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Zheltozems of Russia: Micromorphology, clay minerals, and pedogenetic analysis

Zheltozems de Rusia: micromorfología, minerales de la arcilla y análisis edafogenético
Zheltozems da Russia: micromorfología, minerais de argila e análise pedogenética

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ABSTRACT

Zheltozems (literally "yellow earths") that can be classified as Acrisols, Alisols, or Ultisols, occupy very small areas in Russia; they are strongly modified by human activities. The unchanged profiles are preserved only locally, in particular, in the Sochi arboretum. When compiling the soil map of the arboretum, different Zheltozems were described on gentle and moderately steep slopes and diverse parent materials: calcareous claystone and its heavy-textured derivates. The micromorphology of three characteristic Zheltozem profiles developed on these different parent materials was also studied. The features that they have in common are the following: in all profiles, a specific heavy-textured Bw, or BM 'metamorphic' horizon was identified with a certain set of micromorphological properties: a massive microstructure with fine planes merging into deformed biogenic pores, a monic groundmass with few silt grains that are sometimes oriented, and impregnative iron-oxides pedofeatures. The b-fabric was defined as stipple speckled, poro- and granostriated, locally (mono)striated ressembling stress coatings. There are almost no clay coatings except for very few fine internal ones that are light yellow and homogeneous; clay and iron pseudomorphs (alteromorphs) occur over some skeleton grains. Many of these properties are related to the clay mineral composition. There are varying quantities of smectites and kaolinite-smectites, whereby the former increase with depth. The presence of expanding minerals is known to contribute to the disintegration of coatings. Remnants of these are observed in typic iron-manganic nodules. In terms of WRB, this horizon is an intergrade between cambic and argic, which is not accounted for in soil diagnostics. As three different Zheltozems are studied in the same area, the following genesis of this specific intergrade can be given. The saprolite in one of the profiles is composed of fragments of weathered calcareous argillites (subangular) and sandstones (angular) separated by planes with infillings. The micromass in the argillites is locally depleted of carbonates; some fragments have rusty-black iron-manganic intercalations, external clay coatings and iron quasicoatings. The infillings contain fine carbonate nodules and fragments of clay coatings. The sequence of soils studied enabled us to identify the pedoplasmation phenomena, as described by Stoops and Schaefer (2010). This process starts with the decarbonatization, fragmentation and ferrugination of rock fragments, which are gradually assimilated by the groundmass, so that only a trend to linear arrangement of grains is preserved. The pedoplasmation starts in the saprolite of *in situ* argillite, next follows a transformation of the lithogenic fabric into a pedogenic one with the development of a Bw horizon. These phenomena are more obvious in the profile on the oldest parent material – clayey colluvium. The low porosity and dense fabric of the Bw horizon hinder the removal of carbonates from the underlying layers (saprolite), and this may be a reason for the incompatibility between abundant rainfall inherent to the wet subtropical climate in Sochi region and the high position of the line of effervescence with hydrochloric acid in Zheltozems on calcareous argillite.

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RESUMEN

Los Zheltozems (literalmente "tierra amarilla"), que pueden ser clasificados como Acrisoles, Alisoles o Ultisoles, ocupan áreas muy pequeñas en Rusia y están fuertemente modificados por la acción humana. Los perfiles sin alterar se conservan solo localmente, como ocurre en el arborétum de Sochi. Al realizar el inventario cartográfico de suelos del arborétum, se describieron diferentes Zheltozems desarrollados sobre laderas de pendiente mediana y baja y material parental diverso compuesto por argilitas calizas y sus derivados de grano grueso. En este trabajo se realizó el estudio micromorfológico de tres perfiles característicos de Zheltozems desarrollados sobre estos tipos de material parental. Los rasgos comunes a todos los perfiles incluyen un horizonte Bw específico de textura gruesa, u horizonte metamórfico BM, con una serie de características micromorfológicas: una microestructura masiva con huecos planares finos que derivaban a poros biogénicos deformados, una masa basal mónica con escasos granos de limo a veces orientados y edaforrasgos impregnativos de óxidos de hierro. La fábrica-b se define como moteada, poro y granoestriada, y localmente (mono)estriada debida a caras de presión. Los escasos revestimientos de arcilla son homogéneos y de color amarillo claro; y se observan pseudomorfos (alteroformos) de arcilla y hierro sobre algunos granos del esqueleto. Muchas de estas propiedades están relacionadas con la composición de los minerales de la arcilla, que contienen cantidades variables de esmectitas (que aumentan en profundidad) y esmectitas caoliníticas. La presencia de minerales expansibles contribuye a la desintegración de los revestimientos. Se observan remanentes de éstos en nódulos típicos de hierro-manganeso. De acuerdo con la clasificación WRB, este horizonte presenta características comunes a un horizonte cámbico y árgico, que no se tienen en cuenta en clasificación de suelos. Al haber estudiado tres Zheltozems diferentes en la misma zona, se proponen las siguientes génesis. La saprolita de uno de los perfiles está formada por fragmentos de argilitas calizas alteradas (subangulares) y areniscas (angulares) separadas por planos con rellenos. La micromasa en las argilitas está localmente desprovista de carbonatos, y algunos fragmentos tienen intercalaciones de hierro-manganeso de color oscurro pardo-rojizo, revestimientos externos de arcilla y cuasirevestimientos de hierro. Los rellenos contienen nódulos de carbonato finos y fragmentos de revestimientos de arcilla. La secuencia de suelos estudiados permite identificar el fenómeno de edafoplasmación descrito por Stoops y Schaefer (2010). Comienza con la descarbonatación, fragmentación y ferruginización de los fragmentos de roca que están graduamente asimilados por la masa basal, por lo que solo se conserva la tendencia de la organización linear de granos. La edafoplasmación comienza en la saprolita de la arcillita in situ, seguida de la transformación de la fábrica de litogénica a edáfica con el desarrollo de un horizonte Bw. Estos fenómenos son más patentes en el perfil del material parental más antiguo- un coluvio arcilloso. La baja porosidad y fábrica densa del horizonte Bw enmascaran la pérdida de carbonatos de las capas más profundas (saprolita), lo cual puede ser la razón de la incompatibilidad entre la abundante precipitación inherente al clima subtropical húmedo en la región de Sochi y la elevada posición de la línea de efervescencia con el ácido clorhídrico en los Zheltozems sobre argilitas calizas.

KEY WORDS
Soil genesis, pedoplasmation, saprolite, carbonate pedofeatures, swelling mineral

PALABRAS CLAVE
Génesis de suelos, edafoplasmación, saprolita, edaforrasgos carbonatados, mineral hinchable

PALAVRAS-CHAVE
Génese de solos, pedoplasmação, saprólito, formações carbonatadas, mineral expansível

RESUMO

Os Zheltozems (literalmente "terras amarelas"), que podem ser classificados como Acrissolos, Alissolos ou Ultissolos, ocupam áreas muito reduzidas na Rússia e encontram-se fortemente alterados em consequência da actividade humana. Os perfis inalterados encontram-se apenas localmente, em particular, no Arboreto de Sochi. Na elaboração do inventário cartográfico do Arboreto, descreveram-se diferentes Zheltozems localizados em encostas suaves e moderadamente íngremes e desenvolvidos a partir de diversos materiais originários: argilitos calcários e materiais de textura fina deles derivados. Neste trabalho estudaram-se numa perspectiva micromorfológica três perfis característicos de Zheltozems, desenvolvidos a partir daqueles materiais originários. Referem-se em seguida as características que apresentam em comum. Em todos os perfis, foi identificado um horizonte específico Bw de textura fina ou um horizonte BM 'metamórfico', caracterizados pelas seguintes propriedades micromorfológicas: uma microestrutura massiva com lâminas finas que derivam de poros biogénicos deformados, uma massa basal mónica com alguns grãos de limo orientados e pedocaracteres impregnativos de óxidos de ferro. A tessitura-b foi definida como mosqueada, poro- e granoestriada, localmente monoestriada, fazendo lembrar revestimentos de stresse. Os poucos revestimentos de argila que aparecem são homogéneos e de cor amarela clara; surgem ainda pseudomorfos (alteromorfos) de argila e ferro sobre grãos grosseiros (esqueleto). Muitas destas propriedades estão relacionadas com a composição dos minerais de argila que possuem quantidades variáveis de esmectites (que aumentam em profundidade) e interestratificados esmectite-caulinite. A presença de minerais expansíveis contribuiu para a desintegração dos revestimentos. Reminiscências da presença destes surgem sob a forma de nódulos típicos de ferro e manganês. De acordo com a classificação WRB, este horizonte apresenta características de transição entre os horizontes câmbico e árgico, não estando incluído naquela classificação. Contudo, como se estudaram três Zheltozems diferentes na mesma *zona, é possível descrever a génese deste horizonte. O saprólito de um dos perfis é formado por fragmentos de argilitos calcários alterados (subangulares) e arenitos (angulares) separados por camadas com enchimentos. A micromassa dos argilitos tem marcas localizadas de deplecção de carbonatos; alguns fragmentos têm intercalações de ferro e manganês de cor vermelha, revestimentos externos de argila e quási-revestimentos de ferro. Os enchimentos contêm nódulos finos de carbonatos e fragmentos de películas de argila. A sequência dos solos estudados permite identificar fenómenos de pedoplasmação, tal como descritos por Stoops e Schaefer (2010). O processo começa com a descarbonatação, fragmentação e ferruginização de fragmentos de rocha, que são gradualmente assimilados na massa basal, pelo que apenas o arranjo linear dos grãos é preservado. A pedoplasmação inicia-se no saprólito do argilito in situ, seguindo-se a transformação da tessitura litogénica numa pedogénica com o desenvolvimento de um horizonte Bw. Estes fenómenos são mais nítidos no perfil do material parental mais antigo - material coluvial argiloso. A baixa porosidade e tessitura densa do horizonte Bw camuflam a remoção de carbonatos das camadas subjacentes (saprólito), o que pode explicar a incompatibilidade entre a precipitação abundante inerente ao clima subtropical húmido na região de Sochi e a localização elevada da linha de efervescência com ácido clorídrico nos Zheltozems formados a partir de argilitos calcárias.*

1. Introduction

There are no other soils in Russia that have such a small area and yet are of such great interest for soil scientists as the Zheltozems. Worldwide, Zheltozems have been described in humid subtropics, mostly in the south-eastern parts of North and South America, Asia and Australia (http://soils.usda.gov/technical/classification/orders/ultisols_map.html). Zheltozems occur in Europe in a narrow strip along the eastern coast of the Black Sea, in the altitudinal range from 0 m to 150-200 m above sea level (**Figure 1**). The areas of these soils are frequently interrupted by outcrops of limestone, on which rendzinas are present and the soils concerned have often been strongly disturbed by human activities since the beginning of the last century.

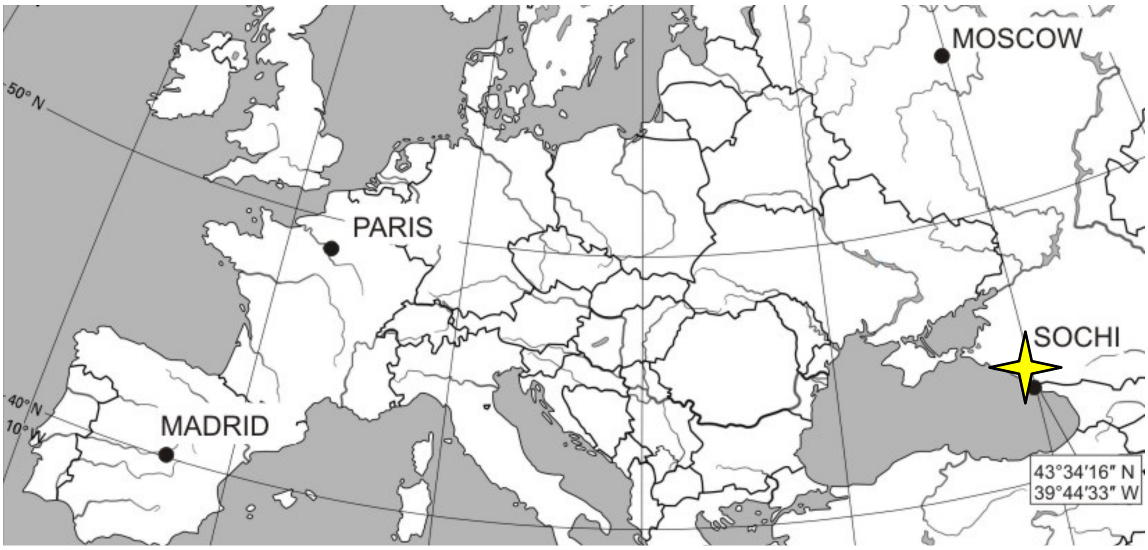


Figure 1. Location of the study object (✦) and its coordinates.

The interest of soil geographers in Zheltozems is traditionally explained by their location: these are the only soils in the country with manifestations of current subtropical pedogenesis. The latter has been thoroughly investigated in Western Georgia starting with the works of the famous scientists S. A. Zakharov (1924), B. B. Polynov (1933), and the followers of this scientific school in Georgia – M. N. Sabashvili (1955) and A. I. Romashkevich (1979). In their studies of Zheltozems, they put emphasis on the advanced weathering and the relationships, both genetic and geographic, with other subtropical soils. The results obtained served as a basis for positioning Zheltozems in the zonal soil sequence as soils of humid subtropics, with a poorer profile drainage than Krasnozems. Some authors mentioned a more frequent occurrence of Zheltozems on hard sedimentary rocks and on their derivates.

In terms of WRB (IUSS Working Group 2006), Zheltozems are mostly referred to Alisols (Krasilnikov et al. 2009) or to Acrisols (Soil Atlas of Europe 2005). In Soil Taxonomy (Soil Survey Staff 1999) they are correlated with the Ultisols (http://www.cals.uidaho.edu/soilorders/i/Ultisols.jpg; Romashkevich 1975; Daraselia 1975). In the Russian Soil Classification System (2008), Zheltozems were placed in the order of metamorphic soils, essentially corresponding to Cambisols in WRB (IUSS Working Group 2006), because of their properties derived from the transformation of lithogenic to pedogenic fabrics; their B horizon may be tentatively correlated with the cambic horizon.

However, the B horizons of Zheltozems have some particular morphological features: bright yellow colours, heavy textures, strong compaction (bulk density 1.4-1.6 g/cm^3), massive structures when wet and the development of fissures when dry, the occurrence of soft weathered fragments of parent rocks, and clay enrichment although the illuviation clay coatings are scarce. Thus, the properties and origin of this horizon may be objectives appropriate for micromorphology. Moreover, in the *in situ* Zheltozem profiles, the saprolite zone is well developed, and the transformation of lithogenic fabric into pedogenic structures may be followed there. Another interesting phenomenon in these soils is the presence of soft carbonate segregations of the beloglazka type discovered in the bottom of some profiles. These seem to be incompatible with the abundant rainfall (about 1500 mm year^{-1}), percolating the soil profile and the acid reaction in the topsoil (Gerasimova et al. 2010; Gurov 2011).

The micromorphology and clay mineralogy of Zheltozems were investigated in the Sochi region (Zyrin et al. 1974; Gueguechkori et al. 1985; Gvalia et al. 1991) and in Georgia (Romashkevich 1975, 1979; Romashkevich and Gerasimova 1973; Yarilova (in Daraselia and Glazovskaya 1974); Chizhikova and Gurov 2012). Along with describing manifestations of strong weathering and enhanced mobilization of iron (fersiallitization), these authors put emphasis on the strong textural differentiation features testifying to the inheritance of soil fabrics from parent rocks – mostly slates and argillites. However, this is in disagreement with low abundance of clay coatings. The impact of rocks was thought to be more pronounced in Sochi Zheltozems than in those of other regions. A similar situation with clay coatings was discussed by Fedoroff and Eswaran (1985) in Ultisols, where the abundance of clay coatings varied strongly from very few to many. Along with coatings, these authors described the fragments of coatings, so the evaluation of illuvial phenomena was rather complicated. One more interesting aspect of the coatings' behaviour was noted by N. Fedoroff as early as 1970: the effect of illuviation coatings on the decomposition of parent rock structure, especially if swelling clay minerals were present (Fedoroff 1970). Nevertheless, the contribution of clay illuviation as testified by clay coatings for the development of B horizons in Zheltozems remains unclear.

Concerning the kind of clay minerals, Romashkevich (1979) indicated the predominance of kaolinite and halloysite. Disordered mixed-lattice formations were also present. Moreover, she noted a profile trend in the distribution of clay minerals: an increase in the abundance of kaolinite and a decrease in the montmorillonite component in mixed-lattice formations in the upper horizons.

Thus, the objectives of this research on Zheltozems in the Sochi arboretum were to reveal the mechanisms of the lithogenic to pedogenic fabric transformation, the formation of clay illuviation and iron oxide pedofeatures, and the behaviour of carbonates as related to soil forming conditions. The pedoplasmation phenomena and secondary carbonates occurrence are also of great interest.

2. Objects and Methods

Zheltozems in Sochi region occur on the ancient marine terraces and in the foothills at altitudes lower than 150 m above sea level. At higher altitudes, on the slopes of the Bol'shoy Caucasus Ridge, acid brown forest soils – Dystric Cambisols predominate. The mean annual temperature in the area of Zheltozems is +14.1 °C and precipitation exceeds 1500 mm but strongly varies; for example, the difference between the years 1988 and 1989 reached 1000 mm. Rains fall mostly in the cold period (with a maximum in December) and in summer a moisture deficit is recorded in the soils (data of Sochi Hydrometeorological station). The mean temperature of the soil surface in August is close to 28 °C, the highest reached 60-64 °C (Besedina 2004).

Since the area is intensively used for resorts and tea growing, only small patches of unchanged Zheltozems are preserved in gardens and those in the Sochi arboretum were the objects of this research. The arboretum is located within the altitudinal range of 10-145 m above sea level, on a ridge composed by hard sedimentary rocks and on the ancient marine terraces flanking this ridge. The rocks are calcareous argillites (claystone) of the Upper Paleogene Sochi suite (Sobolev Geological Survey Group 1959) with sandstone interlayers on sloping surfaces; the flat remnants of the Pleistocene marine terraces are composed of pebbles with sandy material, in some places strongly cemented by iron and manganic compounds and overlain by yellow clayey colluvium up to 5 m thick (Prassolov et al. 1934). The argillites are dark brown, some of them are greenish (with chlorite). The interlayers of grey sandstone with carbonate-clay cement are less than 25 cm thick. The carbonate content in the Sochi suite is 20-25% CO_2 (Sobolev Geological Survey Group 1959). Vegetation similar to the natural one is preserved only on steep slopes. These are hornbeam-oak forests, mostly with a litter and an undergrowth of holly. The tree trunks are interlaced with lianas. The bulk of the territory consists of a forest-garden with exotic introduced trees and shrubs. They grow on dense artificial lawns with patches of green moss in micro-lows. The dominant species introduced are palms (Chinese, Washingtonia, Chamaerops), followed by more than 20 species of pine. Cedars, cypresses, bamboo, araucarias, cycads are also present. Normal growth of these tropical plants indicates a high hydrothermal potential of the area.

When compiling a detailed soil map of Sochi arboretum in 2008-2010, typical Zheltozems profiles were encountered on different parent materials and landforms. The following profiles were selected for the micromorphological study: a *typical Zheltozem* on a gentle slope on clayey yellow colluvium (pit 5), a *residually calcareous Zheltozem* on calcareous argillite on a steeper slope (pit 3), and an *eluvial-gleyic Zheltozem* on a flat terrace with impeded drainage on weathered and partly redeposited argillites (pit 39); pits 5 and 39 were dug on dense lawns at a distance of 3-6 m from large trees, and pit 3 was set at the edge of the natural forest. In the WRB system (IUSS Working Group 2006), these soils basically correspond to Alisol (pit 5), Cambisol (pit 3), and Stagnosol (pit 39), respectively. In all profiles, thin sections were prepared from the humus horizons (within the upper 10-15 cm), eluvial or transitional AB horizon, BM horizon in its upper and lower parts (depth 30-50 cm and 70-90 cm, respectively), and BC or saprolite (1 m and deeper).

The micromorphological studies were performed within the magnification interval 20-70X (microscope – Axioscope 40, Karl Zeiss, Jena). The micromorphological terminology used is according to Stoops (2003), the composition of clay minerals was examined by XRD method (Universal Diffractometer Karl Zeiss, XZG-4A; Jena, Germany; voltage 30 V, plate current 20 mA, the rotational speed of the goniometer 2 degree per minute, radiation of copper, nickel filtered). The samples were preliminarily treated with magnesium chloride for saturation with magnesium cations. The XRD curves were obtained for air-dry samples saturated with ethylene glycol to analyse the swelling minerals; the quantitative ratios of main mineral phases were calculated in accordance with Biscaye method (1964). Samples of Bw horizon were studied with the scanning electron microscope JEOL JCM-6610LV in the Institute of Geography RAS.

3. Results and Discussion

The description of parent rocks was made under the supervision of Liudmila Glazovskaya, Faculty of Geology, Lomonosov Moscow State University (Figure 2).

Calcareous argillite (claystone). The groundmass is composed of carbonate-clay material, and the fragmentary part is composed of quartz, the grain size from 0.04–0.15 mm. A striated pattern of iron oxides is distinct. Quartz is accompanied by K-feldspars; there are also: biotite, elongated grains (0.07 mm); volcanic glass, few chlorites. Iron hydroxides occur along fissures.

The second sample of claystone is similar to the above-described sample. The aleurite fraction is dominated by quartz, there are K-feldspars, no twinning, some pseudomorphs over medium and basic plagioclases, and fresh chlorite grains are common. The fine material is carbonate-enriched, and films of iron hydroxides occur on fragment faces.

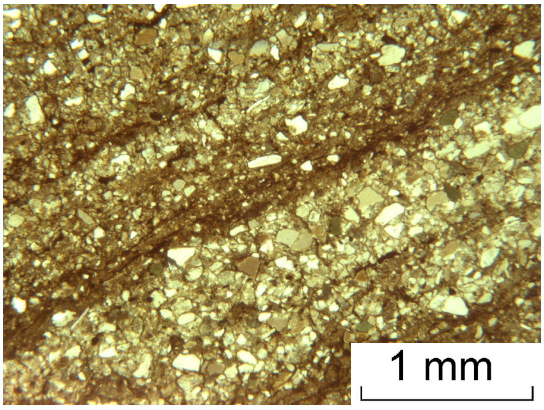


Figure 2a. Argillite, PPL.

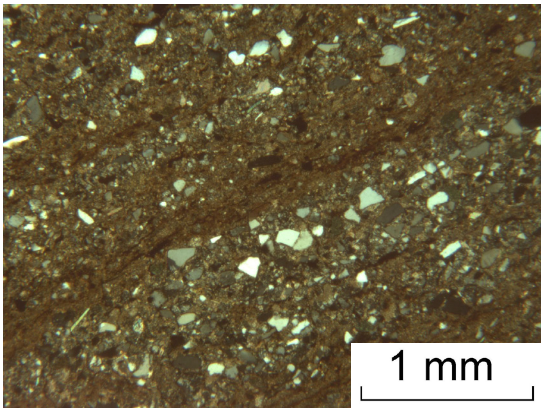


Figure 2b. Argillite, XPL.

Figure 2. Parent rocks (Sochi arboretum).

Fine-grained sandstone. Striated owing to iron hydroxide patterning. Mean size of grains is 0.07 mm. Quartz is dominant, fine fragments of muscovite and plagioclase occur.

The descriptions of three profiles are given, which were chosen among approximately 50 soil pits as representing the characteristic features of Zheltozems in 3 lithological – geomorphic positions.

The profile of the *typical Zheltozem* (pit 5) is characterized by its bright yellow color and distinct textural differentiation. The loamy topsoil (up to 20 cm) has a weak crumb structure. The clayey subsoil identified as a Bw (BM) horizon, is compact and massive, has no coatings; in its lower part (below 1 m), stagnic marble-like pattern is well expressed. The reaction is weakly acid in the topsoil (pH_{water} is 5.5-5.8); the total (extractable) acidity and exchangeable aluminum content drastically increase in the Bw horizon and is one of the reasons to qualify this soil for Endostagnic Alisol (Alumic, Clayic).

In thin sections, the topsoil is characterized by a crumb microstructure, aggregates have diffuse boundaries and are weakly separated; there are few coarse subangular-rounded ones, presumably disintegrating excrements of big earthworms. Fragmented plant residues, brown, fibrous and strongly decomposed are found down to the depth of 40 cm. There is a close porphyric c/f ratio with random clusters of silt and sand grains in the groundmass, an almost undifferentiated b-fabric; and dark rounded nodules, mostly fine with sharp boundaries.

The groundmass in the B horizon is very compact, the microstructure is massive, with few fine planes, channels and chambers, and single moldic voids (**Figures 3a, 3b, 3c, 3d**). The clay micromass has a high birefringence: speckled, striated and porostriated b-fabric, few stress coatings and very few fine illuviation coatings. In the lower part of the horizon, the iron oxide pattern is contrasting: depleted zones alternate with the iron-impregnated zones and iron coatings (**Figure 3e**).

Nodules are not found deeper than 40-50 cm; the colour of the nodules changes with depth: the very dark brown colours of topsoil's nodules give way to rusty ones above the B horizon. They have sharp boundaries, a variable size (up to 0.5 mm) and may include fragments of birefringent clay material, probably fragments of coatings or alteromorphs. Manganic dendrites on skeleton grains appear at the depth of 70 cm (**Figure 3f**). Indications of biotic activity are confined to very few large channels: these may be residues of plant tissues or disintegrating excrements.

The fraction < 1 μm is dominated by chlorite-vermiculite in all horizons (**Figure 5**); illite, kaolinite, finely-dispersed quartz, gibbsite and goethite are also present. However, there are differences in the clay fraction composition along the profile. In the topsoil, finely dispersed quartz and kaolinite are abundant: the mixed-lattice formations display the lowest peak intensities. Kaolinite has acute peaks at 0.71 nm and 0.35 nm testifying to the process of its 'refinement'. Down the profile (depth 30 to 50 cm) the content of finely dispersed quartz decreases, and the kaolinite-smectite mixed-lattice formations appear, they are identified by a broad infilled area between the 0.71 nm and 1 nm (illite) peak, both are recorded down to the depth of 70 cm. Thus, in the most clay-enriched horizon, the amount of kaolinite-smectite formation is the highest. Gibbsite displays low intensity in 0.48 nm area in the topsoil and the high one in the B horizon. Goethite maximum coincides with the intensive yellow colour of the soil. Lepidocrocite was determined within the depth interval 70-220 cm with a maximum at 130 cm.

The profile of the *residually calcareous Zheltozem* (pit 3) on calcareous argillite with sandstone interlayers is homogeneous. A yellow-brown colour is dominant, and features of humus accumulation could be traced to the depth of 25 cm, with soft plates of argillite and sandstone fragments at the bottom. The mid-profile B horizon is clayey, compact, has a massive structure with elements of blocky-platy one in its lower part, where soft fragments of argillites (about 1 cm large) begin to occur; their size and number gradually grow with depth. Deeper than 1 m, the plates of argillites become harder and alternate with sandstone lenses; however both types of rocks may be still hand-broken, and locally contain fine-earth infillings. This part of the profile is defined as saprolite or lithomarge. The effervescence starts at 70 cm, and the pH values increase from 5.7 in the topsoil to 7.4 in the B horizon and 8.2 in the saprolite. No secondary carbonate pedofeatures were found in the profile. The soil was defined as Haplic Cambisol (Calcaric, Clayic).

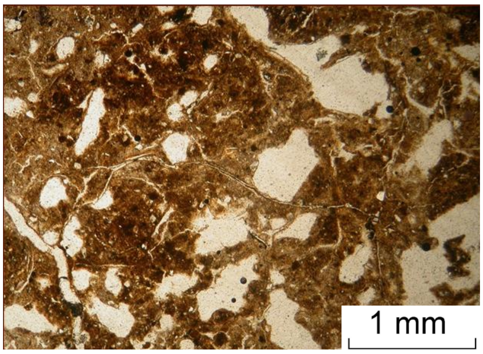


Figure 3a. PPL.

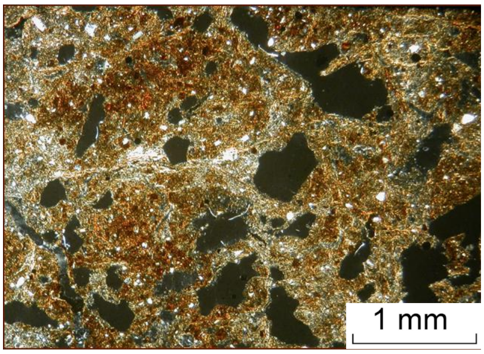


Figure 3b. XPL.

40-44 cm. Upper part of BM horizon with massive microstructure although with many voids – biogenic, moldic and fine planes, in this partial fabric). Few skeleton grains, high birefringence of the groundmass, more distinct in iron-depleted areas.

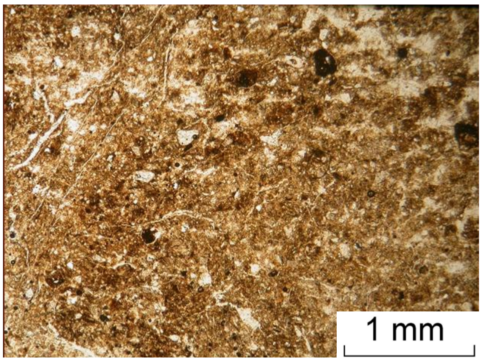


Figure 3c. PPL.

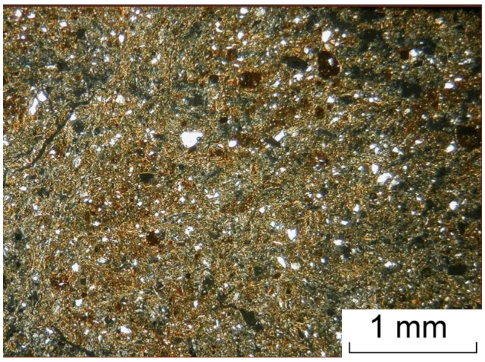


Figure 3d. XPL.

80-85 cm. Middle part of BM horizon, almost without voids except for few fine planes. Compact groundmass, few quartz grains with weak linear orientation.

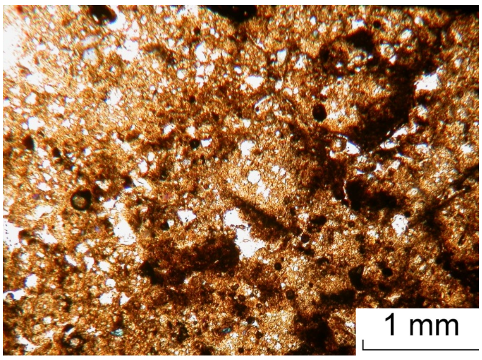


Figure 3e. Impregnation of the groundmass with ferric compounds. PPL.

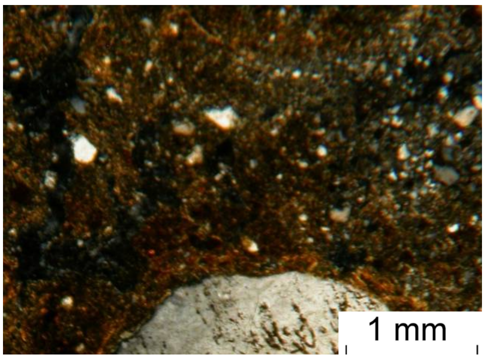


Figure 3f. Manganic dendrites on a coarse grain, and oriented clay around it. XPL.

Lower part of the BM horizon with marbled colour pattern. Pedofeatures.

Figure 3. Pit 5.

Micromorphological characteristics of the topsoil are almost the same as in typical Zheltozems: more traces of faunal activity are recorded, and a trend to the orientation of silt grains in short bands or semi-circles is discernible. There are also dark brown nodules up to 0.5 mm in diameter and iron-impregnated rock fragments. The B horizon has a massive microstructure with fine planes merging into deformed biogenic pores; clay micromass with few silt grains that sometimes display a linear orientation; stipple speckled, poro- and granostriated b-fabric, locally (mono)striated, similar to stress coatings (**Figures 4a, 4b**).

The iron-oxide pedofeatures are diverse, and the impregnative ones are the most common. There are very few fine internal coatings, light yellow and homogeneous, and clay and iron pseudomorphs (alteromorphs) over some skeleton grains.

Most peculiar is the saprolite (**Figures 4c, 4d, 4e**), which is composed of fragments of weathered calcareous argillite (weakly rounded) and sandstone (angular) separated by planes with infillings. The fine mass in the argillite is locally depleted of carbonates, and some fragments have rusty-black iron-manganic intercalations, external clay coatings and iron quasicoatings. The infillings contain fine carbonate nodules and fragments of clay coatings.

In terms of clay mineral composition and profile patterns, this soil differs from the typical Zheltozem: the swelling phase –mica-smectite and individual smectite– is identified in the B horizon, illites are more abundant, and no finely-dispersed quartz. Similar is the ‘refinement’ of kaolinite in the topsoil and appearance of kaolinite-smectite in the B horizon. Iron oxides minerals have a different pattern: lepidocrocite in the topsoil is replaced by goethite with depth.

Thus, the processes of hard rock transformation into the lithomarge are distinct in this profile. In some of the argillite fragments their fine material gets depleted of carbonates; simultaneously, micritic nodules up to 0.5 mm in diameter are formed in the pore space between these fragments. Clay coatings and their fragments accumulate there along with the ferruginous ones that may be both allochtonous and autochtonous.

The profile of the *eluvial-gleyic Zheltozem* (pit 39) on the argillite derivate (colluvium) with impeded profile drainage is weakly differentiated. The topsoil is loamy, friable, has many ferruginous and manganic nodules and impregnation mottles, and the stagnic color pattern is most distinct in its lower part. The B horizon is bright yellow, compact, clayey, and has a massive structure and marble-like color pattern in its lower part. In terms of chemical properties, this soil is an intergrade between the above Zheltozems: the pH values are close to 6.5 in the topsoil, decrease to 5.1 in B horizon and raise to 7.4 below 1 m). The soil is correlated with Haplic Stagnosol (Manganiferric, Albic, Clayic).

Micromorphologically, this profile is similar to the above profiles in terms of c/f ratio, pedality, micromass b-fabric, except for the iron oxide pedofeatures. In the eluvial horizon with stagnic properties, coarse iron nodules, both dark homogeneous (typic) and complex, or polyphase (alteromorphic) with inclusions of pseudomorphs or coating fragments are common (**Figures 6a, 6b**). In the B horizon, iron-impregnated zones occur in the groundmass along with iron-depleted ones; there are also recognizable rock (argillite) fabrics there (**Figures 6c, 6d**). Roots penetrate only through large holes and their remnants occur as moderately decomposed tissues, sometimes with feeding marks (**Figure 6e**).

The clay fraction is mainly composed of mixed-lattice formations (40-57%) with the predominance of chlorite-vermiculites in the upper horizons and participation of chlorite-smectites deeper; illites of dioctahedric type do not practically change throughout the profile. The content of kaolinite is high in the topsoil, and its peak is sharp-angular and narrow. Gibbsite is identified in all horizons, and its maximum coincides with the stagnic area. Iron oxide minerals are distributed irregularly in the profile: goethite has a minimum in the uppermost horizons (contrary to lepidocrocite) and a maximum in the middle part of B horizon.

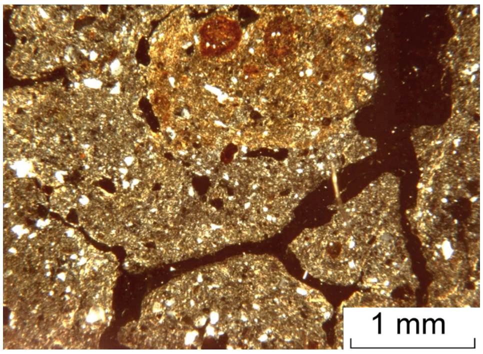


Figure 4a. XPL. Large plane merging into a chamber, rounded inclusion in the upper part.

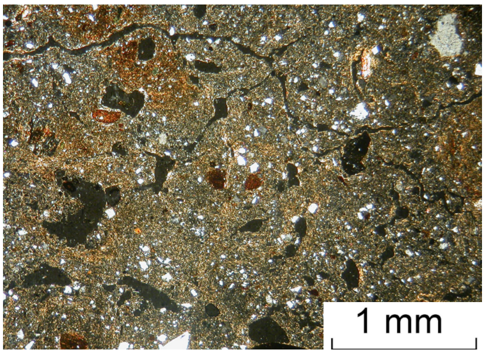


Figure 4b. XPL. Weak fragmentary clay coatings and weathered grains.

18-24 cm. Upper part of BM horizon. Compact groundmass, few coarse grains with a trend of linear arrangement or groups, no aggregates, vughs and planes, speckled b-fabric.

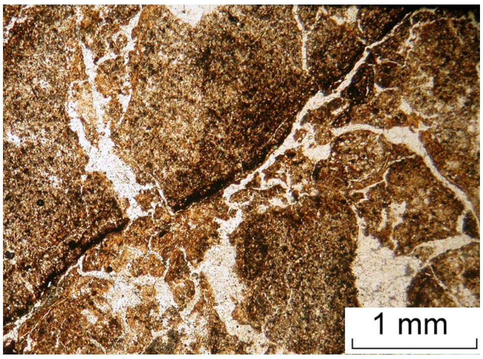


Figure 4c. PPL.

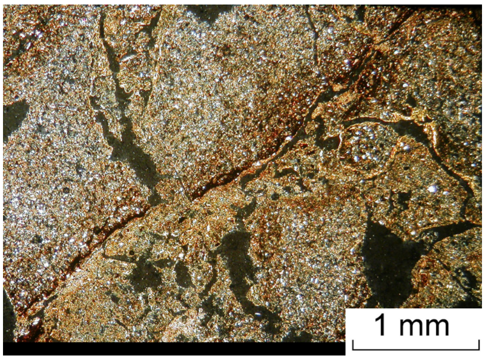


Figure 4d. XPL.

70-80 cm. Lithomarge. Disintegrated sandstone fragment crossed by a fissure with clay coatings in the upper part and with an iron coating at its lower edge. Infilling of fine material and a fine calcitic nodule; clay coatings in the right part of the picture.

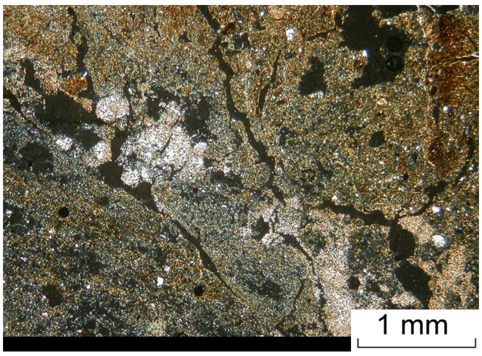
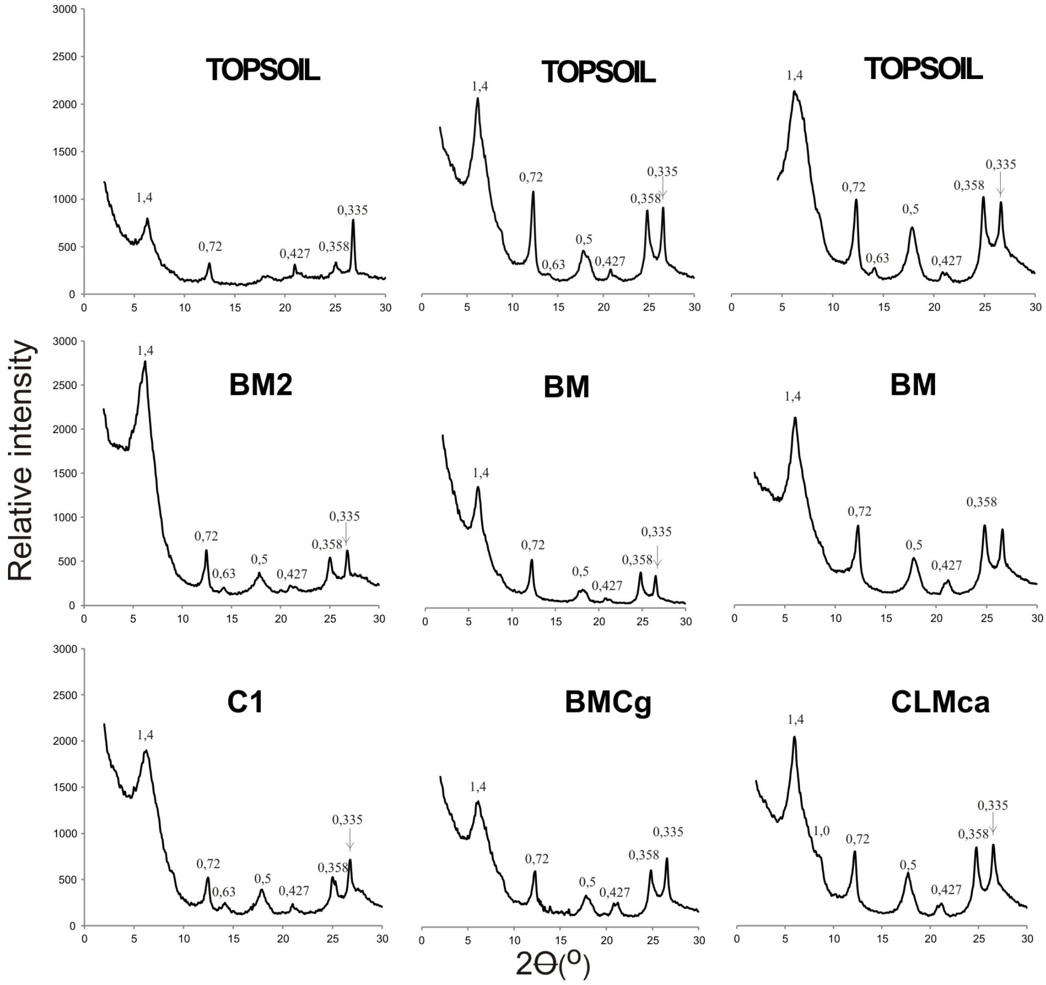


Figure 4e. 70-80 cm. Lithomarge. Segregations of secondary carbonates in the infilling. PPL.

Figure 4. Pit 3.



Typical Zheltozem (Alisol) on clayey yellow colluvium, gentle slope (pit 5).

Eluvial-gleyic Zheltozem (Stagnosol) on the terrace overlain by colluvium (pit 39).

Residually calcareous Zheltozem (Cambisol) on a slope composed of calcareous argillites (pit 3).

Figure 5. XRD curves for soil horizons in the three profiles studied.

Thus, this profile differs of other Zheltozems by the predominance of clay minerals with rigid structures and low amount of the swelling component.

The scanning electron microscopy data are in good agreement with the clay mineral data. Only two samples were investigated with the purpose of comparing the pedogenic versus lithogenic features of fine material. One sample was taken from the B horizon of the profile 3 on *in situ* claystone, depth 30-60 cm, the other represented the B horizon of the Zheltozem on yellow clay colluvium.

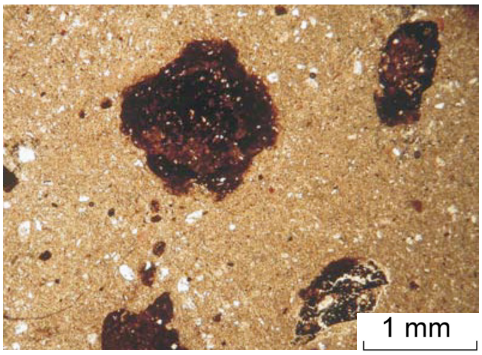


Figure 6a. PPL.

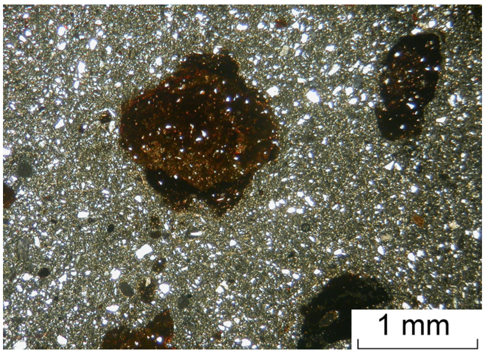


Figure 6b. XPL.

Nodules in the eluvial horizon and black (charred) plant tissue. Close porphyric c/f related distribution.

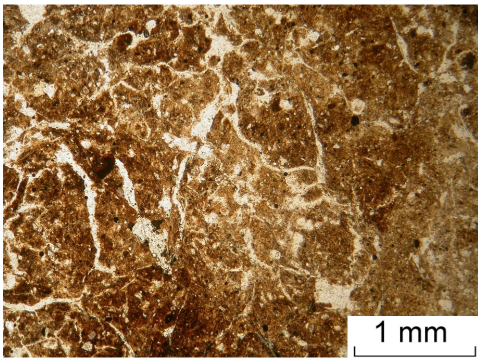


Figure 6c. PPL.

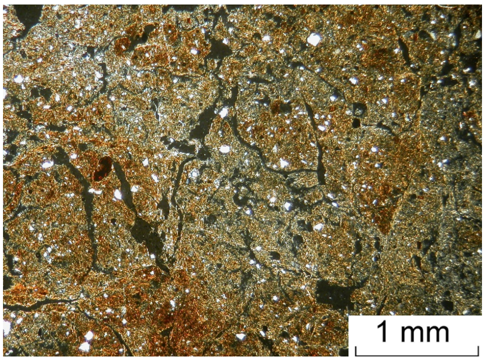


Figure 6d. XPL.

90-100 cm. BM horizon, compact groundmass, almost monic c/f related distribution, fine planes, deformed excrements in former chamber (on the left) and passage way (on the right), the latter is iron-depleted. Speckled b-fabric.

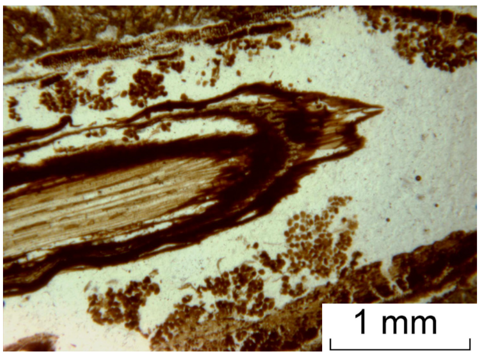


Figure 6e. 100-110 cm. Root residue in a large channel with excrements of mites.

Figure 6. Pit 39.

In the series of magnifications from 1000x to 10000x for the former sample, a polydispersed material coagulated into larger aggregates is identified (**Figure 7a**). The matrix microstructure has a cellular fabric visible at magnification 1000x, it is composed of leaf-like irregularly shaped aggregates of clay particles, presumably mixed-lattice mica-smectites and chlorite-smectites. Clay particles are arranged in aggregates according to 'base-base' rule rather than 'base-cleavage'. The width of matrix aggregates is 4 to 7 μm, the length – 8 to 22 μm. Against this background, kaolinite aggregates occur as sets of leaf-like hexagonal crystals with irregular edges, their size ranging within 1.5 and 3 μm.

The sample of the B horizon of the soil on colluvium (**Figure 7b**) also has a cellular fabric, but the size of aggregates is smaller (length 3-7 μm, width 0.4-1 μm). Therefore, at magnification 1000x, the surface is looking smooth and undulating; however, the character of aggregates is more obvious at 3000x: they are non-compact (loose), which may be due to the interaction of particles mainly according to 'base-cleavage' rule and rarely according to that of 'base-base'.

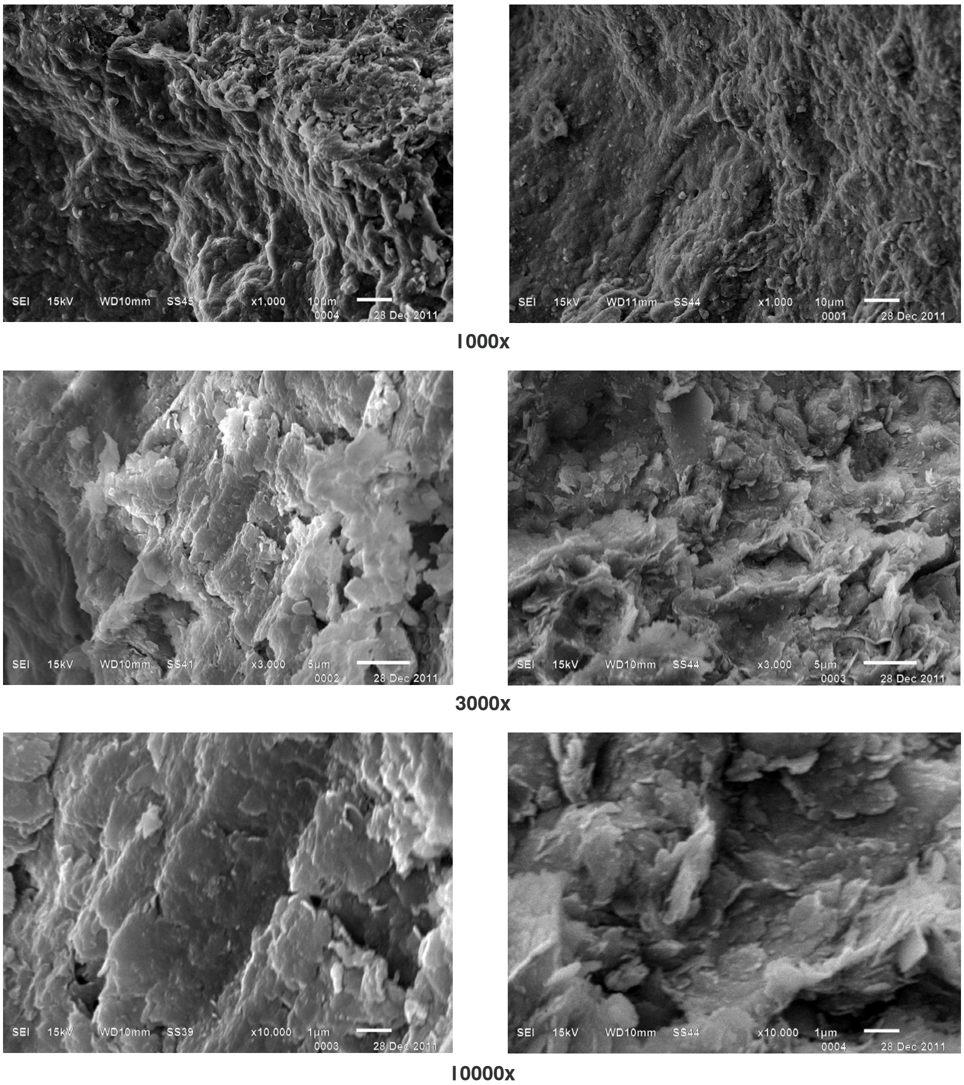


Figure 7. SEM images of two samples of BM horizon on two types of parent material: 7a – argillite, 7b – colluvium.

4. Conclusions

The comparison of three profiles reveals their common and individual features manifesting several processes and effects of parent materials. All soils display properties inherent to a subtropical environment (former and recent): the composition of clay minerals, namely, presence of kaolinite and gibbsite, the mostly clayey groundmass with few skeleton grains of weathering-resistant minerals and alteromorphs, the high abundance and diversity of iron oxide pedofeatures, and the goethite formation in the subsoil. Similar micromorphological properties were described by Fedoroff and Eswaran (1985) in Ultisols. The B horizon is peculiar in its compaction and massive structure, the absence of illuviation coatings, the specific shape of the planes, the very few moldic voids, and the weak redistribution of iron oxides. The topsoils display features related to biotic activity, primarily aggregation; they are less compact and contain less clay – all this differentiates them from the B horizon. The weatherable minerals are far less abundant in comparison with the parent rock: not only unstable volcanic glass from the parent material is absent, but also chlorite and micas.

The pedoplasmation phenomena, as described by Stoops and Schaefer (2010), may be followed in this sequence of profiles. This starts with the decarbonatization, fragmentation and ferrugination of rock fragments (saprolite, profile 3), followed by their gradual assimilation by the groundmass (profile 39), so that only a trend to linear arrangement of grains is preserved (all profiles). These features are most advanced in profile 5, formed on the oldest parent material.

The next step may be the transformation of the lithogenic fabric into the pedogenic one with the development of a specific B horizon (BM metamorphic in Russia and close to cambic in WRB; Aurousseau et al. 1985). This horizon is very compact, has a massive microstructure, planar voids, differentiated b-fabric, almost no clay coatings and no iron nodules. Among the clay minerals, smectites or kaolinite-smectites are identified, although their proportion varies. The latter fact explains many properties of the B horizon since swell-shrink phenomena are known to contribute to the disintegration of coatings, which are partly included in nodules; there may be other reasons as well (Kühn et al. 2010). The abundance of clay coatings in Ultisols (analogues of Zheltozems) strongly varies according to Fedoroff and Eswaran (1985). In our case, clay coatings are better preserved in situations with rigid-structure minerals (profile 39), or in the saprolite (profile 3).

Low porosity and dense fabric of the B horizon may limit the removal of carbonates from the underlying layers, and this may solve the contradiction between abundant rainfall and high effervescence boundary in the residually calcareous Zheltozems.

Most prominent manifestations of pedogenic processes in the sequence of soils studied are the following: weathering –removal of primary carbonates– pedoplasmation in profile 3, pedoplasmation and profile differentiation in profile 5, and iron oxide segregation/ redistribution in profile 39.

This sequence of events is supported by the data on clay minerals. Swelling minerals are most abundant in the youngest Zheltozem, and they are represented by mica-smectite with high proportion of smectite blocks and individual smectite. In typical Zheltozems on old clayey colluvium, there are kaolinite-smectites in the subsoil, whereas the refined kaolinte and finely dispersed quartz are common in the topsoil. The stagnic Zheltozem on the redeposited old colluvium is characterised by high content of kaolinite with perfect structure, occurrence of gibbsite and very small admixture of swelling minerals.

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