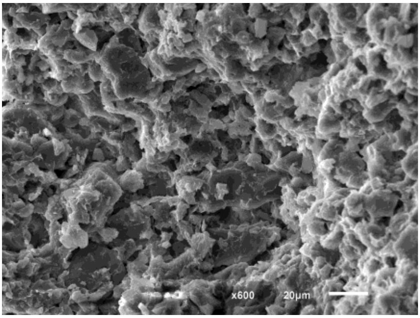

Fig. 8. Speckled b-fabric in plasmic domains, ×600.

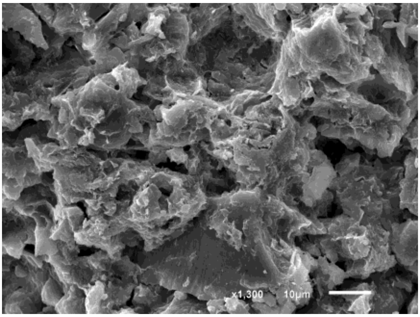

Fig. 9. “Clean” mineral grain (in front) and organomineral films, ×1300.

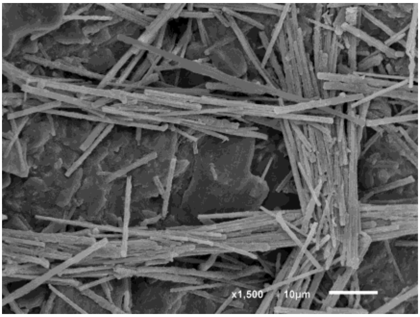

Fig. 10. Coarse-acicular calcite, ×1500.

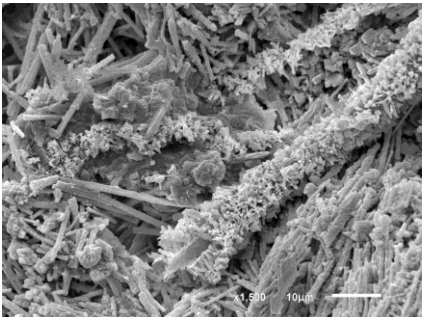

Fig. 11. Calcite crystals over biogenic bodies, ×1500.

the tubes – hyphas of fungi and actinomicetes, composed of subvertically oriented and random crystals (Fig. 11), as well as aggregates of crystals, irregular short-needle or wedge-shaped, and of distinctly short-needle crystals (0.5–1 μm in length and hundredths fractions of micrometer in thickness).

CONCLUSIONS

Bearing in mind the statement on the dependence of the information capacity on the objectives of research, nevertheless, it is possible to note that the importance of each of four hierarchical levels is different for solving pedpogenetic problems. The spatial arrangement at the macro-level permits to reveal the main pedogenetic trends and their proportion. At the meso-level, primarily the contribution of pedofauna and interhorizon translocations of substances along the interpedal and transaggregate voids are recorded, particular elements of pedofeatures (differentiated or homogeneous fabric; kind of surfaces shape, orientation and mutual arrangement of crystals). The micro-level permits to identify substances migrations, as within the horizons, so in the morphons, structural re-arrangement of the groundmass, and some qualitative properties of the latter. Important is recording of the referred distribution of fabric elements enabling the soil scientist to reconstruct the sequence of events. The details description of elementary mineral particles at the submicro-level are aimed at revealing their initial pattern and that after pedogenic modifications; for pedofeatures, the details of their structures should be described. However, we presume that the interpretations of submicroscopic data are at their initial stages.

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For citation: Gerasimova M.I., Bronnikova M.A., Khitrov N.B., and Shorkunov I.G. Hierarchical morphogenetic analysis of kursk chernozem, *Byulleten Pochvennogo instituta im. V.V. Dokuchaeva*, 2016, Vol. 86, pp. 64-76. doi: 10.19047/0136-1694-2016-86-64-76