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Origin, properties and transformation of soil lamellae in rusty soils (Brunic Arenosols) in southeastern Poland

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Abstract

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Lamellae represent a form of illuvial accumulation of the clay fraction commonly found in Quaternary sands. Despite great interest in soils in which lamellae occur, the origin, properties and transformation of lamellae are still not fully understood. In addition, research on lamellae in sandy material was carried out mainly in Podzols, ochre soils (Rubic Arenosols) and Arenosols, while no research was conducted in this respect in rusty soils (Brunic Arenosols). The main aim of the present study was to explain lamellae origin and transformation on the example of rusty soils (Brunic Arenosols) in southeastern Poland basing on their morphology, physical and chemical properties and using micromorphological studies. The research work was performed in southeastern Poland (Kraków Gate region and Central Beskid Foothills) at the research sites Kostrze, Gołęczyna, and Połomia. The parent material of the studied soils was glaciofluvial sands. Soil lamellae in the studied rusty soils exhibit high diversity in terms of morphology and physical and chemical properties. They are characterized by a higher content of fine fractions (<0,05 mm), total organic carbon and non-silicate iron and aluminum compared to interlamellae. A number of morphological and micromorphological features, such as the presence of clay-iron coatings on mineral grains serve as evidence of the pedo-petrogenic nature of lamellae. In the uppermost parts of rusty soils, lamellae show a high degree of degradation, mainly due to biological activity.

1. Introduction

Sandy soils found in different natural environments commonly contain fine-textured illuvial forms referred to as lamellae (Schaetzl, 1992; Rawling, 2000; Holliday and Rawling, 2006; Bockheim and Hartemink, 2013). Soil lamellae are thin layers of clay-enriched material (Gile, 1979) associated with iron oxides (Prusinkiewicz et al., 1998; Lisá et al., 2019) and are characterized by finer texture (Schaetzl, 1992; Bockheim and Hartemink, 2013) and more intensive, redder color (Van Reeuwijk and de Villiers, 1985) than interlamellae material. Lamellae serve as soil stratigraphic markers and relative age indicators in geomorphologic and archeological studies (Gile, 1979; Miles and Franzmeier, 1981; Prusinkiewicz et al., 1998; Holliday and Rawling, 2006).

Reviews of lamellae origin (Rawling, 2000) indicate two main, different ways of their formation. In majority of sandy soils, a pedogenic concept prevails in the literature as the main formation pathway, which is evidenced by the increase of lamellae expression over time (Gile, 1979; Van Reeuwijk and de Villiers, 1985; Holliday and Rawling, 2006; Johnson et al., 2008), intersecting bedding planes (Dijkerman et al., 1967; Prusinkiewicz et al., 1994), content of illuvial clay coatings on quartz grains and bridges between them (Van Reeuwijk and de Villiers, 1985; Kemp and McIntosh, 1989; Schaetzl, 2001) and occurrence of lamellae in the soil solum (and usually absence in parent material) (Holliday and Rawling, 2006). In turn, petrogenic lamellae are sedimentary features, which occur parallel to bedding planes and occur at great depths (Dijkerman et al., 1967; Robinson and Rich, 1960; Muhs, 2017). The formation of such lamellae may be 1) the result of the cyclic sedimentation of fine material in the course of the accumulation of deposits (Bullock and Mackney, 1970; Boubaid et al., 1992) or 2) the result of break-up of silt/clay aggregates deposited primarily in laminae and the dispersion of clay throughout laminae (Kilibarda et al. 2008). Except for the abovementioned views, a polygenesis of the described forms has also been identified, characterized by both geologic and pedologic factors (Rawling, 2000). The number of case studies describing pedo-petrogenic lamellae origin has increased in the last few decades (Coen et al., 1966; Gile, 1979; Boubaid et al., 1992; Soil Survey Staff, 1999; Rawling, 2000; Schaetzl, 2001; Kilibarda et al., 2008; Jankowski, 2012; Obear et al., 2017).

Most of the studies are related to lamellae origin and mechanisms of their formation, but only a few raise the issue of the transformation of lamellae in the soil profile (Kemp and

McIntosh, 1989; Johnson et al., 2008; Bockheim and Hartemink, 2013). The most common factors of lamellae transformation are bioturbation caused by root growth and soil fauna activity (Kemp and McIntosh, 1989; Johnson et al., 2008). Other examples of the mechanical transformation of lamellae are freeze-thaw and drying-wetting cycles (Bryant, 1982; Kemp and McIntosh, 1989). For instance, Bryant (1982) notes the impact of permafrost and inhibition of drainage in the lower part of soil profile on lamellae breakdown. In turn, Bockheim and Hartemink (2013) note biogeochemical processes occurring in the soil as a probable transformation factor of lamellae. In tropical regions lamellae are described as forms resulting from the degradation of Bt horizons, however, as some authors describe (Furquim et al., 2013) the ongoing process of eluviation may contribute to lamellae disappearance. The above studies indicate that lamellae transformation can be observed frequently. However, there is still a lack of studies focused on the direct impact of *in situ* chemical weathering as a main transformation factor of soil lamellae.

Lamellae commonly occur in rusty soils (Brunic Arenosols) around the world (Prusinkiewicz et al., 1998; Jankowski, 2012; Bockheim and Hartemink, 2013; Phillips et al., 2015; Kruczkowska et al., 2020), which are soils typically found in post-glacial areas in temperate climates. Rusty soils (Brunic Arenosols) develop mainly from glaciofluvial, sandy deposits enriched in aluminosilicate minerals. In these soils, so-called siderik Bv horizon according to the Polish Soil Classification (2019) or cambic Bw horizon according to the IUSS Working Group WRB (2015) with features of pedogenic accumulation of iron and aluminum oxides occur below the humus horizon. In international soil classification rusty soils are classified as Brunic Arenosols (IUSS Working Group WRB, 2015). In Polish Soil Classification (2019) rusty soils (Brunic Arenosols) yield a separate typological unit. Polish studies on rusty soils (Brunic Arenosols) have been performed in central and north Poland (Kowalkowski, 1977; Bednarek, 1991; Janowska, 1994; 2001; Manikowska and Bednarek, 1994; Prusinkiewicz et al., 1994; 1998; Bednarek et al., 2010; Chojnicki and Piotrowska, 2010; Jankowski et al., 2011; Jankowski, 2012), in the Roztocze region (Uziak et al., 2010), Lower Silesia region (Kabała, 2005), and in mountain areas (Kowalkowski and Degórski, 2005; Marzec and Kabała, 2008). However, there is a lack of studies on rusty soils (Brunic Arenosols) in southeastern Poland.

Studies on lamellae in sandy soils was carried out mainly in Podzols, ochre soils (Rubic Arenosols), and Arenosols. In rusty soils (Brunic Arenosols) a relatively finer (sandy) texture may lead to translocation and accumulation of the clay fraction in the form of thin soil lamellae (Polish Soil Classification, 2019). Although soil lamellae are often found in rusty soils (Brunic Arenosols), there is little research work devoted to their origin, transformation, and properties. Thus, the main aim of the present study was to explain lamellae origin and transformation on the example of rusty soils (Brunic Arenosols) in southeastern Poland basing on their morphology, physical and chemical properties and using micromorphological studies.

2. Materials and methods

2.1. Study area

The study was carried out in southeastern Poland at three study sites – Kostrze, Gołęczyna and Połomia. Three soil profiles: L1, L2 and L3, respectively, were selected for the study. The study areas were located in the so-called Kraków Gate area (Kostrze site) and in the Central Beskids Foothills (Gołęczyna and Połomia sites). The soil parent material in all the study sites consisted of sandy glaciofluvial deposits (Rutkowski, 1993; Gradziński and Gradziński, 2013; Marciniec and Zimnal, 2016). All the studied sites were characterized by a mean annual air temperature ca. 6–8°C and mean annual precipitation ranging from 650 to 750 mm (Obrębska-Starklowa et al., 1995; Bokwa et al., 2015). The community of *Nardo-Callunetea*, with predominance of grasses, heather, and silver birch *(Betula pendula)* was located at the Kostrze study site. The Gołęczyna and Połomia sites are located under mixed forests with a prevalence of Scots pine (*Pinus sylvestris),* hornbeam (*Carpinus betulus)*, and an admixture of beech *(Fagus sylvatica)*. Detailed information about the study sites is listed in Table 1.

2.2. Field and laboratory studies

The studied soils were described and sampled according to the FAO Guidelines for Soil Description (Jahn et al., 2006). Samples from horizons where lamellae occur were collected separately from lamellae and interlamellae. A detailed description of lamellae morphology including depth of occurrence, thickness, continuity, color, shape, pattern, and boundaries was performed. Undisturbed soil samples were collected for micromorphological analysis from selected horizons (Bv, BC, and parent material). Soil color was determined in the moist state using Munsell Soil Color Charts (Munsell, 1975).

Table 1
Location and site characteristic

No	Site	GPS coordinates	Elevation m a.s.l.	Parent material	Geomorphic position	Vegetation
L1	Kostrze	50°02’08’’N 19°52’10’’E	226	Glaciofluvial sands	Gentle slope (3-5°); aspect N	Heath
L2	Gołęczyna	49°58’29’’N 21°20’88’’E	258	Glaciofluvial sands	Gentle slope (0-3°); aspect NE	Mixed forest
L3	Połomia	49°58’16’’N, 21°22’45’’E	356	Glaciofluvial sands	Gentle slope (0-3°); aspect SW	Mixed forest

Collected samples were air-dried, gently crushed and sieved through a 2 mm steel sieve. Living roots were removed from the soil samples. The particle-size distribution was determined using a laser diffraction method employing a Mastersizer 3000 granulometer, with dispersion in distilled water and ultrasounds. The soil mineral composition was determined for selected soil horizons via X-ray powder diffraction (XRD) on a Rigaku MiniFlex600 benchtop diffractometer. Random powder specimens were analyzed from 2 to 65°2θ at a counting speed of 0.02°/1 s. Total carbon concentration was determined via gas chromatography using a micro-analyzer with simultaneous CHN determination via a vario MICRO cube (Nelson and Sommers, 1996). Due to the absence of carbonates in the studied soils, the total carbon content corresponds to the total organic carbon (TOC) content. Soil pH was measured potentiometrically in distilled water using a 1:1 ratio (Thomas, 1996).

The concentration of total iron and non-silicate forms of both iron and aluminum in the selected soil horizons was determined using flame atomic absorption spectroscopy (Agilent FS F-AAS). In order to determine the total content of iron (Fe_t), 0.5 g of sample were mineralized in an acid mixture consisting of HNO_3, HCl, and HF (2-6-2 ml ratio) via microwave assisted digestion. The „free" iron (Fe_d) was extracted with a citrate-bicarbonate-dithionite (CBD) solution (Mehra and Jackson, 1960). The amorphous forms of iron (Fe_o) and aluminum (Al_o) were extracted using a solution of acid ammonium oxalate (Van Reeuwijk, 2002). The Al_o+1/2Fe_o index was then calculated, as were the weathering index for iron (Fe_d/Fe_t) and iron activity ratio (Fe_o/Fe_d) (Schwertmann, 1964).

Micromorphological analysis was performed on thin sections prepared according to the standard procedures described in the literature (FitzPatrick, 1984) via a polarizing microscope (Nikon Eclipse E600 POL). For micromorphological descriptions, terminology given by Stoops (2003) was used.

The studied soils were classified according to the sixth edition of the Polish Soil Classification (2019) and the WRB system (IUSS Working Group WRB 2015).

3. Results

3.1. Soil and lamellae morphology

The studied soils exhibited morphologic differences (Table 2, Fig. 1). One of the studied soils (profile L1 – Dystric Lamellic Brunic Arenosol (Ochric)) was characterized by the

Table 2
Morphology and classification of the studied soils

Horizon	Depth	Lamellae/ interlamellae	Munsell color	Structure*	Roots	Consistence**	Horizon boundary
	cm		moist				
L1 Brown-rusty soil (proto-lamellar) (PSC 2019); Dystric Lamellic Brunic ARENOSOL (Ochric) (WRB 2015)							
Of	4–0	–	n.a.	n.a.	n.a.		abrupt
A	0–14	–	10YR 2/1	SA	many	SO	clear wavy
Bv***	14–40	–	10YR 4/4	SA	common	SHA	clear smooth
BC1	40–60	INTERLAMELLAE	10YR 5/4	SA, SG	few	SHA	clear wavy
		LAMELLAE	10YR 5/6				
BC2	60–95	INTERLAMELLAE	10YR 5/4	SG	very few	SHA	gradual
		LAMELLAE	10YR 5/8				
C1	95–130	INTERLAMELLAE	10YR 5/4	SA, AB, SG	very few	SHA	gradual
		LAMELLAE	7.5YR 4/6				
C2	130–160	INTERLAMELLAE	10YR 6/3	SA, AB, SG	very few	SHA	gradual
		LAMELLAE	7.5YR 4/6				
C3	160–(200)	INTERLAMELLAE	10YR 6/3	SA, AB, SG	very few	SHA	–
		LAMELLAE	7.5YR 4/6				
L2 Podzolic brown-rusty soil (proto-lamellar) (PSC 2019); Dystric Lamellic Brunic ARENOSOL (Ochric, Protospodic) (WRB 2015)							
Ol	2–0	–	n.a.	n.a.	n.a.	n.a.	n.a.
C	0–10	–	2.5Y 3/3	SA, GR, SG	many	SO	clear smooth
A	10–20	–	2.5Y 4/3	SA, GR	many	SO	clear wavy
E	20–25	–	2.5Y 4/2	GR, SG	common	SO	clear wavy
Bs	25–35	–	10YR 4/6	SA, AB	common	SHA	clear wavy
Bv	35–60	–	10YR 4/4	SA, AB	common	SHA	gradual
BC	60–85	–	10YR 5/4	SG	common	SO	gradual
C1	85–130	INTERLAMELLAE	2.5Y 4/4	SG	few	SHA	gradual
		LAMELLAE	10YR 3/6				
C2	130–(190)	INTERLAMELLAE	2.5Y 4/4	SG	few	SHA	-
		LAMELLAE	10YR 4/4				

Table 2, continue

Horizon	Depth	Lamellae/ interlamellae	Munsell color	Structure*	Roots	Consistence**	Horizon boundary
	cm		moist				
L3 Podzolic brown-rusty soil (humic, covered) (PSC 2019); Dystric Brunic ARENOSOL (Humic, Areninovic) (WRB 2015)							
Ol	4–0	–	n.a.	n.a.	n.a.	n.a.	n.a.
A	0–8	–	7.5YR 3/3	GR	many	LO	clear wavy
E	8–16	–	10YR 4/2	SG	few	SO	clear irregular
BC	16–40	–	10YR 4/6	SG, SA	few	SHA	clear irregular
Ab	40–60	–	10YR 3/3	GR	many	HA	clear wavy
AE	60–75	–	10YR 4/2	SG	common	HA	clear wavy
Bvb	75–110	–	10YR 5/6	SA	common	SHA	clear wavy
C1	110–133	INTERLAMELLAE	10YR 6/6	SG	few	SHA	gradual
		LAMELLAE	7.5YR 4/4				
C2	133–(200)	INTERLAMELLAE	10YR 6/4	SG	few	SHA	-
		LAMELLAE	7.5YR 3/4				

*Structure: SG – single grain, SA – subangular blocky, AB – angular blocky, GR – granular; **Consistence: LO – loose, SO – soft, SHA – slightly hard, HA – hard; ***Bv – siderik horizons (according to the PSC (2019)) with the change of the color of the sand due to the pedogenic accumulation of iron and aluminum oxides; n.a. – not analyzed

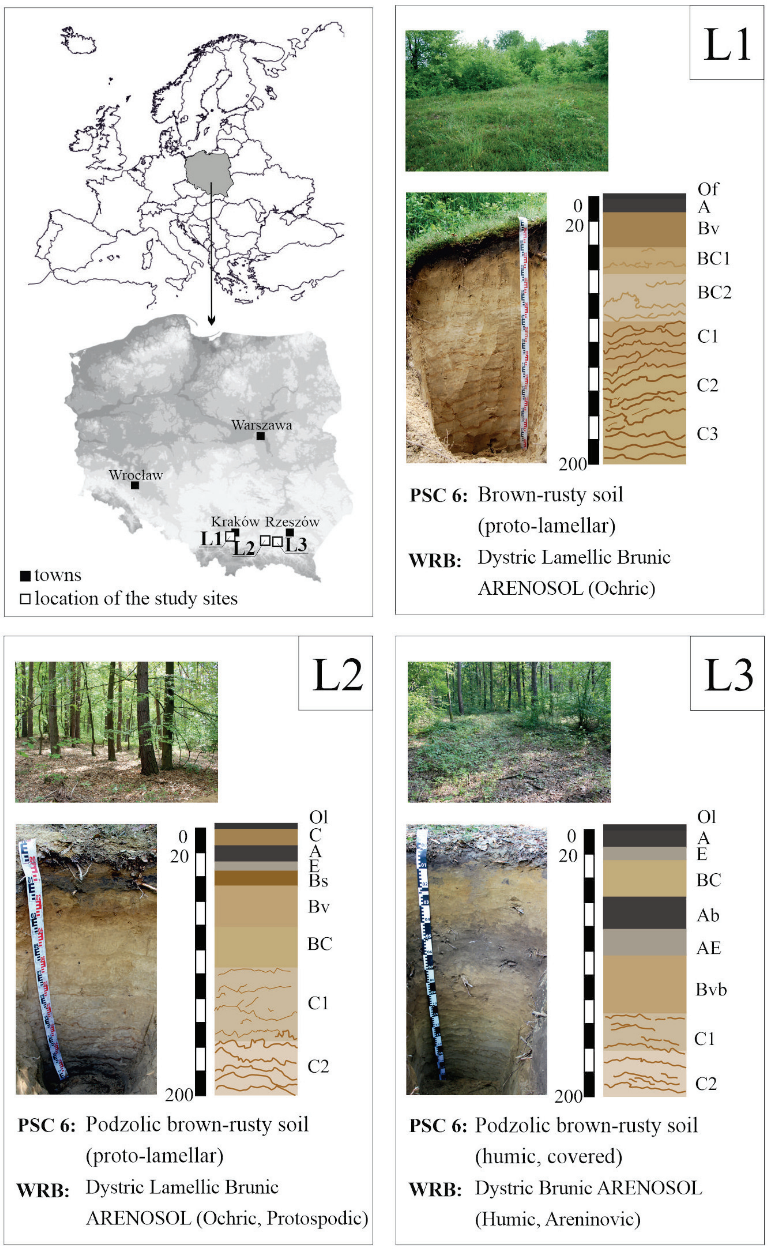

Fig. 1. Location of study area and studied pedons. Morphology of studied rusty soils (Brunic Arenosols). Siderik Bv horizons (according to the Polish Soil Classification (2019)) with the change of the color of the sand due to the pedogenic accumulation of iron and aluminum oxides

occurrence of a sequence of soil horizons typical of rusty soils (Brunic Arenosols): O-A-Bv-C. A thick humus horizon (14 cm) with subangular blocky structure, soft consistence, and clear wavy boundary to the Bv horizon occurred beneath the organic O horizon in profile L1. Relatively thick (26 cm) siderik Bv horizon was characterized by brownish yellow color (10YR 6/6), subangular blocky structure, and slightly hard consistence. A transitional BC horizon with single grain structure was found below. Roots mostly occurred in the upper part of the solum. In profile L2 (Dystric Lamellic Brunic Arenosol (Ochric, Protospodic)) (Table 2), sandy material labelled as C occurred below the organic O horizon. A humus horizon was found below the 10 cm layer of sandy material. An eluvial E horizon with eluviation features (olive-brown color 2.5Y 4/2) occurred above the Bs horizon and thick (25 cm) siderik Bv horizon. Roots occurred in most parts of this soil profile. The uppermost part of profile L3 (see Table 2) consisted of a sequence of A-E-BC horizons with loose and soft consistence and single-grain structure. Below buried soil with a sequence of soil horizons typical of rusty soils (Brunic Arenosols): Ab-AE-Bvb-C occurred. The entire L3 profile (Dystric Brunic Arenosol (Humic, Areninovic)) was characterized by the predominance of single-grain structure, with the exception of siderik and humus horizons, which had a subangular blocky and granular structure, respectively. Hard and slightly hard consistence was identified in the buried soil. Roots commonly occurred in A, Ab and Bvb horizons.

Soil lamellae appeared almost throughout the entire L1 profile (Table 3), except for the Bv and A horizons. Lamellae were first observed at a depth of 40 cm down to a depth of 95 cm. They were mostly thin, discontinuous, and yellowish brown in color (10YR 5/6). In parent material the soil lamellae were thicker (up to 50 mm), continuous, and redder (7.5YR 4/6). Below 130 cm their boundaries were sharp and clear, while in the upper parts of the soil profile their boundaries were ragged and blurry. In the whole L1 profile, soil lamellae followed a wavy and irregular shape, and mostly horizontal and vertical course in the profile. The thickness of interlamellae was similar in all the studied horizons and ranged from 50 to 200 mm. In turn, in the L2 and L3 profiles (Table 3), soil lamellae occurred only in parent material and were characterized by mostly wavy and irregular shape,

Table 3
Morphology of soil lamellae

Horizon	Depth	Thickness	Continuity	Munsell color in moist state	Shape of lamellae	Course in soil profile	Boundaries	Thickness of interlamellae
	cm	mm						mm
L1 Brown-rusty soil (proto-lamellar) (PSC 2019); Dystric Lamellic Brunic ARENOSOL (Ochric) (WRB 2015)								
A	0–14	lack of soil lamellae						
Bv	14–40	lack of soil lamellae						
BC1	40–60	2–3	discontinuous	10YR 5/6	wavy, irregular	horizontal and vertical	ragged, blurry	50–100
BC2	60–95	3–7	mixed	10YR 5/8	wavy, irregular	horizontal and vertical	ragged, blurry	50–200
C1	95–130	1–50	continuous	7.5YR 4/6	wavy, irregular	horizontal	ragged, blurry	50–200
C2	130–160	1–50	continuous	7.5YR 4/6	wavy, irregular	horizontal and vertical	sharp, clear	50–200
C3	160–(200)	1–50	continuous	7.5YR 4/6	wavy, irregular	horizontal	sharp, clear	50–200
L2 Podzolic brown-rusty soil (proto-lamellar) (PSC 2019); Dystric Lamellic Brunic ARENOSOL (Ochric, Protospodic) (WRB 2015)								
C	0–10	lack of soil lamellae						
A	10–20	lack of soil lamellae						
E	20–25	lack of soil lamellae						
Bs	25–35	lack of soil lamellae						
Bv	35–60	lack of soil lamellae						
BC	60–85	fragmented parts of soil lamellae						
C1	85–130	2–10	discontinuous	10YR 3/6	wavy, irregular	horizontal	ragged, blurry	50–150
C2	130–(190)	5–30	continuous	10YR 4/4	wavy, irregular	horizontal	sharp, clear	20–150
L3 Podzolic brown-rusty soil (humic, covered) (PSC 2019); Dystric Brunic ARENOSOL (Humic, Areninovic) (WRB 2015)								
A	0–8	lack of soil lamellae						
E	8–16	lack of soil lamellae						
BC	16–40	lack of soil lamellae						
Ab	40–60	lack of soil lamellae						
AE	60–75	lack of soil lamellae						
Bvb	75–110	lack of soil lamellae						
C1	110–133	1–10	mixed	7.5YR 4/4	wavy, irregular	horizontal	sharp, clear	10–180
C2	133–(200)	1–10	continuous	7.5YR 3/4	straight, irregular	horizontal	sharp, clear	10–180

horizontal course, sharp and clear boundaries, and were either continuous or continuous and discontinuous at the same site. Only in the C1 horizon in the L2 profile lamellae were discontinuous with ragged and blurry boundaries. In the BC horizon in the L2 profile lamellae occurred fragmentarily. The thickness of the studied interlamellae varied from 10 to 180 mm.

3.2. Physical and chemical properties, and mineral composition

The texture of all the studied soils was fine sand, loamy fine sand or sandy loam (Table 4). The soil lamellae usually had a somewhat finer texture and were characterized by higher silt

Table 4
Physical and chemical properties of the studied soils

Horizon	Depth	Lamellae/ interlamellae	Content (%) in fine fraction			Texture (IUSS WRB 2015)	pH	TOC
	cm		sand	silt	clay		H_2O	%
L1 Brown-rusty soil (proto-lamellar) (PSC 2019); Dystric Lamellic Brunic ARENOSOL (Ochric) (WRB 2015)								
Of	4–0	-	n.a.	n.a.	n.a.	n.a.	4.3	23.25
A	0–14	-	77	22	1	loamy fine sand	4.8	1.16
Bv	14–40	-	85	14	2	loamy fine sand	5.4	0.19
BC1	40–60	INTERLAMELLAE	76	23	2	loamy fine sand	5.3	0.13
		LAMELLAE	77	21	2	loamy fine sand	5.2	0.15
BC2	60–95	INTERLAMELLAE	78	20	2	loamy fine sand	5.3	0.08
		LAMELLAE	65	32	3	sandy loam	5.2	0.13
C1	95–130	INTERLAMELLAE	74	24	2	loamy fine sand	5.4	0.08
		LAMELLAE	63	33	4	sandy loam	5.5	0.13
C2	130–160	INTERLAMELLAE	85	13	2	loamy fine sand	5.4	0.07
		LAMELLAE	68	28	4	sandy loam	5.5	0.10
C3	160–(200)	INTERLAMELLAE	82	16	2	loamy fine sand	5.5	0.13
		LAMELLAE	66	30	4	sandy loam	5.5	0.08
L2 Podzolic brown-rusty soil (proto-lamellar) (PSC 2019); Dystric Lamellic Brunic ARENOSOL (Ochric, Protospodic) (WRB 2015)								
Ol	2–0	–	n.a.	n.a.	n.a.	n.a.	4.8	35.86
C	0–10	–	94	2	4	fine sand	4.6	0.81
A	10–20	–	95	4	1	fine sand	4.4	1.07
E	20–25	–	97	3	0	fine sand	4.6	0.33
Bs	25–35	–	86	12	2	loamy fine sand	4.7	0.47
Bv	35–60	–	85	13	2	loamy fine sand	4.6	0.20
BC	60–85	–	97	3	0	fine sand	4.8	0.19
C1	85–130	INTERLAMELLAE	97	3	0	fine sand	5.1	0.19
		LAMELLAE	86	12	2	loamy fine sand	5.2	0.16
C2	130–(190)	INTERLAMELLAE	97	2	1	fine sand	5.7	0.10
		LAMELLAE	89	9	2	fine sand	5.5	0.13
L3 Podzolic brown-rusty soil (humic, covered) (PSC 2019); Dystric Brunic ARENOSOL (Humic, Areninovic) (WRB 2015)								
Ol	4–0	–	n.a.	n.a.	n.a.	n.a.	4.8	37.26
A	0–8	–	n.a.	n.a.	n.a.	n.a.	4.1	2.82
E	8–16	–	95	5	0	fine sand	4.3	0.81
BC	16–40	–	96	2	2	fine sand	4.6	0.73
Ab	40–60	–	89	9	2	fine sand	4.6	1.96
AE	60–75	–	86	12	2	loamy fine sand	5.9	2.09
Bvb	75–110	–	87	12	1	fine sand	6.6	0.70
C1	110–133	INTERLAMELLAE	97	3	0	fine sand	6.6	0.30
		LAMELLAE	88	11	1	fine sand	6.7	0.43
C2	133–(200)	INTERLAMELLAE	97	3	0	fine sand	6.6	0.22
		LAMELLAE	86	12	2	loamy fine sand	6.7	0.31

n.a. – not analyzed

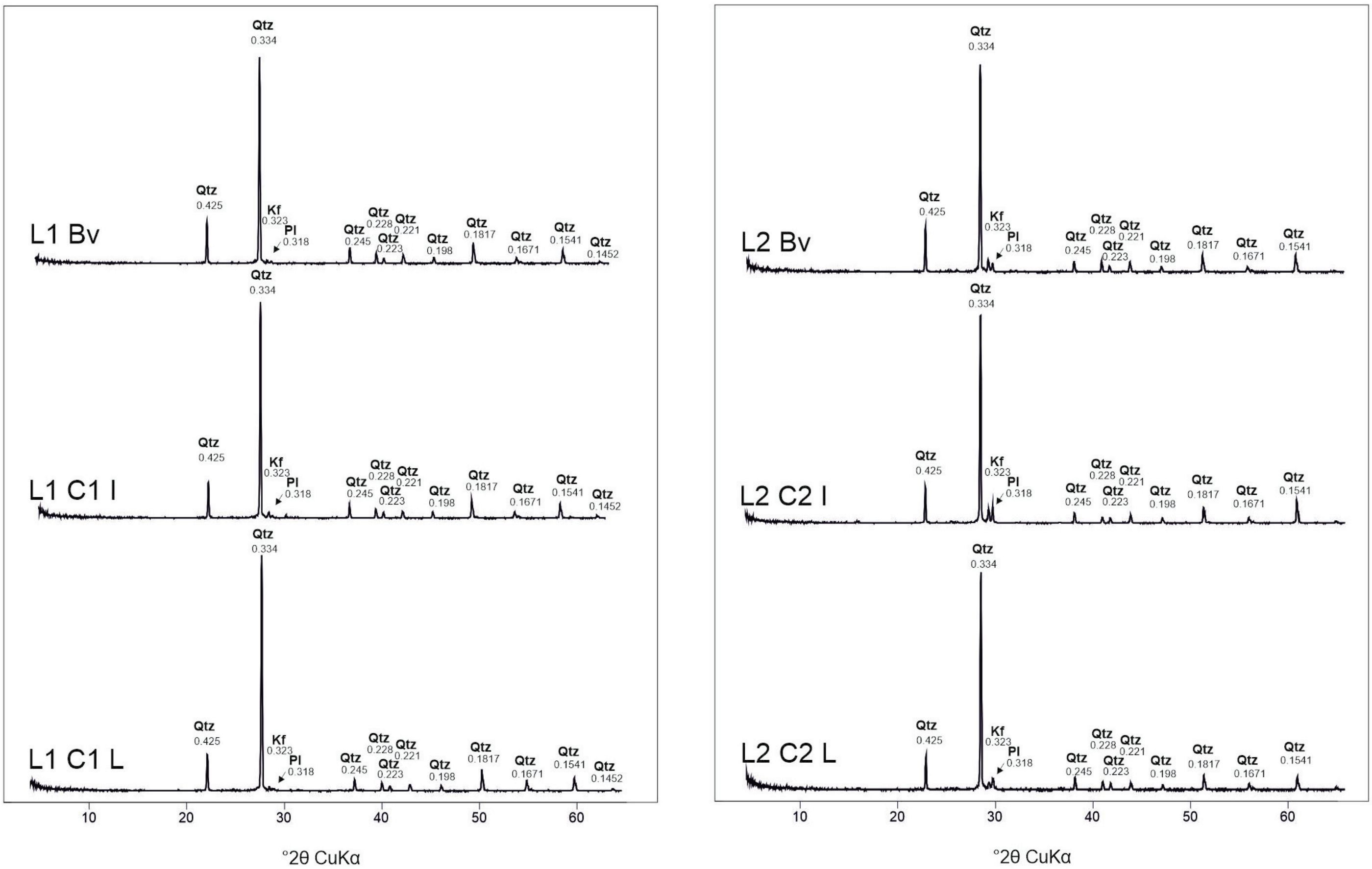

Fig. 2. XRD patterns of bulk soil samples (< 2 mm) obtained from siderik horizons (Bv) and parent material (C) of studied soils: L1 – profile L1, L2 – profile L2, I – interlamellae, L – lamellae, Qtz – quartz, Kf – K-feldspar, Pl – plagioclase

content (up to 4 times higher) and clay content (2 times higher) than interlamellae. The studied rusty soils, lamellae, and interlamellae had a similar mineral composition (Fig. 2) with a predominance of quartz, K-feldspar, and plagioclase.

All the studied soils were mostly acidic (pH values ranged from 4.1 to 5.9). A relatively higher pH values were determined in buried L3 profile (pH values ranged from 6.6 to 6.7) (Table 4). Generally, the studied lamellae had a higher pH than interlamellae, with the exception of BC horizons in the L1 profile and the C2 horizon in the L2 profile. TOC content in the studied organic soil horizons (litter) ranged from 23.25% to 37.26% (Table 4), while in A horizons – from 1.07% to 2.82%. A relatively high content of TOC was determined in the buried siderik horizon (0.70%) in the L3 profile, while in the L1 and L2 profiles it was 0.19% and 0.20%, respectively. TOC content in the studied lamellae was slightly higher (ranging from 0.08% to 0.43%) than in the studied interlamellae (ranging from 0.08% to 0.30%) (Table 4).

The total content of iron (Fe_t) was slightly higher in the L1 profile than the L2 and L3 profiles and ranged from 4.70 to 16.72 g kg^{-1} (Table 5). The Fe_t content in the L2 and L3 profiles was similar and ranged from 5.04 to 7.34 g kg^{-1} and from 4.05 to 6.55 g kg^{-1}, respectively. The content of Fe_t was higher in the lamellae than that in interlamellae (Table 5). The distribution of non-silicate forms of iron (CBD-extractable iron and oxalate-extractable iron) in the soil profile indicated strong enrichment in lamellae in relation to interlamellae. Similarly, the Bs horizon in the L2 profile was enriched in both Fe_d and Fe_o (3.00 and 1.41 g kg^{-1}, respectively). The content of non-silicate forms of iron in siderik Bv horizons in the L1 and L2 profiles was similar and ranged from 1.68 to 1.92 g kg^{-1} for Fe_d and from 0.42 to 0.76 g kg^{-1} for Fe_o, respectively. In turn, the content of Fe_d and Fe_o in the siderik Bv horizon in the L3 profile was lower: 0.68 and 0.67 g kg^{-1}, respectively (Table 5).

The lowest values of the Fe_o/Fe_d index (iron activity ratio) were calculated for the L1 profile, while for the L2 and L3 profiles it was up to three times higher. The degree of weathering ratio (Fe_d/Fe_t), however, was higher for the L1 and L2 profiles than the L3 profile. Both index values (Fe_o/Fe_d and Fe_d/Fe_t) suggested no major differences between lamellae and interlamellae, with the exception of the L3 profile, where values were higher for lamellae than interlamellae (Table 5).

The content of Al_o was moderately high (Table 5) and ranged from 0.62 to 0.82 g kg^{-1} in profile L1, from 0.28 to 1.44 g kg^{-1} in profile L2, and from 0.39 to 1.40 g kg^{-1} in profile L3. The of Al_o+1/2Fe_o index was relatively high for the Bs horizon in the L2 profile (2.14) and Bv horizons in all the studied soils (ranging from 0.97 to 1.44), and was also higher for lamellae (ranging from 0.93 to 1.31) than interlamellae (ranging from 0.49 to 0.94).

Table 5
Content of total and non-silicate forms of iron, amorphous aluminum, and indices of soil development in the selected horizons of the studied soils

Horizon	Depth	Lamellae/ interlamellae	Fe_t	Fe_d	Fe_o	Al_o	Fe_o/Fe_d	Fe_d/Fe_t	$Al_o+1/2Fe_o$
	cm		g kg^{-1}						
L1 Brown–rusty soil (proto–lamellar) (PSC 2019); Dystric Lamellic Brunic ARENOSOL (Ochric) (WRB 2015)									
A	0–14	–	10.71	2.95	0.77	0.82	0.26	0.28	1.21
Bv	14–40	–	8.59	1.68	0.42	0.79	0.25	0.20	1.00
BC2	60–95	INTERLAMELLAE	5.91	1.23	0.32	0.62	0.26	0.21	0.78
		LAMELLAE	7.62	2.32	0.52	0.68	0.22	0.30	0.94
C3	160–(200)	INTERLAMELLAE	5.61	1.53	0.35	0.76	0.23	0.27	0.94
		LAMELLAE	16.72	4.18	0.99	0.81	0.24	0.25	1.31
L2 Podzolic brown–rusty soil (proto–lamellar) (PSC 2019); Dystric Lamellic Brunic ARENOSOL (Ochric, Protospodic) (WRB 2015)									
A	10–20	–	6.43	1.50	0.79	0.45	0.53	0.23	0.85
E	20–25	–	6.29	2.06	0.81	0.69	0.40	0.33	1.09
Bs	25–35	–	5.60	3.00	1.41	1.44	0.47	0.54	2.14
Bv	35–60	–	5.95	1.92	0.76	1.06	0.40	0.32	1.44
BC	60–85	–	5.88	1.81	0.61	0.54	0.34	0.31	0.85
C2	130–(190)	INTERLAMELLAE	5.04	2.23	0.71	0.28	0.32	0.44	0.64
		LAMELLAE	7.34	4.49	1.51	0.45	0.34	0.61	1.21
L3 Podzolic brown–rusty soil (humic, covered) (PSC 2019); Dystric Brunic ARENOSOL (Humic, Areninovic) (WRB 2015)									
Ab	40–60	–	6.27	1.58	0.66	1.27	0.42	0.25	1.60
AE	60–75	–	5.87	0.68	0.67	1.40	0.99	0.12	1.74
Bvb	75–110	–	5.31	0.68	0.39	0.77	0.57	0.13	0.97
C1	110–133	INTERLAMELLAE	4.18	0.40	0.20	0.39	0.50	0.10	0.49
		LAMELLAE	5.29	0.92	0.75	0.55	0.82	0.17	0.93

3.3. Micromorphological properties

Micromorphological studies of the Bv and Bs horizons show a dominance of more or less rounded quartz grains in soil material forming a mostly subangular blocky microstructure. However, in some places siderik Bv horizons exhibited some features of single-grain microstructure. The Bv and Bs horizons were characterized by complex packing voids and channel microporosity. In the groundmass a small quantity of mica, feldspar, and chlorite was noted. Remains of poorly decomposed

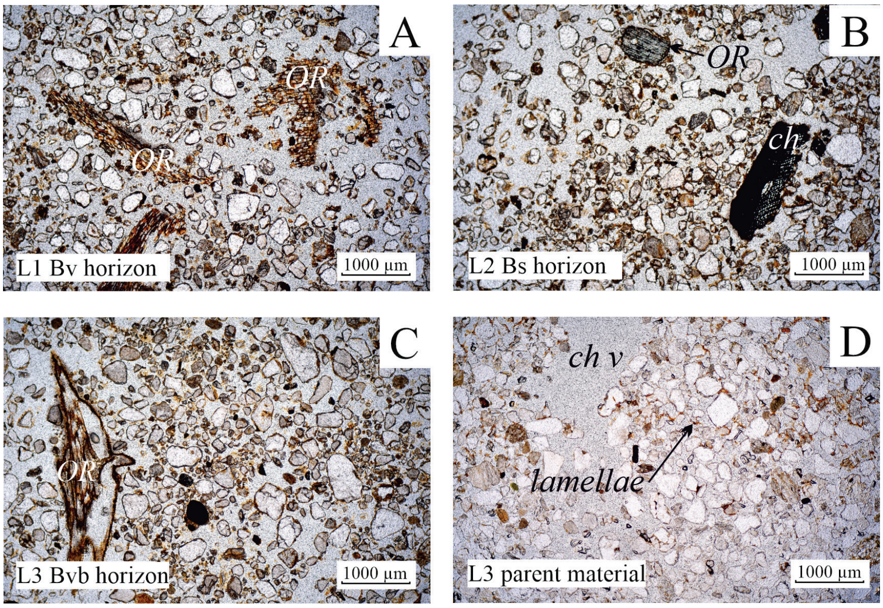

Fig. 3. Organic materials and evidence of high biological activity in studied soils. (A) Organic remnants (OR) with visible tissue structure in siderik Bv horizon in L1 profile; (B) Organic remnants (OR) and charcoal (ch) in illuvial Bs horizon in L2 profile; (C) Organic remnant (OR) in Bvb horizon in L3 profile; (D) channel pore (ch v) crossing lamellae in parent material in L3 profile

roots (Fig. 3A, C) and charcoals (Fig. 3B) were very common in coarse material of the studied soils. The fine fraction in the Bv and Bs horizons was dominated by iron compounds mostly in the form of coatings and zones of enrichment with a concentration of amorphous organic matter (Fig. 4). The presence of single illuvial clay coatings and a few Fe-Mn nodules were also observed.

Lamellae in the BC1 horizon in the L1 profile were characterized by the occurrence of fine quartz grains and weakly-developed clay-iron coatings on quartz grains (Fig. 5). Below,

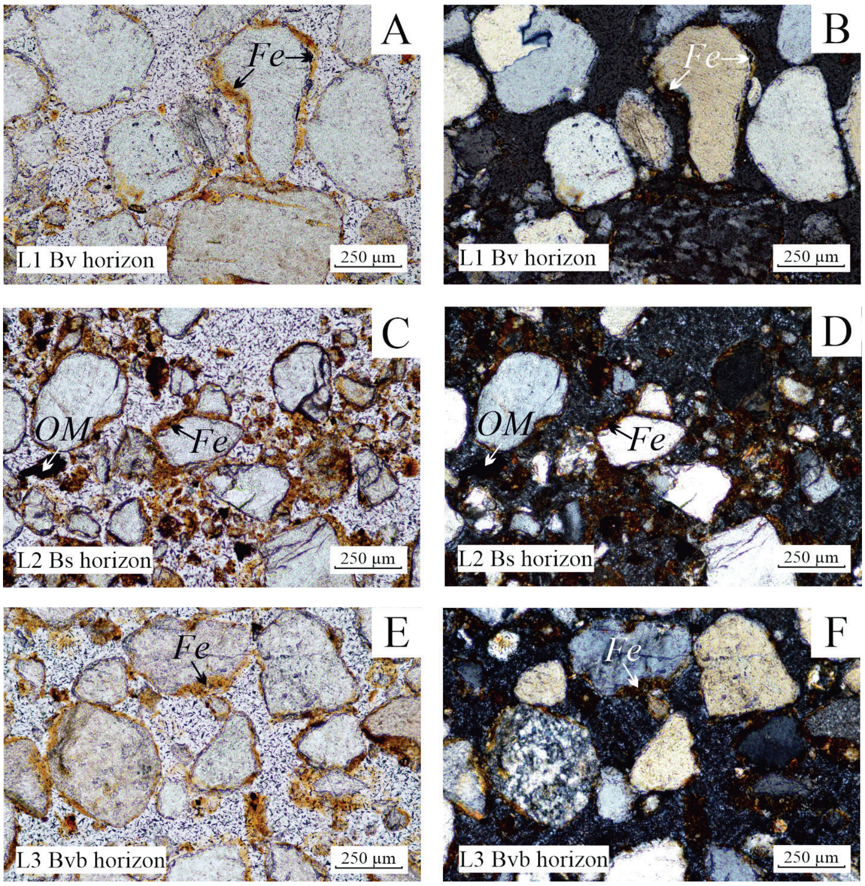

Fig. 4. Micromorphological features of siderik Bv horizons and illuvial Bs horizon. (A, B) Bv horizon in L1 profile with iron coatings (Fe) on mineral grains; (C, D) Illuvial Bs horizon in L2 profile with cracked iron coatings (Fe) on mineral grains and amorphous organic matter (OM); (E, F) Bvb horizon in L3 profile with iron coatings (Fe) on mineral grains. Plane-polarized light (PPL) (A, C, E) and cross-polarized light (XPL) (B, D, F)

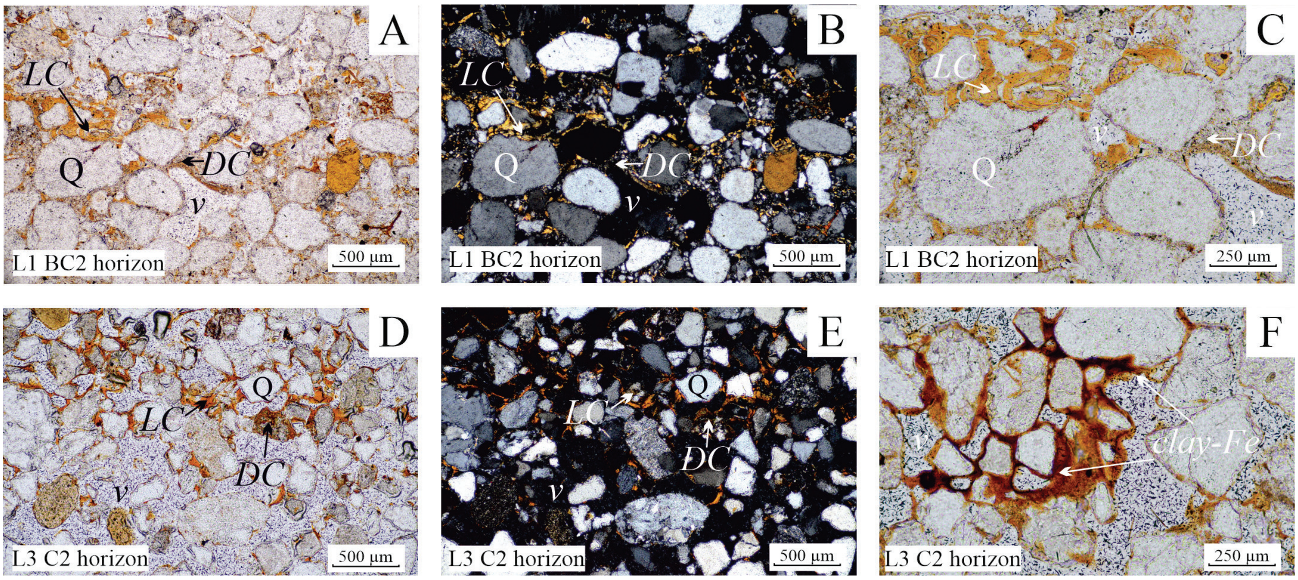

Fig. 5. Soil lamellae coatings and bridges in selected horizons. (A, B, C) Lamellae in BC2 horizon in L1 profile with microlaminated clay coatings (LC – limpid clay coatings, DC – dusty-clay coatings) and infillings occurring on and between quartz grains (Q); (D, E) Lamellae in C2 horizon in L3 profile with microlaminated clay coatings (LC – limpid clay coatings, DC – dusty-clay coatings) and infillings; (F) clay-iron coatings (clay-Fe) occurring on and between quartz grains (Q); v – voids. Plane-polarized light (PPL) (A, C, D, F) and cross-polarized light (XPL) (B, E)

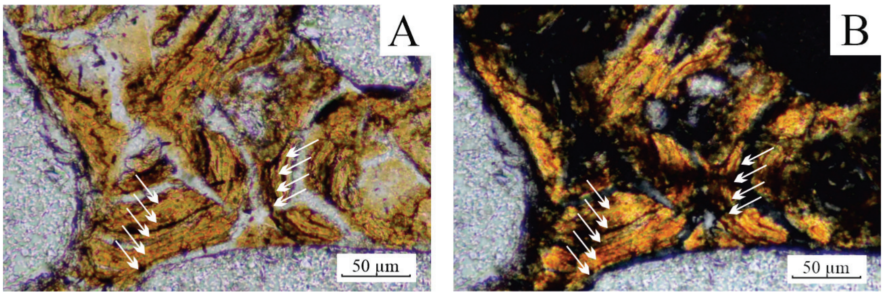

Fig. 6. Lamellae in BC2 horizon in L1 profile with microlaminated clay coatings and infillings on and between quartz grains (white arrows). Plane polarized light (PPL) (A) and cross-polarized light (XPL) (B)

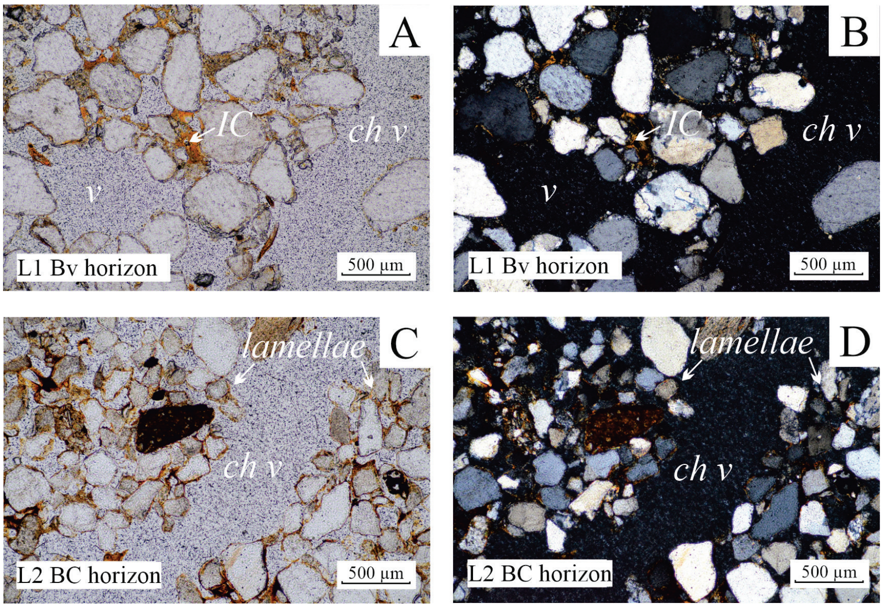

Fig. 7. Fragments of degraded soil lamellae with illuvial clay (IC) on mineral grains in Bv horizon in L1 profile (A, B) and lamellae divided by channel void (v) in BC horizon in L2 profile (C, D)

in lamellae in the BC2 horizon, well-formed, layered, yellowish clay coatings characteristic of illuviation prevailed. In turn, both dusty and dispersed iron-clay coatings in lamellae were observed in the parent material. Lamellae noted in the C2 horizon in the L3 profile consisted of various types of clay-iron coatings and bridges linking quartz grains. More compacted, well-formed, layered, yellowish-red clay-iron coatings predominated in the abovementioned horizon (Fig. 45). However, the presence of more dispersed limpid and dusty clay coatings was also observed.

The presence of former soil lamellae in the siderik Bv horizon was noted in the L1 profile (Fig. 7). Fragmented parts of soil lamellae occurred as a form of elongated, discontinuous zones of clay-iron coatings on mineral grains (Fig. 7). In turn, clear fragments of soil lamellae were not observed in the siderik horizon in the L3 profile.

4. Discussion

4.1. Rusty soils (Brunic Arenosols) in southeastern Poland

All the studied rusty soils (Brunic Arenosols) had developed from sandy parent material of glaciofluvial origin. The examined rusty soils (Brunic Arenosols) slightly differ in terms of soil-forming processes, which is likely related to dominant vegetation type (Table 1, Fig. 1). However, the physical and chemical properties of the studied rusty soils (Brunic Arenosols) are similar to those of rusty soils (Brunic Arenosols) found in other areas in Poland (Kowalkowski, 1977; Bednarek, 1991; Janowska, 1994; 2001; Manikowska and Bednarek, 1994; Konecka-Betley and Janowska, 1996; Prusinkiewicz et al., 1998; Jankowski, 2014; Bryk, 2016). One of the features of such soils is the presence of a diagnostic siderik Bv horizon, which occurs in all pedons. Accumulation of organo-mineral complexes as coatings on quartz grains is typical of Bv horizons (Bednarek, 1991). Such coatings were found in Bv horizon in the L1 profile which confirmed the formation of a siderik Bv horizon. Such a feature is typical of rusty soils (Brunic Arenosols), and together with other features, such as well-developed soil structure and loamy fine sand texture (Tables 2 and 3), allows to classify this pedon as a *brown-rusty soil (proto-lamellar)* (Kabała et al., 2019; Polish Soil Classification, 2019) and Dystric Lamellic Brunic Arenosol (Ochric) (IUSS Working Group WRB, 2015). Micromorphological features of the Bv horizon in the L1 profile suggest the presence of enrichment zones of oriented clay accompanying iron oxides (Fig. 4A, B). Moreover, the L1 profile was characterized by the lack of depletion of iron and aluminum compounds in the A horizon in comparison to the siderik Bv horizon (Table 5), which is also a characteristic feature of rusty soils (Brunic Arenosols), and has been described in other studies (Konecka-Betley, 1968; Bednarek, 1991; Martyn and Niemczuk, 2011; Jankowski, 2014).

In turn, the L2 and L3 profiles exhibit weak features of podzolization reflected by the occurrence of weakly developed eluvial E or transition AE horizons, and in the L2 profile the occurrence of an illuvial Bs horizon. However, the micromorphological features of the Bs and Bv horizons found in the studied soils were very similar in terms of the type of most of coatings on mineral grains, but in the Bv horizon the coatings were continuous, nonlaminated, more dusty, featuring a ragged edges (Fig. 4D, E). The coatings were also lighter in color than those noted in the Bs horizon. These coatings are characteristic for Bv horizons (Hirsch et al., 2019). In turn, some of the iron coatings found in the Bs horizon were cracked and consisted of darker organo-mineral material (Fig. 4 C, D), which is a characteristic feature of illuvial Bs horizons (De Coninck et al., 1974; Buurman et al., 2005; Wilson and Righi, 2010). As described by many authors (Kuźnicki and Skłodowski, 1974; Kowalkowski, 1977; Janowska, 1994; Manikowska and Bednarek, 1994; Kowalkowski, 1998; Konecka-Betley, 2001; Kabała, 2005; Jankowski, 2014), podzolization in rusty soils (Brunic Arenosols) is a common phenomenon related to the effects of acidifying vegetation (mostly non-native Scots pine) and favorable, sandy parent material. In both study sites (L2 and L3) Scots pine was one of the dominant species in mixed forests. Additionally, in the L3 profile the eluvial horizon had developed not only in buried soil, but also in overlying material at a depth of 8 cm, which may show a strong impact of acidifying vegetation on the podzolization process in rusty soils.

Profile distribution of non-silicate forms of iron and aluminum also indicates a podzolization. In the L2 profile the content of non-silicate forms of iron and aluminum indicates the eluviation of the most mobile forms of Fe and Al from the eluvial horizon (Table 5). In turn, in the L3 profile, the highest content of Al_o and Fe_o was noted in buried A and AE horizons, which also shows its accumulation in the uppermost horizons of the former soil. Similar observations were conducted by Manikowska and Bednarek (1994) in the A and Bv horizons in fossil rusty soil. Such accumulation may also indicate a "depodzolization effect", as described by Barrett and Schaetzl (1998) and Jankowski (2014) in other podzolized, rusty soils.

One of the features distinguishing the investigated rusty soils (Brunic Arenosols) from those described by other authors is the presence of lamellae, which serves as some evidence of at least a partial displacement of iron, aluminum, and the clay fraction in the profiles of the rusty soils (Brunic Arenosols).

4.2. Soil lamellae in the studied soils

In all the studied rusty soils (Brunic Arenosols), soil lamellae were well-developed in the BC horizon and parent material (Table 3). According to the literature (Bullock and Mackney, 1970; Boubaid et al., 1992; Kilibarda et al., 2008; Muhs, 2017), such well-expressed lamellae found at greater depths indicate petrogenic origin. However, our investigation suggests a pedo-petrogenic origin of lamellae. Field observations and micromorphological studies have confirmed that soil lamellae studied herein are not fully related to stratified layers of sand in parent material and BC horizons and often cross-cut bedding planes. The very wavy and irregular shape (Table 3, Fig. 1) noted in all the studied horizons with lamellae in all the soils additionally confirmed that the origin of the examined lamellae is pedo-petrogenic.

Moreover, some data indicate that deposition of sandy material in fluvial environment played an important role in accumulation of illuvial clay, because features such sorting and packing of mineral grains and pore discontinuities have an impact on redistribution and accumulation of clay particles (Boubaid et al., 1992; Schaetzl, 1992; Rawling, 2000). Micromorphological data (Figs. 5, 6 and 7) indicate the domination of illuviation (treated as pedogenic process) on lamellae origin. One of the most important evidence of the impact of pedogenic processes on lamellae formation in the examined rusty soils (Brunic Arenosols) is the presence of well-developed, illuvial coatings within lamellae in all the studied horizons (Fig. 5). The enrichment of illuvial clay may be the result of the translocation of clay particles in permeable sandy material (Kühn et al., 2010), probably before rusty soil formation (Bond, 1986; Schaetzl, 1992), as shown by micromorphological observations that indicate the presence of oriented clay coatings on mineral grains, even in parent material (Fig. 5).

Soil lamellae were also characterized by the presence of iron or clay-iron coatings (Fig. 5F), which are the result of iron redistribution, as described by Miedema et al. (1987) and by Stoops and Marcelino (2018) in consecutive stages of clay illuviation in lamellae. Thus, the impact of pedogenic processes is important for lamellae origin and transformation (Torrent et al., 1980; Kemp and McIntosh, 1989; Phillips, 2004; Kilibarda et al., 2008; May and Veit, 2009; Jankowski, 2012; Phillips et al., 2015; Lisa et al. 2019).

Moreover, the morphology of all the studied rusty soils (Brunic Arenosols) (Table 2, Fig. 1) and observed lamellae disappearance in siderik Bv horizons, improvement of their expression in transitional BC horizons, as well as presence of lamellae in parent material (Table 3) indicate that lamellae formed prior to siderik Bv horizon.

Our research results indicate that lamellae mostly occur in transitional BC horizons and in the parent material and are usually absent (or occur only fragmentarily) in the siderik Bv horizon. In other studies describing rusty soils (Brunic Arenosols), lamellae were also absent in siderik Bv horizons (Jankowski, 2012; Hirsch et al., 2019; Kruczkowska et al., 2020). Such a result may indicate the impact of processes occurring in the upper part of the solum on lamellae transformation and their degradation. One of the possible causes of lamellae fragmentation may be high biological activity reflected by the presence of many roots and some burrows in the soil (Table 2) as well as channel microporosity (Figs. 3 and 7). High biological activity may lead to the bioturbation of soil material, which may cause an interruption in lamellae. Similar observations were made by Johnson et al. (2008) on sandy soils along Indian Creek in central Iowa, USA, and by Holliday and Rawling (2006) in dune fields on the Southern High Plains, USA. The above authors described a high impact of bioturbation in the active biomantle zone on the periodic disruption of lamellae. The siderik Bv horizon in the L1 profile is an example of such processes. Although in macroscopic observations soil lamellae were not visible in the Bv horizon, micromorphological studies indicated the presence of fragments of former lamellae (papules) with well-developed, oriented clay featuring visible, small-scale lamination (same as in well-developed and preserved lamellae in BC horizons) on coarse grains in the Bv horizon (Fig. 6). Similar observations of lamellae fragments were described by Robinson and Rich (1960) in the upper part of the soil in the form of small, clay-enriched minerals, elongated nodules, which may suggest the previous presence of lamellae that experienced degradation by soil processes. This is also an another evidence of formation of lamellae prior to siderik horizon formation. These lamellae were degraded due to the development of siderik Bv horizon and an intense biological activity strictly related to Bv horizons. The observed channels that break and divide the lamellae as well as the many cracks and pores found within fragmented lamellae material together with organic remnants indicate an impact of bioturbation on lamellae degradation (Fig. 7).

In turn, soil lamellae were absent in siderik Bv horizons in the L2 and L3 profiles and even micromorphological studies did not show the presence of lamellae fragments. Lamellae occur fragmentarily in the transitional BC horizon in the L2 profile, which is also the result of the deep degradational impact of bioturbation (Fig. 7). The relatively large number of roots and organic matter residues noted in field observations, as well as presence of burrows (indicating impact of pedofauna), divided lamellae. Such morphological and micromorphological features indicate mainly the impact of biological activity (Kooistra and Pulleman, 2010).

Soil lamellae in transitional BC horizons and the parent material were found to be well-expressed. Lamellae material beside clay and iron-clay coatings consist of fine quartz grains and amorphous organic matter. Observations of lamellae sequences in the studied rusty soils (Brunic Arenosols) showed the highest thickness and more color intensity in the uppermost lamellae in such sequences, and weakening expression with depth. Better developed clay and clay-iron coatings and the higher concentration of these coatings in the upper part of lamellae sequences may indicate an improvement in lamellae expression due to illuviation and accumulation of the finest particles. Similar results have been obtained by other researchers studying lamellae in sandy material (Berg, 1984; Kemp and McIntosh, 1989; Rawling, 2000; Holliday and Rawling, 2006; Johnson et al., 2008). Such improvement of lamellae expression in uppermost part of transitional BC horizons and in parent material occur most likely after formation of siderik Bv horizons.

5. Conclusions

1. Well-developed lamellae in the transitional BC horizon and parent material occur in rusty soils (Brunic Arenosols) formed from glaciofluvial sands in southeastern Poland. They exhibit a slightly higher content of silt and clay fractions, and total organic carbon and higher content of non-silicate iron and aluminum compounds in comparison to interlamellae.
2. Origin of the studied lamellae is pedo-petrogenic. Lamellae were formed as a result of clay illuviation prior to the development of rusty soil, which was shown by the common occurrence of illuvial clay, iron, and iron-clay coatings on coarse grains.
3. Lamellae occur only fragmentarily in the siderik Bv horizon due to their biogenic degradation in the biomantle zone and this was evidenced by micromorphological analysis. In transitional BC horizons and in parent material expression of soil lamellae were improved due to illuviation and accumulation of clay and iron compounds.

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Geneza, właściwości i transformacja lamelli w glebach rdzawych południowo-wschodniej Polski

Słowa kluczowe

Gleby piaszczyste
Poziom siderik
Geneza gleb
Mikromorfologia
Iluwiacja

Streszczenie

Lamelle są formą iluwialnego nagromadzenia frakcji iłowej powszechnie występującą w piaszczystych utworach czwartorzędowych. Pomimo dużego zainteresowania badaniem gleb, w których lamelle występują wciąż nie jest w pełni rozpoznana geneza, właściwości i transformacja lamelli. Dodatkowo, badania nad lamellami w piaszczystym materiale przeprowadzane były głównie w glebach bielicowych, ochrowych oraz w arenosolach, natomiast brakuje badań prowadzonych pod tym kątem w glebach rdzawych. Głównym celem badań było wyjaśnienie genezy lamelli oraz ich transformacji w glebach rdzawych (Brunic Arenosols) południowo-wschodniej Polski na podstawie ich morfologii i właściwości fizycznych i chemicznych z wykorzystaniem badań mikromorfologicznych. Badania przeprowadzono na obszarze południowo-wschodniej Polski (Brama Krakowska oraz Pogórze Środkowobeskidzkie), na stanowiskach badawczych: Kostrze, Gołęczyna i Połomia. Materiałem macierzystym badanych gleb są piaski fluwioglacjalne. Lamelle glebowe w badanych glebach rdzawych wykazują duże zróżnicowanie pod względem morfologii oraz właściwości fizyko-chemicznych. Charakteryzują się wyższą zawartością drobnych frakcji (<0,05 mm), węgla organicznego oraz pedogenicznych form żelaza i glinu w porównaniu z interlamellami. Szereg cech morfologicznych oraz mikromorfologicznych, takich jak m.in. obecność i wykształcenie ilastych i ilasto-żelazistych otoczek na ziarnach kwarcu jest dowodem na pedo-petrogeniczną genezę tych form. W ujęciu profilowym zwraca uwagę fakt, że w stropowych częściach gleb rdzawych lamelle wykazują duży stopień zdegradowania spowodowany przede wszystkim aktywnością biologiczną. Z kolei w poziomach BC i materiale macierzystym są bardzo dobrze wyrażone i charakteryzują się wzmożoną ekspresją.