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DEGRADATION, REHABILITATION, AND CONSERVATION OF SOILS

Morphogenetic Diagnostics of Soil Formation on Tailing Dumps of Coal Quarries in Siberia

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Abstract—Morphological diagnostics of soil-forming processes in the young soils of technogenic landscapes are considered. Comprehensive multilevel studies of soils developed on the tailings of coal mines of different age in a wide range of climatic conditions in Siberia are performed. The processes of the mineral substrate transformation predominate at the initial stages of soil formation. Then, with the development of the soil profiles, the processes of the organic matter transformation begin to play the major role, and the organoprofiles of the soils specific to the particular climatic zone are formed. Micro- and submicroscopic studies allow us to judge the character of major soil processes and to identify the features attesting to the activity of some associated processes.

Keywords: technogenic landscapes, embryozems, micromorphology, soil evolution, humus

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INTRODUCTION

Nowadays, with year-to-year accelerating rates of mining in Russia, the technogenic landscapes have become an ordinary phenomenon not only in traditionally industrial regions but also in many other regions. Owing to their specific properties and regimes, these landscapes attract much attention of experts in various scientific fields, and the research related to these landscapes remain timely for decades. For the most part, technogenic landscapes are composed of deposits removed from other geochemical environments, and their functioning is aimed at achieving an equilibrium between the properties of these rocks and the environment; that is why they are of extraordinary interest to soil scientists. In our opinion, the mechanisms of achieving this equilibrium or, in other words, the soil-forming processes deserve particular attention, as the identification of these processes permits assessing the specific features and transformation trends.

Siberia covers above 80% of all mineral and energy resources of Russia [30]. Their uneven distribution determines the presence of highly technogenically loaded areas; therefore, the problems concerning the identification of young soil formation become still more acute owing to the substantial diversity of both technogenic bodies proper and the climatic conditions in the areas of their location.

The existing approaches to the diagnostics of soil-forming processes that develop on the surface of technogenic landscapes may be subdivided into two major groups. The first group comprises investigations focused mainly on rock properties. Above all, the particle-size distribution and the mineral composition are taken into account, and more rarely, the content of soluble salts, pH of the medium, and the cation exchange capacity of the soils [10, 15, 21, 41, 46, 50]. Researchers of the second group deal with the identification of soils by the type of their organoprofile [3–5, 9, 23–24, 36–39, 48]. The first group of approaches is based on the properties inherited from the parent rocks, whereas the second group of studies provides information on the ongoing soil processes. However, these processes are controlled to a great extent by the lithogenic buffering capacity [2]; therefore, even this information is not always enough for genetic interpretation of soil forming processes. Hence, the comprehensive approaches and methods based on the determination of both acquired and inherited substrate features are necessary for identifying the processes that develop in the soils of technogenic landscapes.

The comparative geographical and structural organizational approaches are assigned to this group; their application combined with the morphological methods permits obtaining new data for each soil organization level [12, 34]. Micromorphological methods are of par-

Table 1. Climatic conditions of soil formation in the studied region

Parameter	Coal mine nam				
	Olzherasskii	Listvyanskii	Chernogorskii	Chadanskii	Kaa-Khemskii
Geomorphological region	Kuznetskii Alatau	Kuznetskaya depression	Minusinskaya depression	Khemchikskaya depression	Central-Tuva depression
Climate type	Humid	Subhumid	Semiarid	Arid	Extracontinental arid
Sum of active temperatures, °C	1500–1700	1700–1900	1900–2000	2100–2200	2100–2200
Annual precipitation, mm	750–1400	400–500	250–300	220–270	170–250
Hydrothermal coefficient according to Selyaninov	1.9	1.5	1.2	1	0.7
Moistening coefficient according to Ivanov	2.2	1.3	0.7	0.6	0.3
Zonal soils	Soddy deeply podzolic	Leached chernozems	Southern chernozems	Dark chestnut	Steppe cryoaridic*

* Soil type according to Volkovintser [8].

ticular interest in the study of young soils of technogenic landscapes, because they allow us to perform the early identification of the products of soil functioning at the initial stage of soil development [16, 42] and thus to predict the further evolution of young soils.

In this connection, our study was aimed at revealing the regularities and the specific features of soil formation in technogenic landscapes located under different natural and climatic conditions of Siberia using the methods of multilevel morphological studies.

OBJECTS AND METHODS

The soils of technogenic landscapes widespread in various natural zones of Siberia were taken as the objects of our study. The soils formed on the tailing dumps of coal mines meet this criterion. In Siberia, they are located in different climatic zones. By different estimates, their total area ranges from 100000 to 300000 ha, increasing significantly every year. The studied tailing dumps are subdivided by their age into three groups [3]: young (up to 10 years old), of medium age (10–20 years) and old (older than 20 years).

We studied the soils in autonomous positions of technogenic bodies located in humid and subhumid (mountain-taiga and forest-steppe zones of Kemerovo oblast), semiarid (Khakassia steppe), and arid and extracontinental arid (dry steppe in Tuva) climate. Thus, the studied objects form a sequence by increasing aridity and continentality of climate (Table 1).

The studied territories are characterized by the technogenic landscapes represented by dumps of sedimentary rocks (argillites, siltstones, and sandstones) of different age. Young soils (all of them with a high content of rock fragments) are formed on these substrates. In the soil profile, the content of stony fractions exceeds 70%, fine earth is no more than 25%, and physical clay is less than 10% [39].

Macro-, micro-, and submicroscopic investigations were conducted. The macromorphological identification was performed on the basis of classification of soils of technogenic landscapes developed by Gadzhiev and Kurachev [9]. Soil profiles were described according to the routine procedures adopted in soil science [33].

For the identification of soil-forming processes on micro- and submicromorphological levels, the fine-earth samples were collected from the soil profiles and packed in special boxes. Owing to a high stoniness, sometimes it was impossible to preserve the initial fabric; therefore, individual aggregates were analyzed. Micromorphological observations were performed with a Hitachi TM-300 scanning electron microscope supplied with a Bruker Quantax 70 EDS device for the elemental analysis of the surface. This microscope model, owing to the available low-vacuum regime, permits studying samples in the range of magnification to 2000–5000 (depending on the dielectric permeability of sample) without metal sputtering. This ensures more precise results of assessing the elemental composition. The analyzed samples were stuck on a conductive tape fixed to a metallic ground, which was next put into the microscope. The microscope analysis included three stages: (1) typification and revelation of the main morphological elements of the studied sample using a stereoscopic microscope; (2) taking images of the found structural units using the scanning microscope; (3) analysis of the elemental composition at the surface of revealed bodies for their identification. Besides the soils formed at the surface of technogenic landscapes, we analyzed the samples of natural zonal soils, as well as of the soil-forming rocks. The data obtained were interpreted on the basis of the international collaborative work *Interpretation of Micromorphological Features of Soils and Regoliths* edited by Stoops [49] as well as the paper by Gerasimova et al. [13].

RESULTS

The macromorphological investigation of soils on the tailing dumps of coal mines located under various climatic conditions showed that their profile differentiation starts with the formation of specific organic horizons. According to the classification of soils in technogenic landscapes, each soil type is identified by a relevant type-diagnostic horizon [9]. For example, in the investigated areas, the initial, organo-acumulative, soddy, and humus-accumulative embryozems were registered. The authors of the classification system we use point out that each type of embryozems correlates with a certain stage of soil formation identified by the degree of manifestation of organo-accumulative, soddy, or humus-accumulative processes. On the surface of technogenic landscapes in Kuzbass and KATEK, where this classification was first tested, the stages enumerated successively replace each other. The rate of transition from the initial to organo-accumulative and further to soddy and humus-accumulative embryozem is controlled by the geogenic conditions in the technogenic landscape (the soil-forming rocks and topography), as well as the specific features of bioclimatic parameters of the environment. The investigated soils should be considered as an evolutionary sequence rather than the stages of self-development [4], because the described change in soil-formation stages is accompanied by the succession of biocenoses [38] and modifications of microclimate and the initial substratum properties.

The initial embryozems correspond in the classification systems of Russian soils [21, 29] to the subgroup of lithostrata of naturfabricats group of technogenic surface formations. Organo-accumulative embryozems correspond to the psammozem type, which are assigned to the order of weakly developed soils in the trunk of primary soil formation. Soddy and humus-accumulative types of embryozems are the closest to humus psammozems and humus pelozems in the order of weakly developed soils; hence, they are also included in the trunk of primary soil formation column [29].

A high stoniness appears to be a common feature of all soil profiles in all investigated regions. Initially, the soil-forming rocks represent a chaotic mixture of the overburden and enclosing rock fragments varying in size [27, 32]. The heterogeneity of coarse material pattern is also preserved in soils, although being transformed in the course of pedogenesis.

The processes of physical disintegration are the most pronounced in the *initial embryozems* characterizing the first stage of the substratum transformation [26]. The absence of any macromorphological signs indicating the soil development is a distinctive feature of these soils (Fig. 1a). The profile is not differentiated into genetic horizons because of a relative young age of these soils, which are widespread on young and middle-age tailing dumps. (Table 2). On old dumps, initial embryozems are encountered only in the sites with extreme edaphic conditions. Since the dump-composing rocks are mainly gray or dark gray, the surface of initial embryozems is subject to the effects of significant temperature fluctuations; this, in turn, favors an active disintegration intensified by sedimentational stratification in the enclosing sedimentary. Disintegration of fragments slows with the depth, where these fluctuations are less significant than on the surface. Therefore, the amount of stones in the studied soils increases down the profile.

Organo-accumulative embryozems represent the next stage of soil evolution in the technogenic landscapes in Siberia [26]. Vegetation development results in accumulation of organic residues (litter) and formation of an organo-accumulative horizon (Fig. 1b). However, a high content of stones in the upper part of the profile is responsible for its drying, which limits the development of microorganisms decomposing plant residues. That is why the organo-accumulative horizon influences the transformation of the underlying mineral part of the soil profile mainly through the regulation of water and heat regimes.

In the profile of organo-accumulative embryozems formed on young and middle-age dumps, the organic horizon consists of preserved and slightly decomposed residues of forbs. The same material constitutes similar horizons in the organo-accumulative embryozems on the old dumps, excluding those in the mountain-taiga zone. In the latter case, under the conditions of a markedly pronounced humid climate, woody vegetation becomes predominant. Therefore, in this type of embryozems, the litter horizon is represented mainly by undecomposed forest litter.

This soil type is not developed on young dumps in the two most arid regions of investigations performed, which is one of the specific features of technogenic landscapes in Siberia. Under the conditions of an arid extracontinental climate, organo-accumulative embryozems are not formed on the middle-age dumps either (Table 2).

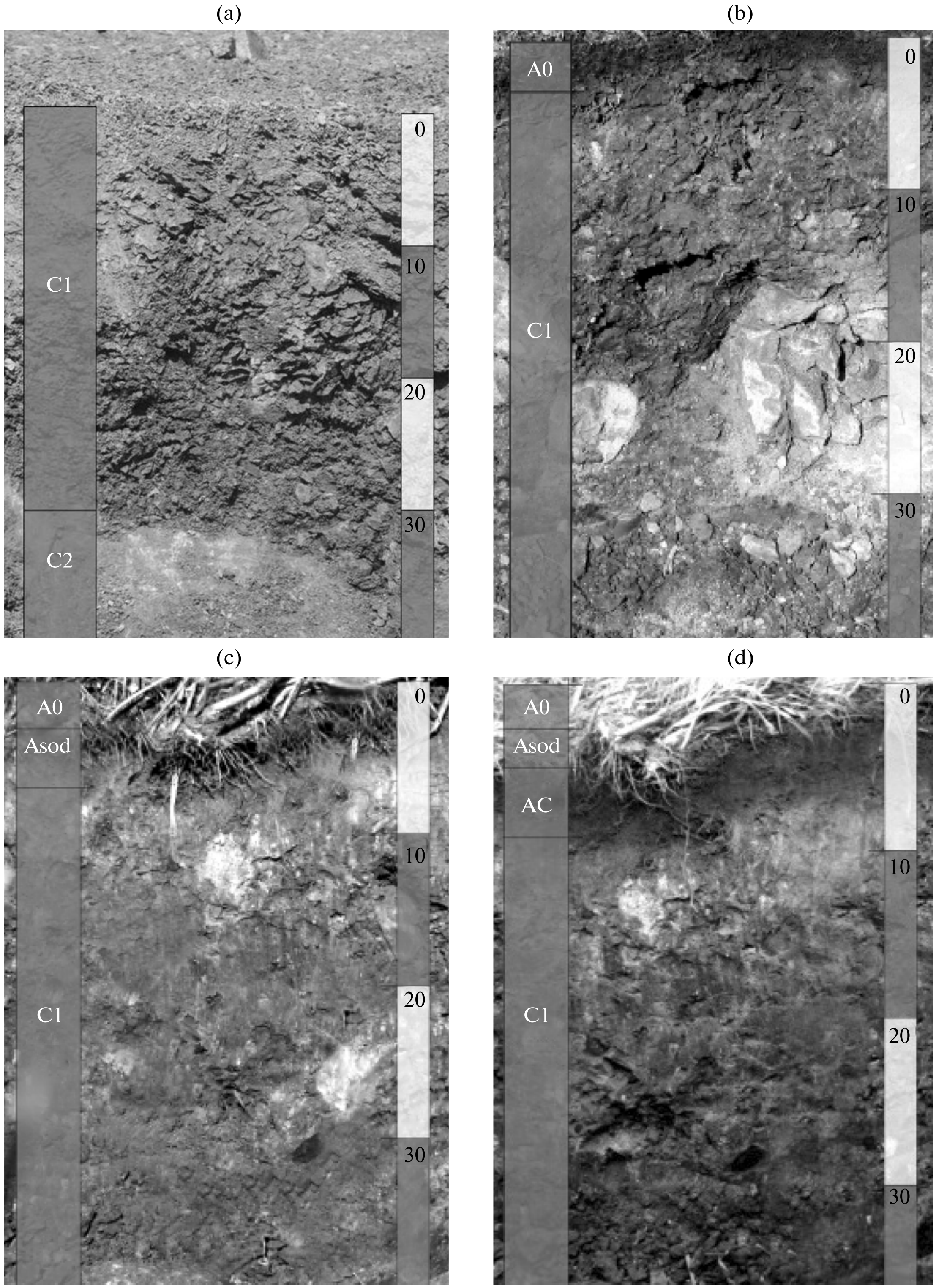

Fig. 1. The profiles of embryozems: (a) initial, (b) organo-accumulative, (c) soddy, and (d) humus-accumulative.

Soddy embryozems are characterized by the presence of one more organic horizon, i.e., soddy horizon, in their profile (Fig. 1c). Unlike the two above-described soil types, soddy embryozems are not widespread. They are formed only on dumps located in a less arid climate. In a humid climate, soddy embryozems were registered only on middle-age dumps. The reason is that with the developing woody vegetation, the soddy process is

Table 2. Differentiation of embryozems in technogenic landscapes of southern Siberia

Coal mine name	Embryozems			
	initial (C)	organo-accumulative (A0–C)	Soddy (A0–Asod–C)	Humus-accumulative (A0–Asod–AC–C)
Young (less than 10 years) dumps				
Olzherasskii	+	+	+	–
Listvyanskii	+	+	+	–
Chernogorskii	+	+	–	–
Chadanskii	+	–	–	–
Kaa-Khemskii	+	–	–	–
Middle-age (10–20 years) dumps				
Olzherasskii	+	+	+	–
Listvyanskii	+	+	+	+
Chernogorskii	+	+	–	–
Chadanskii	+	+	–	–
Kaa-Khemskii	+	–	–	–
Old (more than 20 years) dumps				
Olzherasskii	+	+	–	–
Listvyanskii	+	+	+	+
Chernogorskii	+	+	+	–
Chadanskii	+	+	–	–
Kaa-Khemskii	+	+	–	–

replaced by litter accumulation [1]. Therefore, soddy embryozems are again replaced by organo-accumulative soils on old dumps. Soddy embryozems are preserved only in places where the development of trees is suppressed for some reason. As a rule, these are territories of former roads or technological sites.

This soil type is the most widespread on dumps in the forest-steppe zone (Table 2). For example, in a subhumid climate, soddy embryozems are present on both middle-age and old dumps, whereas in a semiarid climate (the surface of technogenic landscapes in Khakassia), soddy embryozems are registered only on old dumps.

When assessing the soddy horizon, its discontinuous distribution should be noted, in particular, in the soils developed on young and middle-age dumps. In the case of continuous occurrence of the soddy horizon, it passes sharply to the underlying part of the profile. This interrelation between organic and mineral horizons testifies to the insignificant contribution of biological processes in the substratum transformation [32].

Humus-accumulative embryozems have a humus-accumulative horizon in addition to the litter and sod horizon (Fig. 1d). They are spread only locally on the dumps of coal mines in Siberia; they are found only in the forest-steppe zone on old dumps (Table 2). Above all, this is due to the fact that, initially, the soil-forming substratum in technogenic landscapes has a low content of physical clay (no more than 15%), which is expedient for binding the humus formed to the mineral phase [35]. Humus accumulation becomes possible only on old tailing dumps and only when the disintegration processes provide accumulation of a sufficient amount of fine fractions.

Thus, the analysis of macromorphological features pointed to the prevalence of mineral substratum transformation or, according to Gerasimov [11], the primary soil formation at the first stages of soil profile development. This is manifested in the disintegration of stone fragments and profile differentiation by their content. Further, with the developing communities of living organisms on dumps, the processes of transformation of organic residues start playing the leading role in soil profile formation. The forest-steppe conditions (subhumid climate) appear to be optimal for humus accumulation. With growing climate aridity, this process becomes less pronounced visually, and each climatic type is characterized by the formation of a specific soil organoprofile. The same trend is noted with growing humidity of climate.

As was shown above, soil formation identification on the surface of technogenic landscapes on a macro-

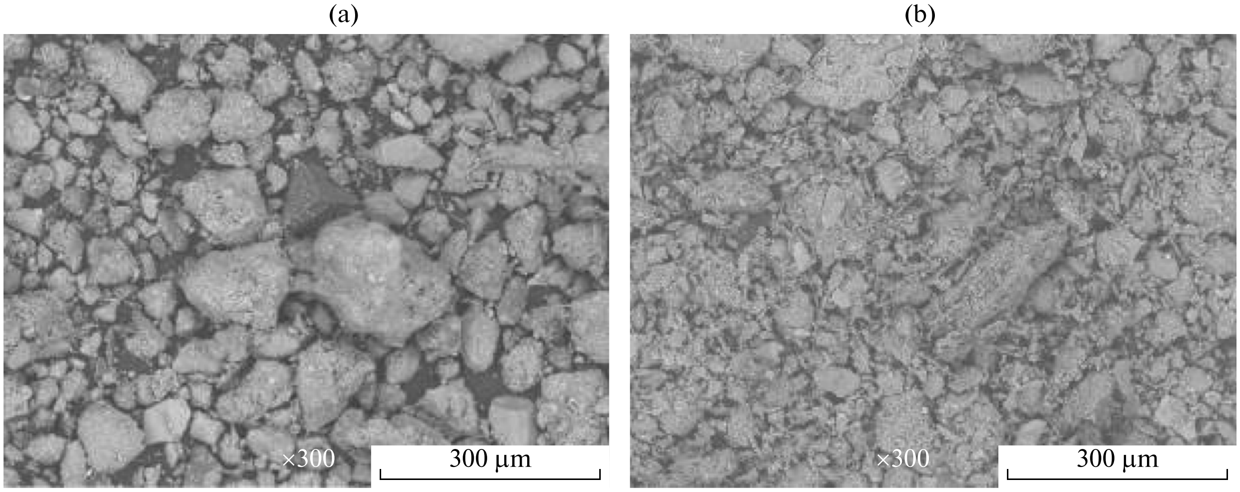

Fig. 2. Microphotographs of fraction <0.25 mm: (a) loess-like loam and (b) C1 horizon of the soddy embryozem.

morphological level permits revealing the principal processes and estimating their intensity and direction, as well as the potential of climatic factors. However, when working in different natural and climatic zones, it is hard to judge the zonal specific of soil formation, in particular, upon investigation of soils belonging to one taxonomic level. The absence of visual macromorphological features does not permit us to reveal the processes operating in the mineral horizons. Therefore, to characterize in more detail the soil formation specifics, micromorphological studies were performed.

Micro- and submicromorphological observations showed that both coarse and fine material in the analyzed soils differ radically from that in the natural soils in the adjacent areas. The fine-earth particles show a close-to-spherical shape in the upper horizons of natural soils and loess-like loam (Fig. 2a), whereas the fine-earth particles in the dump soils resemble platy or flaky aggregates (Fig. 2b). According to microfabric [28], the undisturbed soil mass is layered, since the soil-forming rocks are stratified. In the course of weathering, rock fragments disintegrate into separate macro- and microplates. Owing to this process, as well as to the different velocity of heating and cooling, particles of different size acquire a horizontal orientation in the profile, which fits the most compact package of particles of this shape. The fine mass produced by disintegration fills the space between the larger particles. This ensures a high density of embryozems typical of them on coal dumps [36]. The horizon produced by this package is an aquiclude despite its high stoniness [14].

Weak transformation of the substratum is a consequence of its insufficient disintegration as well as of the low intensity of structure-forming processes in embryozems, in particular, of those related to the soil mesofauna activity. Since the soils are relatively young, their fine fraction is extremely rarely associated in microaggregates. A few pedogenic aggregates were found only in the humus-accumulative embryozems of old dumps formed in subhumid climate (Fig. 3a). Unlike them, almost the entire micromass is included in aggregates in the leached chernozems, which are the zonal soils for this territory (Fig. 3b).

It is important to note that, unlike multilevel peds forming a complicated structure [47] in natural soils (Fig. 4a), the aggregates in technogenic soils form a one-level structure. They also differ in their shapes. Microaggregates are close to spherical in the humus-accumulative horizons of natural soils, whereas in the studied young soils they are angular (Fig. 4b).

The enumerated micromorphological properties of the initial soil-formation stages influence both the air and water regimes in young soils and also control the redox processes in embryozems. Therefore, the processes of chemical transformation of organic and mineral soil components typical of zonal soddy-podzolic and gray forest soils develop in the young soils in subhumid and humid regions. Iron-manganic concretions were registered by micromorphological observations in the fine earth of soils in the old dumps (Figs. 5a, 5b). The bulk of observed neoformations (pedofeatures) belong to the autochthonous type; i.e., their diffuse boundaries and spherical shape testify to their formation immediately in the studied soils rather than in any other environment [13].

The presence of iron-manganic concretions in natural soils results from poor drainage and gleying [19]. The seasonal excessive moistening in the compacted young soils in technogenic landscapes along with the high humidity of the climate in some of the studied regions (Table 1) causes a short-term gleying. The subsequent drying due to strong heating determines the establishment of a contrasting reduction-oxidation regime in young soils, which leads to the formation of microconcretions. Note that the absolute predomi-

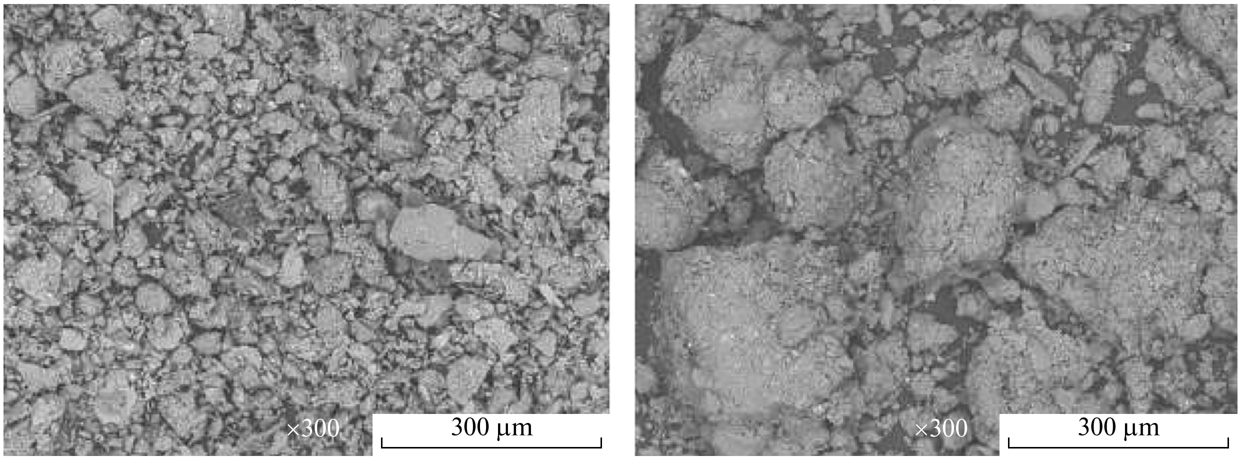

Fig. 3. Microphotographs of fraction <0.25 mm: (a) AC horizon of the humus–accumulative embryozem and (b) A horizon of the leached fertile chernozem.

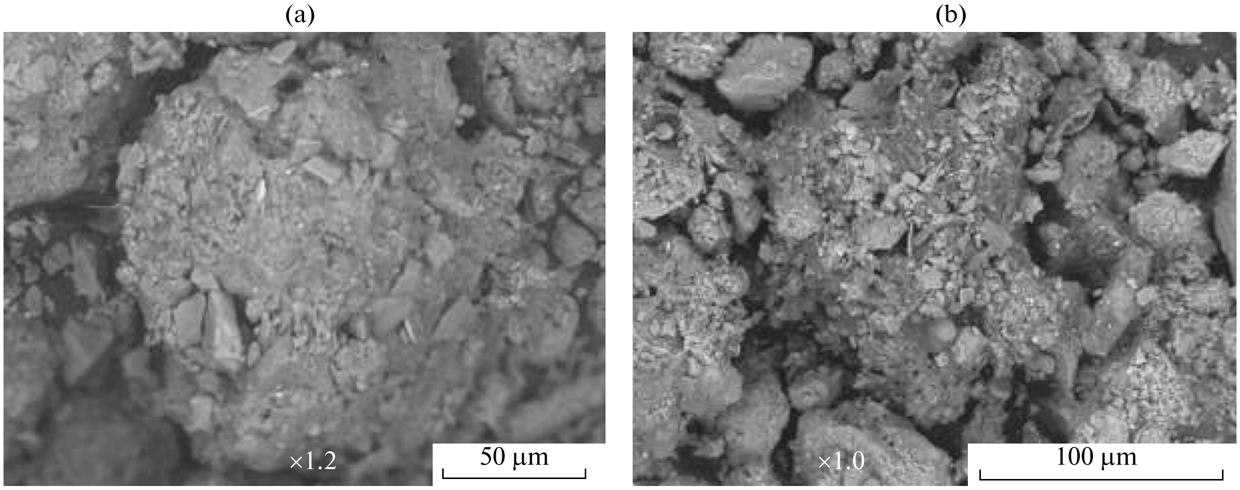

Fig. 4. Soil microaggregates: (a) A horizon of leached chernozem and (b) AC horizon of the humus-accumulative embryozem.

nance of oxidation processes were earlier recognized in these soils [3, 4].

This contrasting regime in zonal soils along with their recurrent leaching results in the development of eluvial podzolic horizons [19]. Therefore, taking into consideration the concept forwarded by Zaidel'man [18] on podzolization as a particular form of gleying, we may draw a conclusion about appearing prerequisites for eluvial–gley process development in the soils of technogenic landscapes in the regions of humid and subhumid climate. At the early stages, the local redistribution of mobilized substances may take place owing to segregation in microconcretions. Under favorable conditions, the further development of young soils will be accompanied by the formation of eluvial horizons and the removal of tailing transformation products.

The only difference between the microconcretions in the soils of technogenic landscapes and those in zonal soils consists in the different Fe/Mn ratio. As is seen in Fig. 5b, the Fe/Mn ratio is approximately 75, whereas it ranges from 2 (in humus) to 25 (in eluvial) horizons gleyed to a different degree [17, 18, 44]. This inconsistency is caused by the different methodological approaches to their investigation rather than by the concretion formation. In the routine analyses of iron-manganic concretions, the total elementary composition of the entire neoformation is determined, whereas the scanning electron microscopy analyzes only its upper 1-μm-thick layer. As was found by Shoba [43], these neoformations are formed owing to biological segregation with the subsequent physicochemical precipitation of iron and manganese on the concretion surface. Since reduction–oxidation Fe^{2+}–Fe^{3+} and Mn^{2+}–Mn^{4+} vapors have different standard potentials

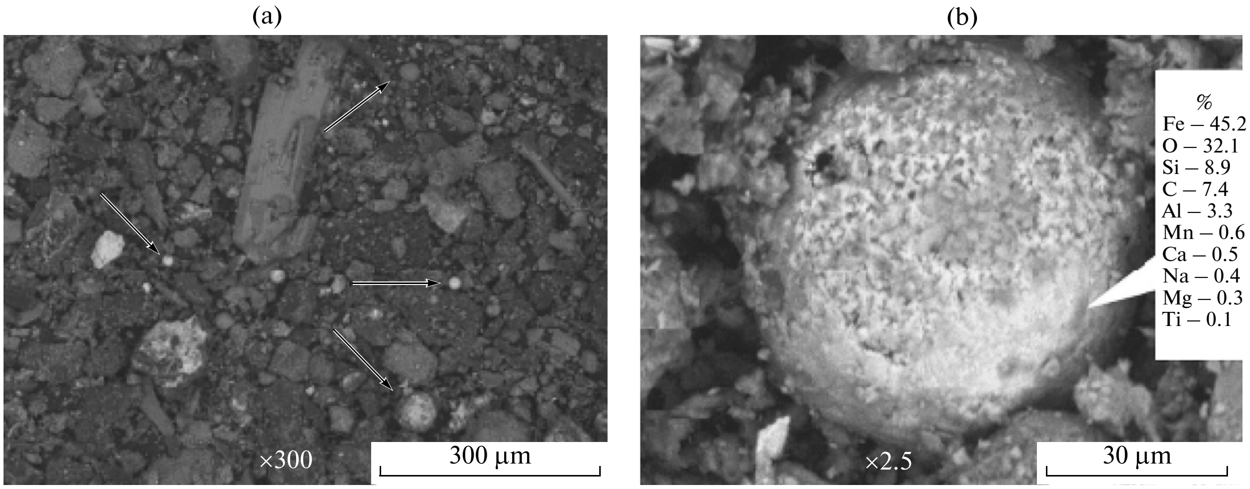

Fig. 5. Iron-manganic concretions in the soils of technogenic landscapes.

controlling their solubility in many respects [6, 20], the formation of concretions is accompanied by their periodic precipitation. This results in a layered structure of a spherule differentiated in terms of the content of elements [45, 49]. In this case, a widely ranging Fe/Mn ratio points to a sharply contrasting redox regime of embryozems rather than to a strong excessive moistening.

These processes cannot be referred to as the principal ones in the young soils of the subhumid regions. At the present stages of development of embryozems in the subhumid areas, humus accumulation remains the leading process. Further, with increasing gleying and podzolization, the development of young soils will occur along with the formation of soils close to gray forest soils in their properties and regimes, and not to chernozems as was believed earlier [4].

Humus is formed in an absolutely different way in steppe regions. For example, the products of incomplete mineralization of plant residues were found during the investigation in the samples from the old tailing dumps in steppe regions. Gerasimova et al. [12] suggest naming these products "coal-like particles" because of their typical color and the lost tissue structure. Solntseva and Rubilina also noted the formation of this organic form in the soils affected by coal tailing dumps [40]. When analyzing the upper horizons of the soddy-podzoliuc soils, they noted *mummification* of organic matter affected by concentrated solutions of acids and acidic salts, which is expressed in charred plant residues. Somewhat earlier, Kuminova [25] and Volkovintser [7] also pointed to the formation of mummified organic matter in natural soils under arid and extracontinental (cryoarid) climatic conditions. Scarce reserves of soil water, high temperature, and a short biologically active season provide that plant residues entering the soil are not decomposed for a long time, but they are dried and mummified [25]. This conclusion is supported by low humification coefficients and indicates the suppressed mineralization of plant falloff [7]. In other words, mummification is a specific process of organic matter accumulation typical of the zonal soils in cryoarid areas [8]. Therefore, the appearance of such bodies in soils with a weakly acid reaction under similar hydrothermal conditions appears to be explicable. However, the described mummified organic substances were revealed during research in young soils of the other regions as well, including the regions with semiarid climate (Fig. 6c). This fact allows one to suggest that the soils in these areas show more pronounced xeromorphism as compared to zonal soils. As a result, embryozems of only early stages (i.e., initial and organo-accumulative stages) are formed in the technogenic landscapes (Table 2).

The described soil features are widespread, being a zonal sign, since they are encountered in almost all soil types of the considered evolutionary sequence. Hence, the processes identified by this research develop everywhere in the analyzed soils. Their ratio may be determined by the presence of relevant neoformations, while the process intensity is controlled by the number of these formations. Therefore, the methods of quantitative micromorphology should be applied for a more detailed description of the revealed processes.

Thus, when identifying the soil-formation processes, the macromorphological analysis permits assessing the intensity and the direction of the leading soil-formation processes and their degree of manifestation under different natural climatic conditions, whereas micro- and submicromorphological methods supplement information about their mechanisms and zonal manifestation specifics. Revealing the features inherent to the accompanying processes

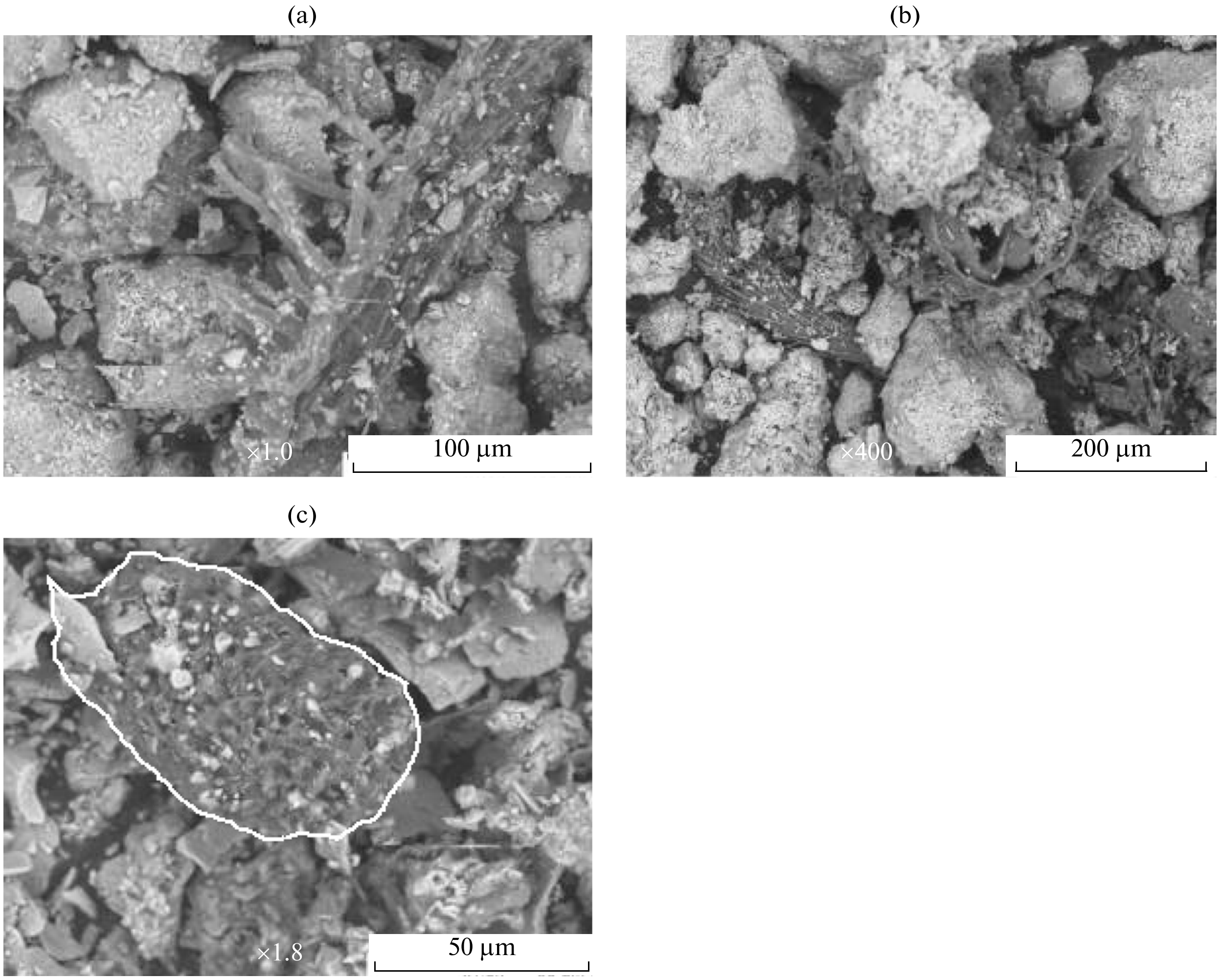

Fig. 6. Biogenic organic matter: (a) plant residues, (b) remains of invertebrates, and (c) mummified organic matter.

enables us to predict the further evolution of soils in technogenic landscapes.

CONCLUSIONS

The performed morphogenetic studies in revealing the geographic-genetic regularities and specific features of soil formation in technogenic landscapes in Siberia showed that the macromorphological analysis permits assessing the intensity and the direction of the leading soil-forming processes and their degree of manifestation under different natural climatic conditions. It is found that the processes of mineral substratum transformation, or, in other words, primary soil formation, prevail at the first stages of soil formation. This is manifested in disintegration of stony fragments and profile differentiation by their content. Further, in the course of soil development, the organic matter transformation starts playing the leading part in profile formation. The organic matter features become less manifested visually with growing climate aridity; this is pronounced in the formation of a soil organoprofile specific to each climatic zone. A subhumid climate appears to be optimal for humus accumulation.

The use of micromorphological methods for soil formation identification adds substantially to macromorphological investigations and provides data on the mechanisms of processes and the zonal features of their manifestation. The specifics noted in micromorphological observations prove that the features inherited from the rock prevail in soil micromass in technogenic landscapes, which is very rarely microaggregated. Individual aggregates are found in humus-accumulative horizons of old dump soils formed in subhumid climate. All these signs testify to the low intensity of structure-forming processes in the studied soils.

Fine- and coarse particles are of platy shape; therefore, they produce a compact fabric upon soil formation and form acquifuge; in humid and subhumid climate, this results in seasonal strong moistening of soils and creates prerequisites for the development of eluviation and gleying. The developing contrasting reduction–oxidation regime is accompanied by the formation of iron-manganic concretions.

The revealed features testifying to the operation of accompanying processes make it possible to predict the further soil evolution in technogenic landscapes. For example, in a humid climate under a short-term stagnant water regime, the upper part of the profile is podzolized. With allowance for the zonal specific, the further soil evolution will be accompanied by the formation of thick eluvial horizons and removal of transformation products of the dump material.

In a subhumid climate, when the eluvial–gley process and humus accumulation develop simultaneously in young soils, soils close to gray forest soils with respect to their regimes (and not to chernozems as was believed earlier) will be formed.

The soils of technogenic landscapes in arid areas show more pronounced xeromorphism as compared to the zonal soils. Under these conditions, organic matter transformation is accompanied by mummification of plant residues rather than by humification. As a result, soil evolution on the surface of coal dumps reaches the organo-acumulative (more rarely, sod) stage of soil formation.

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