soil sequences atlas III

edited by

Marcin Świtoniak
Przemysław Charzyński

SOIL
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ATLAS
III

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M. Świtoniak, P. Charzyński (Editors)
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CONTENTS

FOREWORD

Soil Sequences Atlas III is a continuation of two earlier volumes published in 2014 and 2018. As in the previous studies, the variability of soil cover is presented in the form of soil sequences characteristic of particular types of landscapes. Each of the chapters contains a general description of the environment (lithology, topography, land use, climate), a set of soil data (soil profile photo, description of morphology, laboratory data) and their interpretation in terms of the pedogenesis and systematic position according to the WRB (2015) system. The "catenary approach" (expressed in the form of individual figures) helps to better understand the relationships between individual components of the environment and soils.

Chapters are arranged roughly according to the main soil-forming process in sequences and referring to the World Reference Base for Soil Resources except for Technosols, which as "unnatural" soils are placed at the end of the book. At the beginning of the book, two landscapes dominated by Gleysols and gleyic processes were described – tidal flats and marshes in Germany and the flood plain of the Vistula River in Poland. Next, the mountain areas with Andosols (Slovakia), Lithosols and Podzols (Poland) were presented. The issue of the environment with the dominant podsolization process was continued in the subsequent chapters from Lithuania and Russia. Chapters 8 and 9 are related to Hungarian and Ukrainian soils with a pronounced accumulation of humus in epipedons (Chernozems, Umbrisols, Phaeozems). The book ends with a section on issues related to clay-illuviated (Luvisols), coarse textured (Arenosols) and technogenic (Technosols) soils in Poland, Estonia and Czechia. Sixteen Reference Soil Groups are featured, and represented by 61 soil profiles in total. One of the objectives of the Soil Sequences Atlas is to explain the relationships (predictable to some extent) between the landscape and soil cover. The collected data are intended to be a useful educational tool in the teaching of soil science, supporting the understanding of the causes of soil cover variability, and also as a WRB classification guideline. They are intended to be useful not only to students but also practitioners in agriculture, forestry, environmental protection and landscape planning.

The Atlas was developed as part of the EU Erasmus+ FACES project (Freely Accessible Central European Soil).

Marcin Świtoniak

Przemysław Charzyński

LIST OF ACRONYMS

Al_o – aluminium extracted by an acid ammonium oxalate solution
Al_t – iron extracted by solution of $HClO_4$–HF
BS – base saturation
CEC – cation exchange capacity
CEC_{clay} – CEC of the clay
$EC_{1:2}$ – electrical conductivity of a 1:2 soil-water extract
$EC_{1:2.5}$ – electrical conductivity of a 1:2.5 soil-water extract
EC_e – electrical conductivity of the soil saturation extract
Eh – redox potential related to the standard hydrogen electrode
ESP – exchangeable sodium percentage
FAO – Food and Agriculture Organization of the United Nations
Fe_d – iron extracted by a dithionite-citrate-bicarbonate solution
Fe_o – iron extracted by an acid ammonium oxalate solution
Fe_t – iron extracted by solution of $HClO_4$–HF
HA – potential (hydrolytic) acidity ($pH_{8.2}$) by the Kappen method
IUSS – International Union of Soil Science
N_t – total nitrogen
OC – organic carbon
pH_a – pH measurement referred to the actual soil moisture
pH_e – pH of saturation paste
pH_{ox} – pH measurement after incubation of soil samples under laboratory conditions within two months
pH_{pox} – pH measurement after oxidation with 30% H2O2
rH – the index used to assess redox conditions in water and soils calculated from pHa and Eh values (negative logarithm of the hydrogen partial pressure)
SAR – sodium adsorption ratio
SP – moisture content at saturation (saturation percentage)
S_t – total sulphur
TEB – total exchangeable bases

METHODS

The soils were classified according to WRB 2015[1]. The soil morphology descriptions and symbols of soil horizons are given after Guidelines for Soil Description[2]. The samples were taken from selected soil horizons and after preparation (drying, separation of root and sand fraction >2 mm by sieving) it was analyzed in the laboratory. Texture was determined by (i) combining the Bouyoucos[3] hydrometer and sieve method or (ii) by pipette and sieve method. Organic carbon (OC) content was determined by the wet dichromate oxidation method, and total nitrogen (Nt) content by the Kjeldahl method. The reaction was measured in H_2O and 1 M KCl in 1:2.5 suspension for mineral samples, and 1:10 suspension for organic samples. Calcium carbonate ($CaCO_3$) content was determined by Scheibler volumetric method. Potential (hydrolythic) acidity (HA) was determined by Kappen method and exchangeable cation (bases) content was estimated by leaching with 1 M ammonium acetate with a buffer solution pH 8.2. Pedogenic forms of iron and aluminum were extracted: Fe_t and Fe_d by $HClO_4$–HF, Fe_d by sodium dithionite–citrate–bicarbonate[4] and Fe_o and Al_o by ammonium oxalate buffer solution[5]. Other soil analyses were performed according to the standard methods[6]. Color has been described according to Munsell[7]. It was recorded (i) in the moisture condition (single value) or (ii) in the dry and moisture condition (double values).

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[1] IUSS Working Group WRB, 2015. World Reference Base for soil resources 2014, update 2015 International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Report No. 106. FAO, Rome.

[2] FAO, 2006. Guidelines for Soil Description, Fourth edition. FAO, Rome.

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[5] Mckeague, J.A., Day, J.H., 1966. Ammonium oxalate and DCB extraction of Fe and Al. Canada Journal of Soil Science 46, 13–22.

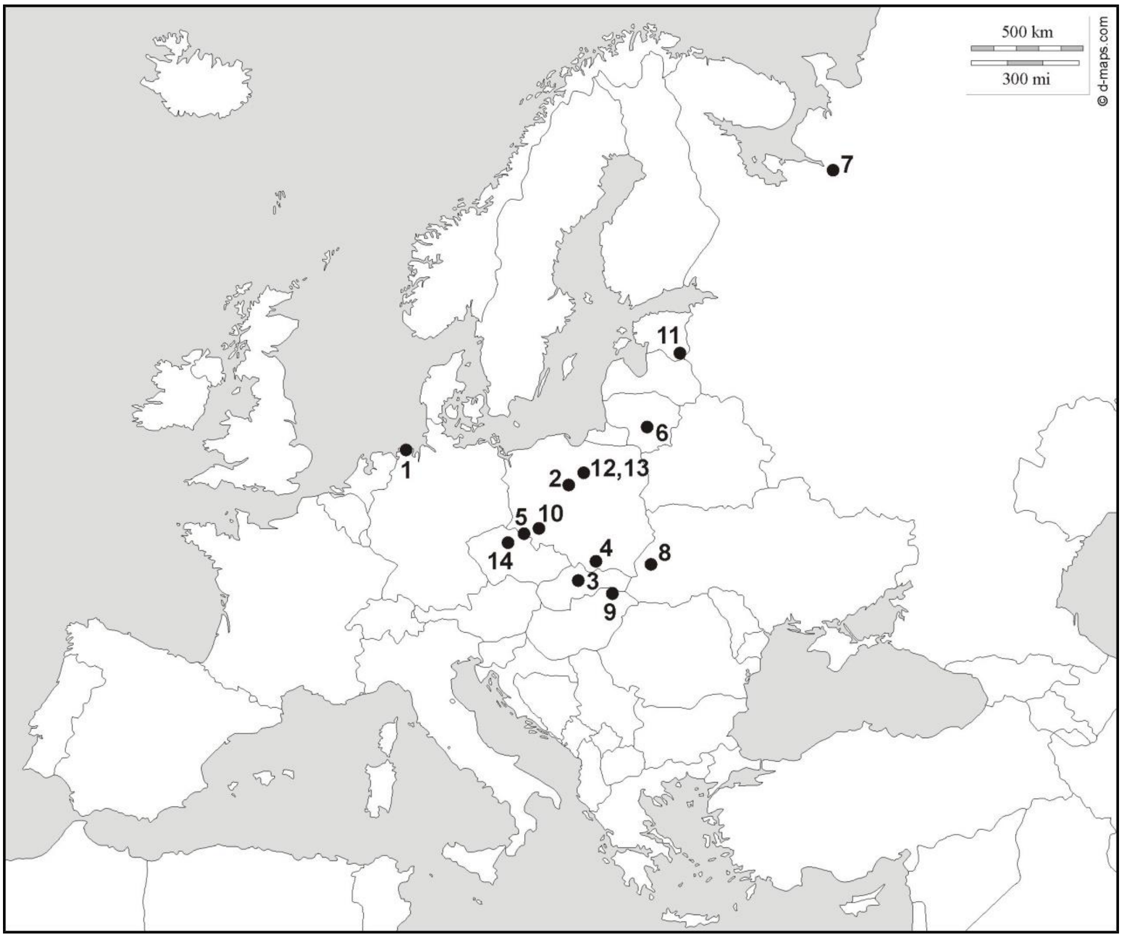
[6] Van Reeuwijk, L.P. 2002. Procedures for soil analysis. 6th Edition. Technical Papers 9. Wageningen, Netherlands, ISRIC – World Soil Information.

[7] Munsell Soil Colour Charts, 2009. Grand Rapids, Michigan USA.

SOIL REFERENCE GROUPS INDEX

	SOIL REFERENCE GROUP	COUNTRY	PAGE
1	ALISOLS	POLAND	156
2	ANDOSOLS	SLOVAKIA	42, 44
3	ARENOSOLS	ESTONIA	164
		LITHUANIA	98
		POLAND	176, 178, 188, 190, 192
		RUSSIA	116
4	CAMBISOLS	HUNGARY	138
		POLAND	56, 64, 84, 150
		SLOVAKIA	46, 48
5	CHERNOZEMS	UKRAINE	130
6	FLUVISOLS	POLAND	32
7	GLEYSOLS	GERMANY	12, 14, 16
		POLAND	28, 30, 62, 180
8	HISTOSOLS	ESTONIA	168
		LITHUANIA	104
		POLAND	182
9	LEPTOSOLS	POLAND	58, 60, 68, 76, 77
10	LUVISOLS	ESTONIA	166
		POLAND	86, 88, 152, 158
		UKRAINE	128
11	PHAEOZEMS	CZECHIA	208
		POLAND	26, 194, 196
		UKRAINE	122, 124, 126
12	PLANOSOLS	POLAND	66
13	PODZOLS	LITHUANIA	100, 102
		POLAND	78, 80, 82
		RUSSIA	112, 114
14	RETISOLS	POLAND	154
15	TECHNOSOLS	CZECHIA	204, 206
16	UMBRISOLS	HUNGARY	140, 142

STUDY AREAS



NUMBER OF CHAPTER - REGION AND COUNTRY:

1 – Tidal flat and marshes of Barrier islands, Spiekeroog, Germany
2 – Flooded zone of the lower Vistula River valley, Poland
3 – Kremnica Mountains, Slovakia
4 – Magura Nappe rocks, Luboń Wielki Mountain, Poland
5 – Karkonosze Mountains, Poland
6 – Sandy glaciolacustrine plain, Lithuania
7 – Karst sinkhole, East European Plain, Russia
8 – Sokal Hills, Volhynian Upland, Ukraine
9 – Tokaj Mountains, Sinta Hill, Hungary
10 – Mt. Ślęża, Poland
11 – Haanja Upland, Estonia
12 – Tunnel valley, Brodnica Lake District, Poland
13 – Pleistocene terraces, Drwęca Valley, Poland
14 – Dumpside of Bílina lignite open cast mine, Czechia

Geo-Pedogenesis of marine sediments at the North Sea Barrier Island Spiekeroog, NW-Germany

Thomas Pollmann, Birte Junge, Luise Giani

Fig. 1. Location

Globally, 400,000 km coastline (Gierloff-Emden, 1980) forms the transition zone between oceans and continents. Shallow transition zones enable the deposition of marine sediments and thereby the development of wide tidal flats and tidal marshes, and mangrove swamps in the tropics. The main driver of sediment deposition is the post-glacial sea level rise (Allen, 2000). Other requirements facilitating sedimentation are sufficient sediment supply and geomorphic stable areas (Long and Mason, 1983). Furthermore, sedimentation is supported by a large tidal range. Soil formation and thereby transformation of sediments in the transition zone starts in the pioneer zone of the tidal flat by colonization of higher plants. This zone is affected by daily, periodical floodings and holds soils with an EC_e of 36-38 dS m^{-1}. Soil formation proceeds further with increasing surface elevation in the adjacent salt marsh - comprised of a lower zone, influenced by periodical spring tides, and a higher zone inundated during episodical storm tides only - with soils having an EC_e of 17-21 and 12-15 dS m^{-1}, respectively (Giani et al., 1993). Floodings may interrupt and set back pedogenesis initiating recurrent geogenesis. This alternation of geogenic and pedogenic processes is defined as geo-pedogenesis (Brümmer, 1968).

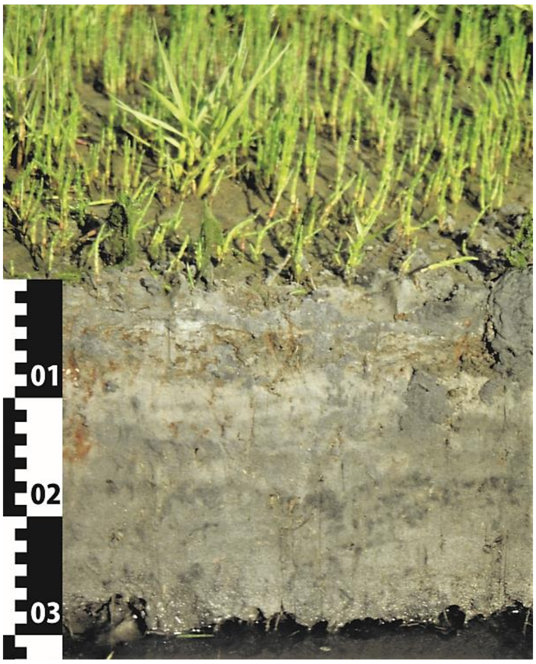
Lithology and topography

Different sediment sources, geomorphology and hydrodynamics of coastal plains result in the deposition of sediments differing in sand, silt, clay, carbonate and organic matter contents at different surface elevations (Dellwig, 1999; Gerrard, 1981; Rabenhorst and Needelman, 2016). Varying sedimentation conditions may cause characteristic stratification in the deposits. Carbonate, organic matter, sulfur dynamics and sedimentation rates are crucial pedogenetic factors, determining different pathways of soil formation (Witte and Giani, 2017). In the North, the nearly flat inundation-influenced transition zone of Spiekeroog (Fig. 1) is adjoined by a dune complex, that holds soil chronosequences (Pollmann et al., 2018). North of this transition zone lies a beach plain, which borders the open sea. Southwards, the transition zone tidal sediments and soils extend to the mainland.

Land use

Some areas in the transition zone were cut off from the sea by embankments used for land cultivation and flood protection purposes. However, the transition zone soils are not used for land cultivation. Theses soils are affected by saline sea water and bear halophytic plant species. Their distribution is subdivided into three zones in accordance to the degree of soil development and surface elevation (Giani et al., 1993). Saltwort (*Salicornia maritima*) and cordgrass (*Spartina townsendii*) are characteristic species in the lowest pioneer zone influenced by daily tides.

Profile 1 – Eutric Orthofluvic Tidalic **Gleysol** (Arenic, Ochric, Hypersalic)
Localization: Tidal flat dominantly covered with saltwort (*Salicornia maritima*), 1.3 m a.s.l.,
N 53°45’40.6’’ **E** 7°43’14.6’’



Morphology:

Cl – 0–15 cm, sand, dark olive gray (5Y 3/2), with yellowish red (5YR 5/8) mottles, moist, single grain structure, few fine roots, gradual and smooth boundary;

Cr – 15–(30) cm, sand, dark gray (5Y 4/1), wet, single grain structure, few fine roots.

Table 1. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm							Textural class
		> 2.0	2.0-0.63	0.63-0.2	0.2-0.125	0.125-0.063	0.063-0.002	<0.002	
Cl	0–15	1.4	44.2	47.7	5.3	0.0	0.0	0.0	S
Cr	15-(30)	0.8	51.7	40.8	4.6	0.0	0.0	0.0	S

Table 2. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH KCl	$CaCO_3$ [g·kg^{-1}]	EC_e [dS·m^{-1}]
Cl	0–15	2.0	0.3	6.7	6.8	5 - 20	36.1
Cr	15-(30)	-	-	-	6.0	0 - 5	36.7

Table 3. Sorption properties

Horizon	Depth [cm]	Na^+/Ca^{2+}	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	CEC	BS [%]
			[cmol(+)·kg^{-1}]						
Cl	0–15	8.2	8.7	13.1	2.5	71.3	95.6	1.8	100
Cr	15-(30)	8.6	7.5	11.7	2.3	64.4	85.9	1.7	100

Profile 2 – Calcaric **Gleysol** (Clayic, Humic, Salic)

Localization: Salt marsh typically covered with grasses, mash-rosemary (*Limonium vulgare*) and wormseed (*Artemisia maritima*), 2.1 m a.s.l., **N** 53°45’51.8’’ **E** 7°43’1.2’’

Morphology:

Ah – 0–18 cm, humus horizon, clay, grayish brown (10YR 5/2), moist, angular blocky structure, many fine roots, clear and smooth boundary;

Cl1 – 18–33 cm, clay, brown (7.5YR 5/4), with yellowish red (5YR 5/8) mottles, moist, angular blocky, fine roots, gradual and smooth boundary;

Cl2 – 33–43 cm, heavy clay, light brownish gray (10YR 6/2), with yellowish red (5YR 5/8) mottles, moist, angular blocky structure, few fine roots, gradual and smooth boundary;

Cl3 – 43–63 cm, clay, dark gray (10YR 4/1), with yellowish red (5YR 5/8) mottles, moist, massive coherent, very few fine roots;

Cr – 63–(100) cm, clay, dark gray (2.5Y 4/1), wet, massive coherent, no roots.

Table 4. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm							Textural class
		> 2.0	2.0-0.63	0.63-0.2	0.2-0.063	0.063-0.02	0.02 - 0.002	<0.002	
Ah	0–18	0.0	0.0	0.1	9.7	20.1	13.4	56.7	C
Cl1	18–33	0.0	0.0	0.4	15.9	19.2	9.8	54.7	C
Cl2	33–43	0.0	0.0	0.1	7.9	18.8	12.7	60.5	HC
Cl3	43–63	0.0	0.0	0.1	9.9	18.7	13.4	57.9	C
Cr	63–(100)	0.0	0.0	2.0	15.3	21.7	12.2	48.8	C

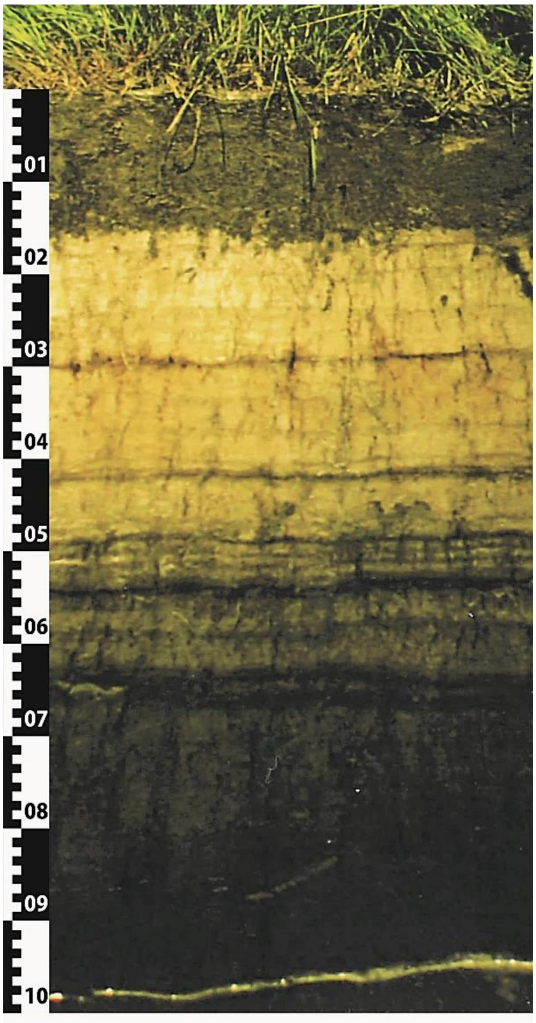
Table 5. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH KCl	$CaCO_3$ [g·kg^{-1}]	EC_e [dS·m^{-1}]
Ah	0–18	42	4.5	9.3	7.7	88	-
Cl1	18–33	39	3.5	11.1	7.6	62	-
Cl2	33–43	45	4.1	11.0	7.6	70	-
Cl3	43–63	40	3.5	11.4	7.5	77	-
Cr	63–(100)	27	2.7	10.0	7.6	97	13.4

Table 6. Sorption properties

Horizon	Depth [cm]	Na^+/Ca^{2+}	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	CEC	BS [%]
			[cmol(+)·kg^{-1}]						
Ah	0–18	5.6	10.2	12.2	1.7	57.2	81.3	81.3	100
Cl1	18–33	3.2	12.5	12.1	1.7	40.3	66.6	66.6	100
Cl2	33–43	4.1	13.6	15.4	2.7	55.9	87.6	87.6	100
Cl3	43–63	4.8	13.1	13.2	2.7	62.3	91.3	91.3	100
Cr	63–(100)	3.8	14.9	14.1	2.4	57.0	88.4	88.4	100

Profile 3 – Eutric Orthofluvic **Gleysol** (Arenic, Drainic, Humic)
Localization: Embankment (since 1882/83) cultivated with grassland, 2.4 m a.s.l.,
N 53°46'9.1'' **E** 7°42'0.3''



Morphology:

Ap – 0–17 cm, sand, very dark gray (10YR 3/1), slightly moist, granular structure, many fine roots, abrupt and smooth boundary;

Cl – 17–52 cm, sand, yellowish brown (10YR 5/4) with yellowish red (5YR 5/8) mottles, moist, single grain structure, few fine roots, clear and smooth boundary;

Cr1 – 52–65 cm, sand, grayish brown (5Y 5/2) moist, single grain structure, few fine roots, clear and smooth boundary;

Cr2 – 65–(100) cm, sand, gray (5Y 5/1), wet, single grain structure, no roots.

Table 7. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm							Textural class
		> 2.0	2.0-0.63	0.63-0.2	0.2-0.125	0.125-0.063	0.063-0.002	<0,002	
Ap	0-17	0.0	45.4	52.1	2.0	0.0	0.2	0.3	S
Cl	17-52	1.0	42.3	54.7	1.7	0.0	0.0	0.3	S
Cr1	52-65	0.6	40.8	56.6	1.1	0.4	0.1	0.4	S
Cr2	65-100	0.0	44.9	52.4	2.1	0.2	0.1	0.3	S

Table 8. Chemical and physicochemical properties

Horizon	Depth [cm]	OC $[g \cdot kg^{-1}]$	Nt $[g \cdot kg^{-1}]$	C/N	pH KCl	$CaCO_3$ $[g \cdot kg^{-1}]$
Ap	0-17	66.9	6.2	10.8	4.9	0.0
Cl	17-52	-	-	-	4.9	0.0
Cr1	52-65	-	-	-	-	0.0
Cr2	65-100	-	-	-	-	0.0

Table 9. Sorption properties

Horizon	Depth [cm]	Na^+/Ca^{2+}	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	CEC	BS [%]
			$[cmol(+) \cdot kg^{-1}]$						
Ap	0-17	0.4	8.5	2.0	0.4	3.4	14.3	25.6	56
Cl	17-52	0.4	1.3	0.5	0.2	0.5	2.6	4.7	56
Cr1	52-65	-	-	-	-	-	-	-	-
Cr2	65-100	-	-	-	-	-	-	-	-

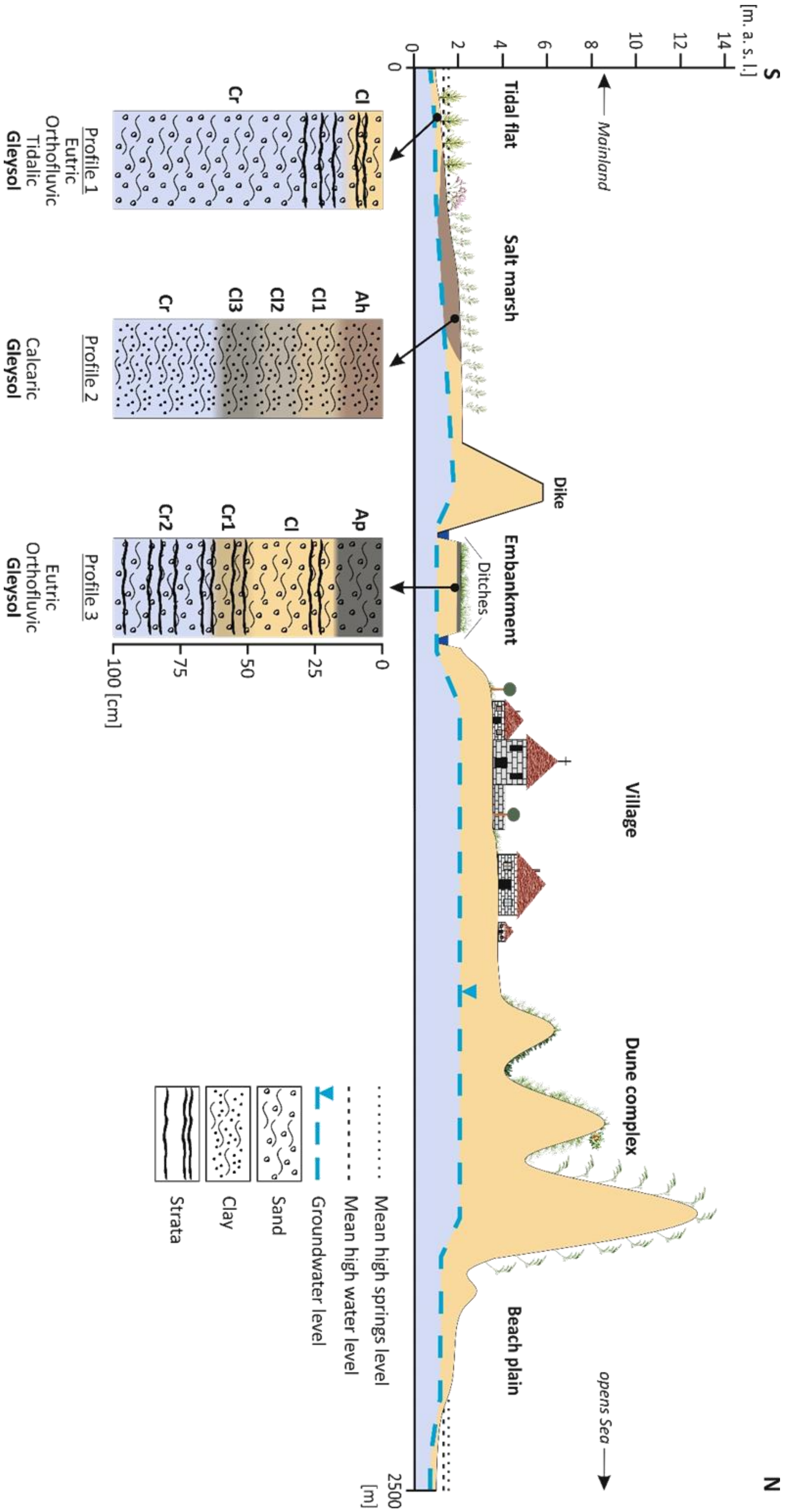


Fig. 2. Cross section of Spiekeroog Island with the studied soil sequence in marine sediments

A higher-lying zone experiencing periodic floodings, less frequently during biweekly high water springs adjoins the pioneer zone and is covered with dominantly saltmarsh grass (*Puccinellia maritima*), marsh-rosemary *(Limonium vulgare)* and sea aster (*Aster tripolium*). The following third and highest elevated zone becomes inundated during storm tides only, and shows a distinct pattern of red fescue (*Festuca rubra*), couch grass (*Elymus repens*) and a clove species (*Armeria maritima*) (Pott, 1995).

Climate

The climate is temperate oceanic (Köppen-Geiger Cfb type) (Geiger, 1961). The average annual air temperature is 8.8 °C (de.climate-data.org/location/890092). The warmest months are July and August (18 °C) and the coldest January and February (2 °C). The average annual precipitation is 795 mm with a maximum typically received in August (80 mm).

Soil genesis and classification

Profile 1 is located in the tidal flat south of the island. Its surface elevation (1.3 m a.s.l.) is below the mean high water level (1.39 m a.s.l. according to Holt et al., 2017). Consequently, the profile becomes flooded according to the rhythm of the daily tides (***Tidalic*** qualifier). Slightly calcareous marine sand supplied by the incoming tide become trapped by stands of halophytic saltwort (*Salicornia maritima*) and accumulates progressively. Slight variability in sediment supply and in sedimentation conditions led to a visible stratification in more than 25 % of the soil volume (*fluvic* material). This was evinced by alternating strata of sands with lighter and darker colours, which mainly differed in OC content. Since the *fluvic* material extended deeper than 5 cm from the mineral soil surface and exceeded a minimal thickness of 25 cm, the ***Orthofluvic*** qualifier was applied. The profile was comprised of a Cl and a Cr horizon, that formed within slightly calcareous sands (***Arenic*** supplementary qualifier; Table 1 and 2) and were affected by saline waters, which resulted in high EC_e values (> 30 dS m^{-1}; Table 2) in both horizons. This, in combination with the required minimal horizon thickness of 15 cm, allowed for their designation as *salic* horizons and the supplementary qualifier ***Hypersalic*** was applicable. The soil comprises sea-derived organic matter (mainly algae), that was simultaneously deposited with the sands during inundations. The low C/N ratio in the soil (Table 2) is typical of soils affected by sea-derived organic matter, that generally has low contents of C-rich compounds, such as cellulose and lignin, and tends to have lower C/N ratios than terrestrial organic matter (Spohn et al., 2013). The OC content within 10 cm from the mineral soil surface was 0.2 % (Table 2), which was sufficient to fulfil the criteria of the supplementary qualifier ***Ochric***. During low tide the groundwater level sinks to about 30 cm below the ground surface, which enables atmospheric oxygen to enter the soil. The aeration causes the oxidation of ferrous iron predominantly in mottles in the Cl horizon. The ferrous iron enters the periodically aerated Cl horizon via capillary rise from the Cr horizon below, where continuous *reductive* conditions allow for its permanent supply. The combination of the Cl horizon with oxidic mottles higher than 5 % of the exposed area and the Cr horizon below, with more than 95 % of the exposed area having a colour considered to be reductimorphic (5Y 4/1), allowed for the designation of *gleyic* properties. Whereas the Cl horizon showed a neutral soil reaction, the Cr horizon below exhibited slightly acidic soil conditions, even though carbonates were detected in situ (Table 2). This finding suggests the presence of sulfidic compounds, e.g. iron sulfide (FeS) and pyrite (FeS_2). Their oxidization during sample preparation prior to pH measurement could have caused the formation of sulfuric acid, which, due to a low carbonate content, could not have been buffered completely and would have caused a drop in pH. Sulfidic compounds are commonly found in marine sediments and soils and may initiate the formation of Acid Sulfate Soils (Giani et al., 2003). The BS was 100 % throughout the profile, by which the criteria of the ***Eutric*** qualifier was fulfilled. The exceeded TEB above CEC was due to co-determination of base cations of the soil solution (Table 3). The high share of primarily Na^+ and to a lesser extend of Ca^{2+} at TEB is typical for soils affected by sea water (Amelung et al., 2018). Although the soil evinced *salic* horizons within 50 cm from the soil surface, the location below the line of mean high water springs precluded its classification as a **Solonchak**. However, it met the criteria for a **Gleysol** and was classified as a ***Eutric Orthofluvic Tidalic*** **Gleysol** (***Arenic, Ochric, Hypersalic***) (IUSS Working Group WRB, 2015).

Profile 2 is located in a salt marsh, adjoining the tidal flats in the north. Salt marshes evolve from tidal flats through continuous sedimentation of marine deposits. Once the sediment surface reaches heights approx. 20 cm below the mean high water level, a dense salt meadow vegetation replaces the lacunar stands of saltwort (*Salicornia maritima;* see Profile 1) and facilitates further deposition of fine marine sediments (Amelung et al., 2018). The profile's surface elevation (2.1 m a.s.l.) is above the mean high water springs level (1.54 m a.s.l. according to WSV, 2016 and BSH, 2017). Thus, the soil is not affected by daily and biweekly tides and becomes inundated during storm tides only. The soil consisted of calcareous clays and heavy clay (***Clayic*** supplementary qualifier), that have accumulated on top of sands (located at a depth below the profile) originally formed the surface of a previously existing tidal flat at this location (Table 4). The clays showed slightly alkaline soil reactions and OC contents were between 27 and 45 g kg^{-1} (Table 5). The OC content had a weighted average to a depth of 50 cm sufficiently high (≥ 1 %) to apply the supplementary qualifier ***Humic***. An increasing proportion of terrestric OC was marked by higher C/N ratios than in Profile 1. The carbonate content, as well, was significantly higher than in the sandy tidal flat (Table 2 and 5). The marked difference in carbonate contents can be attributed to a relatively high content of silt (Table 4), as carbonates are predominately present in this grain-size fraction (Giani et al., 2003). The carbonates with concentrations ≥ 2 % in the entire solum were inherited from the parent material, that was identified as *calcaric* material. Since *calcaric* material occurred between 20 and 100 cm, the ***Calcaric*** qualifier was applied. An 18 cm thick Ah horizon with an angular blocky structure and many fine roots, formed the topsoil. Below, a sequence of three Cl horizons followed. They showed mottles of iron oxides in varying degrees, predominantly in and around coarse pores in more than 5 % of the exposed area. In combination with an underlying Cr horizon, having *reductive* conditions and a soil colour considered to be reductimorphic (2.5Y 4/1) in more than 95 % of the exposed area, *gleyic* properties could be determined. Rooting decreased with depth and increasing soil moisture. While the upper three horizons (Ah, Cl1 and Cl2) had an angular blocky soil structure, caused by shrinking and swelling of the clays in reaction to variations in water content; the lower Cl3 and Cr horizons showed no ped formation (massive coherent), indicating constantly moist to wet conditions in these horizons. The soil was marked by changes in the composition of adsorbed cations, when compared to Profile 1 (Table 3 and 6). The growing influence of precipitation resulted in leaching of Na^+ from the cation exchange surfaces, which was reflected by a decrease in Na^+ concentration and Na^+/Ca^{2+} ratio. Early stage of desalinization was also indicated by a decrease in EC_e in the subsoil when compared to Profile 1 (Table 2 and 5). The EC_e in the Cr horizon fulfilled the criteria for a *salic* horizon and the supplementary qualifier ***Salic*** was applicable. The BS was 100 % in the entire profile, fulfilling the criteria of the ***Eutric*** qualifier (Table 6). However, since this qualifier conveys redundant information (high BS is already indicated by the ***Calcaric*** qualifier), it was excluded from the soil name based on rule-consistency. The soil was classified as a ***Calcaric*** **Gleysol** (***Clayic, Humic, Salic***) (IUSS Working Group WRB, 2015).

Profile 3 is located in an embanked area, cut off from the influence of the sea by the construction of a dike between 1882 and 1883 (Meyer-Deepen and Meijering, 1989). Nowadays, the 11 ha area, adjoining the village of Spiekeroog, is grassland and is occasionally used as horse pasture. In the past it was cropland. For cultivation reasons the groundwater level has been lowered by ditch drainage (***Drainic*** supplementary qualifier). The profile comprised sands throughout (***Arenic*** supplementary qualifier) and exhibited clear horizontal stratification (***Orthofluvic*** qualifier) evinced by alternating sandy strata having light and darker colours (Table 7). Through ploughing, stratification was eradicated in the topsoil. There, a 17 cm thick Ap horizon with a granular structure and a high OC content formed, which had a C/N ratio similar to Profile 2 (Table 8). The high OC content reflects a human-induced enrichment with organic matter, intended to improve soil fertility. The thickness of the Ap horizon was insufficient to apply the supplementary qualifier ***Aric*** (required ploughing depth ≥ 20 cm). Below the Ap, a Cl horizon with mottles of iron oxides in more than 5 % of the exposed area, and two Cr horizons followed. The Cr horizons had soil colours considered to be reductimorphic (5Y 5/2 and 5Y 5/1) in more than 95 % of the exposed area. The hydromorphic soil features enabled the designation of *gleyic* properties. The weighted average of OC to a depth of 50 cm was 2.3 %, by which the supplementary qualifier ***Humic*** applied. The soil showed acidic soil reaction and was free of carbonates (Table 8). Within an embanked area the soil is free from the influence of saline waters. Precipitation water leached cations from the exchange surfaces, which resulted in a significant decrease in concentrations of Na^+ and Mg^{2+} and Na^+/Ca^{2+} ratio compared to Profile 1 and 2. The BS was 56 % within 52 cm from the soil surface (Table 9). The criteria for the supplementary qualifier ***Eutric*** is a BS ≥ 50 % in the major part between 20 and 100 cm from the mineral soil surface. Since it is most likely, that this relevant part exceeded a BS of 50 %, the supplementary qualifier ***Eutric*** was applied. The soil was classified as a ***Eutric Orthofluvic*** **Gleysol (*Arenic, Drainic, Humic*)** (IUSS Working Group WRB, 2015).

Soil sequence

The studied soil sequence illustrates progressive deposition of marine sediments and their formation into soils (Fig. 2). These processes were driven mainly by the frequency of seawater inundations and specific sedimentation environments in different vegetation zones determined by surface elevation. The ***Eutric Orthofluvic Tidalic*** **Gleysol** (***Arenic, Ochric, Hypersalic***) (Profile 1) in the low-lying tidal flat was affected by daily floodings. Turbulent sedimentation conditions allowed only for sedimentation of sands (supplementary qualifier ***Arenic***), which became progressively fixed by saltwort stands. Soil formation was indicated only by gleying due to recurrent inundations and a daily alternating ground water level. Strong marine influence was marked by high soil salinity (supplementary qualifier ***Hypersalic***) and mainly sea-derived organic matter of low content (supplementary qualifier **Ochric**). As sedimentation proceeded and surface elevation reached heights close to the mean high water level, the saltwort stands became replaced by dense salt meadows. The dense vegetation cover decreased the velocity of the tide waters, causing calmer sedimentation conditions and enabling the deposition of finer materials, such as silt and clay. A lower groundwater level and the sediment change from slightly calcareous sands to clayic, *calcaric* materials (supplementary qualifier ***Clayic*** and ***Calcaric*** qualifier) strongly dictated the formation of the ***Calcaric*** **Gleysol** (***Clayic, Humic, Salic***) in Profile 2, which became inundated during storm tides only. Here, an increasing influence of precipitation water caused a cation composition at the exchange surfaces differing from Profile 1, and provided the conditions for desalinization to begin as well as leaching and exchanging of base cations. Swelling and shrinking of the clays in reaction to varying soil water contents caused ped formation. Higher plant density and productivity in the salt meadows resulted in higher OC contents (supplementary qualifier ***Humic***) than in the tidal flat (Profile 1). The ***Eutric Orthofluvic*** **Gleysol** (***Arenic, Drainic, Humic***) in the embanked grassland (Profile 3) was highly affected by human impacts. It became disconnected from the sea in 1882/83 and the groundwater level was artificially lowered via ditch drainage (supplementary qualifier ***Drainic*****)**. These hydrological changes facilitated desalinization, exchanging of base cations and changes in cation composition at the exchange surfaces, which resulted in the soil having the lowest BS, Na^+ concentration and Na^+/Ca^{2+} ratio of the studied soil sequence. Soil cultivation caused enrichment of organic matter in the ploughed horizon resulting in a high OC content (supplementary qualifier ***Humic***).

In general, the studied soil sequence demonstrates the dominating effect of seawater inundation frequency controlling vegetation zoning, sedimentation conditions, grain-size and carbonate content of deposits and soil salinity. Surface elevation determining inundation frequency, was also shown to control groundwater level and associated gleying in the soils. Human impact via embankment, drainage and land cultivation enhanced desalinization, leaching and exchanging of cations and humus enrichment in the topsoil.

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Soil maturity sequence within a flooded zone of the lower Vistula River valley (Toruń Basin, Poland)

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Fig. 1. Location

The Vistula River and its floodplain is the axis of the Toruń Basin (Fig. 1). The floodplain is the lowest of the system of terraces formed in the Late Glacial and Holocene periods (Galon, 1961, 1968; Niewiarowski, 1987; Tomczak, 1982, 1987). The accumulation of mineral deposits of fluviatile origin began about 1.8–1.9 ka BP (Niewiarowski and Weckwerth, 2006; Tomczak, 1982, 1987). It was influenced by changes in environmental conditions, such as climatic variations and deforestation of the catchment, as well as frequency and magnitude of floods associated with these factors (Starkel, 1994, 2000). As a result, three litho-(morphogenic) levels of the floodplain were formed (Babiński, 1984; Kordowski, 2001; Niewiarowski, 1987). The youngest of them (flooded zone) is highly influenced by human activity (river regulation) beginning in the middle of the 19th century. Hence it is called the "anthropogenic level" (Babiński, 1984). It was formed due to hydrotechnical works in the river channel in order to improve navigation and reduce ice-jams (Grześ, 1986; Wojtkiewicz, 1926). The regulation caused the lowering of the river bed bottom and resulted in a lowering of the ground water table. The river bed bottom was lowered by approximately 1.0 m between the mid-19th century and 1945 (Makowski and Tomczak, 2002) or even as much as 1.3–1.5 m (Babiński, 2005). A change in hydrological and sedimentological conditions in the flooded zone also occurred after the building of the Włocławek Reservoir and dam in 1968–70. This affected the management of the newly established level of the floodplain. At the end of the 1980s, an increasing trend for land reclamation (deforestation, ploughing of grasslands) appeared (Michalski, 2013, 2014).

Lithology and topography

The presented soils were located within a flooded zone (embanked area) of the right-bank lower Vistula floodplain (Toruń Basin). The floodplain has a relatively flat surface with positive and negative landforms of riverine origin (former islands, sandy bars and inter-bar channels) incorporated into the land as a result of river channel regulation works (mid-19th century to present). The flooded zone can be divided into two morpho-lithogenic levels: i) pre-regulation (before the mid-19th century) and ii) post-regulation (after the mid-19th century). The natural border between them is a chain of former inter-bar channels, which are elongate and more-or-less parallel to the present-day river channel. The differences in terrain altitudes between the most highly elevated positive forms of the levels are small (reaching about 0.1–0.5 m). The denivelations within each of both levels are relatively high and range up to 1.5-2.0 m. They are associated with former inter-bar channels (connected or not with modern-day river channel). The studied soils of the lower Vistula floodplain are mainly developed from fluviatile sands and silty loams (Kordowski, 2001, 2003; Michalski, 2013).

Profile 1 – Cambic Protostagnic **Phaeozem** (Siltic, Aric)

Localization: the lower Vistula River floodplain, flooded area, arable land, 33.2 m a.s.l.,
N 53°05'16'', **E** 18°17'48''

Morphology:

Apg – 0–30 cm, *mollic* horizon with *stagnic properties*, silt loam, very dark grayish brown (2.5Y 5/2; 2.5Y 3/2), moist, moderate granular structure, highly gleyed (10G 6/1; 10G 4/1) burrows infilled with moderately decomposed organic material, fine and few roots, abrupt and wavy boundary;

Bwg – 30–58 cm, *cambic* horizon with *stagnic properties*, loam, dark grayish brown (2.5Y 5/3; 2.5Y 4/2), slightly moist, moderate subangular structure, open and infilled root/ earthworm channels, very fine and very few roots, clear and wavy boundary;

Cg1 – 58–77/85 cm, parent material with *stagnic properties*, silt loam, olive brown (2.5Y 6/3; 2.5Y 4/3), slightly moist, structure, common medium oximorphic mottles, open and infilled root/ earthworm channels, very fine and very few roots, abrupt/clear and wavy boundary;

Cg2 – 77/85–112 cm, parent material with *stagnic properties*, silt loam, olive brown (2.5Y 6/3; 2.5Y 4/3), slightly moist, moderate subangular structure, open and infilled root/ earthworm channels, many medium oximorphic mottles, gradual and smooth boundary;

Cg3 – 112–(146) cm, parent material with *stagnic properties*, loam, olive brown (2.5Y 6/3; 2.5Y 4/3), slightly moist, moderate subangular structure, many medium oximorphic mottles, open and infilled root/ earthworm channels;

Groundwater table had not been observed to a depth of 250 cm.

Table 1. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
Apg	0–30	0	0	1	4	13	14	24	14	12	18	SiL
Bwg	30–58	0	0	1	8	23	20	24	9	6	9	L
Cg1	58–77/85	0	0	0	2	8	25	37	13	5	10	SiL
Cg2	77/85–112	0	0	0	1	6	25	43	10	3	12	SiL
Cg3	112–(146)	0	0	0	1	14	27	33	8	5	12	L

Table 2. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
Apg	0–30	17.7	1.82	10	7.8	6.9	6
Bwg	30–58	5.1	0.59	9	8.0	7.5	11
Cg1	58–77/85	4.5	0.46	10	8.2	7.6	14
Cg2	77/85–112	4.2	0.50	8	8.2	7.6	9
Cg3	112–(146)	4.2	0.47	9	8.3	7.5	9

Table 3. Sorption properties

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	HA	CEC	BS [%]
		[cmol(+)·kg^{-1}]							
Apg	0–30	16.9	2.55	0.219	0.082	19.7	0.091	19.8	99
Bwg	30–58	14.2	1.30	0.089	0.013	15.6	0.069	15.7	99
Cg1	58–77/85	20.4	1.10	0.091	0.039	21.6	0.421	22.0	98
Cg2	77/85–112	16.2	1.12	0.073	0.062	17.4	0.361	17.8	98
Cg3	112–(146)	12.8	1.17	0.058	0.084	14.1	0.542	14.6	97

Profile 2 – Calcaric Mollic **Gleysol** (Siltic, Humic)

Localization: the lower Vistula River floodplain, flooded area, abandoned river channel, remnants of riparian forest and willow shrubs, 31.5 m a.s.l., **N** 53°05’07”, **E** 18°17’58”

Morphology:

Ahl – 0–20 cm, *mollic* horizon with *gleyic properties*, silt loam, olive brown (2.5Y 5/1; 2.5Y 3/1), dry, moderate granular structure, common ferruginous soft concretions, very fine or fine many roots, clear and smooth boundary;

ACl – 20–36 cm, transitional horizon, silty clay loam, dark grayish brown (2.5Y 6/2; 2.5Y 4/2), slightly moist, moderate granular structure, common ferruginous soft concretions, fine common roots, clear and wavy boundary;

Cl1 – 36–78 cm, parent material with *gleyic properties*, silt loam, dark grayish brown (2.5Y 6/2; 2.5Y 4/2), slightly moist, moderate angular structure, many ferruginous soft concretions, very fine few and very few roots, clear and smooth boundary;

Cl2 – 78–98 cm, parent material with *gleyic properties*, silt loam, greenish gray (10G 6/1; 5BG 5/1), moist, moderate angular structure, many ferruginous soft concretions, very fine and very few roots, clear and wavy boundary;

Cr1 – 98–113/125 cm, parent material with *gleyic properties*, silt loam, bluish gray (10G 6/1; 5BG 5/1), moist, strong angular structure, abundant ferruginous soft concretions, single shell remnants, very fine and very few roots, clear and irregular boundary;

Cr2 – 113/125–(140) cm, parent material with *gleyic properties*, silt loam, dark bluish gray (10G 5/1; 5BG 4/1), wet, massive structure, medium highly decomposed and very few roots;

Groundwater table had been observed at a depth of 140 cm.

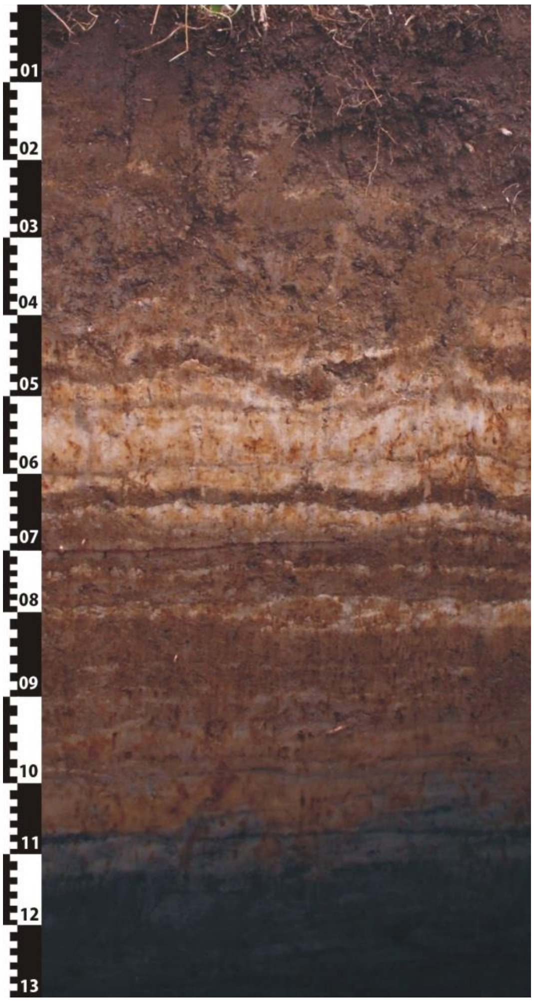
Table 4. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
Ahl	0–20	0	0	8	8	7	7	16	21	16	17	SiL
ACl	20–36	0	0	1	2	4	8	21	22	13	29	SiCL
Cl1	36–78	0	0	0	1	2	7	22	26	17	25	SiL
Cl2	78–98	0	0	0	1	2	6	24	29	14	24	SiL
Cr1	98–113/125	0	0	0	1	1	7	22	27	16	26	SiL
Cr2	113/125–(140)	0	0	0	0	1	7	34	32	7	19	SiL

Table 5. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		CaCO$_3$ [g·kg^{-1}]
					H$_2$O	KCl	
Ahl	0–20	71.6	6.33	11	6.6	5.9	6
ACl	20–36	14.5	1.51	10	8.0	7.1	22
Cl1	36–78	10.6	1.12	9	8.1	7.1	23
Cl2	78–98	9.5	1.01	9	8.2	7.2	26
Cr1	98–113/125	10.3	1.11	9	8.1	7.3	30
Cr2	113/125–(140)	10.7	1.03	10	7.9	7.3	23

Profile 3 – Eutric Fluvic Mollic **Gleysol** (Geoabruptic, Humic, Siltic)
Localization: the lower Vistula River floodplain, flooded area, meadow, 32.8 m a.s.l.
N 53°05’06”, **E** 18°18’05”



Morphology:

Ahl – 0–23 cm, *mollic* horizon with *gleyic properties*, silt loam, very dark gray (2.5Y 5/1; 2.5Y 3/1), dry, moderate granular structure, few ferruginous soft concretions, very fine or fine many roots, gradual and wavy boundary;

Al – 23–46/49 cm, *mollic* horizon with *gleyic properties*, silty clay loam, dark grayish brown (2.5Y 7/4; 2.5Y 4/2), dry, moderate granular structure, common ferruginous soft concretions, very fine many roots, abrupt and wavy boundary;

Cl1 – 46/49–63 cm, parent material with *gleyic properties*, fine sandy loam, dark grayish brown (2.5Y 6/3; 2.5Y 4/2), slightly moist, weak subangular structure, many ferruginous soft concretions, very fine common roots, abrupt and wavy boundary;

Cl2 Cl3 Cl4 – 63–107 cm, parent material with *gleyic properties*, distinguished 3 layers (I) 63-78 cm, (II) 80-93 cm, (III) 93-107 cm, silt loam, (I) dark gray (2.5Y 5/3; 2.5Y 4/1), (II) dark grayish brown (2.5Y 5/4; 2.5Y 4/2), (III) dark gray (2.5Y 6/2; 2.5Y 4/1), (I) slightly moist (II and III) moist, moderate subangular structure, many ferruginous soft concretions, very fine very few roots, (I) abrupt and smooth, (II) gradual and wavy, (III) clear and wavy boundary;

Cr1 Cr2 – 107–(145) cm, parent material with *gleyic properties*, distinguished 2 layers (I) Cr1 107-114 cm, (II) Cr2 114-(145) cm, silt loam, (I) dark greenish gray (10G 6/1; 10G 4/1), (II) greenish black (10G 6/1; 10G 2/1), (I) wet, (II) very wet, massive structure, (I) common ferruginous soft concretions, (II) very fine very few roots, (I) gradual and wavy boundary;

Groundwater table had been observed at a depth of 145 cm.

Table 6. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
Ahl	0–23	0	0	2	5	5	9	21	22	14	22	SiL
Al	23–46/49	0	0	0	1	2	9	23	23	15	27	SiCL
Cl1	46/49–63	0	0	0	5	37	27	21	2	3	5	FSL
Cl2	6378	0	0	1	1	7	12	25	19	13	22	SiL
Cl3	80–93	0	0	1	1	1	7	34	27	10	19	SiL
Cl4	93–107	0	0	1	1	9	28	36	11	5	9	SiL
Cr1	107–114	0	0	0	0	6	31	38	13	4	8	SiL
Cr2	114–(145)	0	0	0	1	15	17	27	17	10	13	SiL

Table 7. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		CaCO$_3$ [g·kg^{-1}]
					H$_2$O	KCl	
Ahl	0–23	64.5	5.49	12	7.4	6.8	9
Al	23–46/49	12.8	1.25	10	8.1	7.1	16
Cl1	46/49–63	2.1	0.21	10	8.3	7.3	9
Cl2	6378	8.9	0.86	10	8.1	7.0	10
Cl3	80–93	8.4	0.84	10	8.2	7.3	14
Cl4	93–107	5.5	0.52	11	8.1	7.2	10
Cr1	107–114	4.9	0.45	11	7.9	7.4	13
Cr2	114–(145)	8.9	0.78	11	7.6	7.2	18

Profile 4 – Pantoeutric Pantofluvic **Fluvisol** (Arenic, Aric, Geoabruptic, Ochric, Endogleyic)
Localization: the lower Vistula River floodplain, flooded area, arable land, 33.1 m a.s.l.
N 53°05'32", **E** 18°15'15"

Morphology:

ACp – 0–29 cm, humus horizon with disturbed lamination, loamy fine sand, light olive brown (2.5Y 6/3; 2.5Y 5/4), dry, weak granular structure, very fine or fine and few roots, abrupt and smooth boundary;

C1 – 29–34 cm, parent material with disturbed lamination, loamy fine sand, pale yellow (2.5Y 8/2; 2.5Y 7/3), dry, single grain structure, infilled earthworm channels, very fine and very few roots abrupt and smooth boundary;

C2 – 35–60 cm, laminated parent material, fine sand, pale yellow (2.5Y 8/2; 2.5Y 7/3), dry, single grain structure, infilled root and earthworm channels, abrupt and smooth boundary;

C3 – 60–65 cm, laminated parent material, silt loam, dark grayish brown (2.5Y 5/2; 2.5Y 4/2), slightly moist, moderate subangular structure, eartworm channels, abrupt and smooth boundary;

C4
Cl1 – 65–138 cm, laminated parent material with no or weakly expressed *gleyic properties*: distinguished 2 layers (I) C4 65-82 cm, (II) Cl1 82-138 cm, very fine sandy loam, (I) pale yellow (2.5Y 8/2; 2.5Y 5/2), (II) light olive brown (2.5Y 7/3; 2.5Y 5/4), slightly moist, weak subangular structure, infilled root and earthworm channels, infilled burrows, (I) abrupt or (II) clear and wavy boundary;

Cl2 – 138–(150) cm, laminated parent material with *gleyic properties*, silt loam, olive (5Y 6/2; 5Y 5/3), moist, weak subangular structure, abundant soft ferruginous concretions;

Groundwater table had not been observed to a depth of 250 cm.

Table 8. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
ACp	0–29	0	0	0	5	40	35	15	1	1	3	LFS
C1	29–35	0	0	0	0	36	41	16	2	1	4	LFS
C2	35–60	0	0	0	0	66	27	5	0	1	1	FS
C3	60–65	0	0	0	2	9	27	38	9	4	11	SiL
C4	65–82	0	0	0	3	28	35	20	4	1	9	VFSL
Cl1	82–138	0	0	0	1	19	49	22	4	1	4	VFSL
Cl2	138–(150)	0	0	0	0	2	17	60	7	3	11	SiL

Table 9. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		CaCO$_3$ [g·kg^{-1}]
					H$_2$O	KCl	
ACp	0–29	4.2	0.35	12	7.9	7.4	4
C1	29–35	1.9	0.17	11	8.4	7.8	8
C2	35–60	-	-	-	8.6	8.1	6
C3	60–65	5.0	0.46	11	8.1	7.5	14
C4	65–82	1.7	0.15	11	8.5	7.9	8
Cl1	82–138	2.8	0.21	13	8.4	7.7	12
Cl2	138–(150)	3.8	0.36	11	8.4	7.6	16

Table 10. Sorption properties

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	TEB	HA	CEC	BS [%]
		[cmol(+)·kg^{-1}]							
ACp	0–29	6.92	0.718	0.252	0.011	7.90	0.431	8.33	95
C1	29–35	9.63	0.711	0.123	0.019	10.5	0.298	10.8	97
C2	35–60	4.85	0.322	0.068	0.013	5.25	0.517	5.77	91
C3	60–65	21.5	1.428	0.256	0.054	23.2	0.510	23.7	98
C4	65–82	11.0	0.623	0.111	0.032	11.8	0.341	12.1	98
Cl1	82–138	15.6	0.819	0.081	0.053	16.5	0.352	16.8	98
Cl2	138–(150)	25.9	1.118	0.114	0.078	27.2	0.557	27.8	98

Land use

Because of the high fertility of the soils, the vast majority of them has been converted into arable lands or meadows. Only small areas of the studied floodplain are covered by remnants of potential communities: riparian forests (*Salix* spp., *Populus alba)* and willow shrubs (*Salix* spp.). The most common herb layer species are: *Ficaria verna*, *Symphytum officinale*, *Phalaris arundinacea*, *Galium aparine*, *Urtica dioica*, *Rubus* spp. and *Humulus lupulus*. The species composition within the edges of arable lands and artificial meadows reveal a huge influence of human activity (e.g. expansion of *Solidago gigantea* and *Acer negundo*). The main crops in the studied area are: corn (*Zea mays*) and vegetables (carrot, parsley and onion).

Climate

The region is located in the zone of moist and cool temperate climate (IPCC, 2006). According to Köppen−Geiger Climate Classification, the region is located in the warm temperature and fully humid zone with temperate and warm summer (Kottek et al., 2006). The average annual air temperature is about 7°C. The warmest month is July (17.6°C), while the coldest one January (about -4°C). The average annual precipitation is approximately 550 mm. July is the wettest month with average precipitation around 90 mm (Wójcik and Marciniak, 1987a, b, 1993).

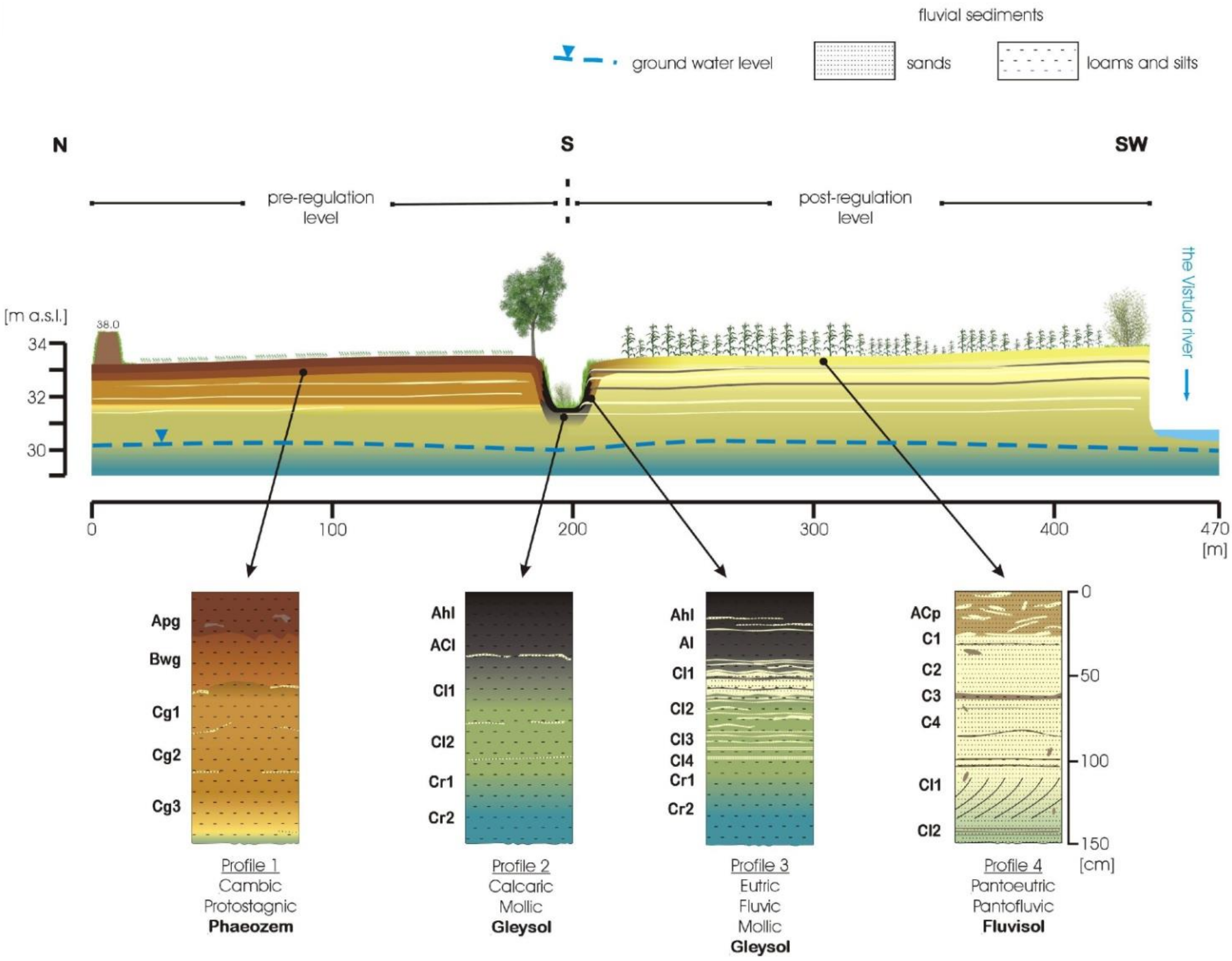


Fig. 2. Sequence of soils within a flooded zone of the lower Vistula river valley

Soil genesis and systematic position

Floodplain soils were formed in a pedo-sedimentary environment, for which alternation of pedological and geological processes is typical. Pedogenesis of alluvium-derived soils is to a significant degree a function of land surface stability. Soil-forming processes evolve to a more or less significant extent depending on sedimentation rates, which vary. Hence, the analysed soils are morphologically very diverse (Fig. 2). They are developed from aggrading parent materials, which can be described simply as transported and transformed materials from eroded soils and river bed. Furthermore, some properties of the recent alluvial soils can be inherited from pedons of sediment source areas (e.g. nutrient contents, sorption and buffer properties, texture).

The studied soils are entirely built from fluviatile deposits that have been transformed by pedogenesis either very weakly (Fig. 2., Profile 4) or moderately (Fig. 2., Profile 1–3). The domination of horizons and layers formed from sands and silt loams was expressed by the ***Arenic*** (Table 8, Profile 4) and ***Siltic*** (Tables 1, 4 and 6, Profiles 1–3) supplementary qualifiers. Alluvial sands and silt loams represent relatively well-permeable materials. In natural and seminatural conditions, well developed granular structures form, promoting the transfer of water and air through the soil profile. Soils in higher topographic positions (within both pre-regulation and post-regulation levels) were transformed into arable lands. As a result of ploughing (to even deeper than 60 cm in fine-grained soils) the primeval lamination is disturbed and newly deposited materials are incorporated into the A horizon (Fig. 2, Profiles 1 and 4). Physical transformation (ploughing to a depth ≥20 cm) of the upper parts of pedons was expressed by the ***Aric*** supplementary qualifier. Furthermore, the permeability of top parts of the soil profiles is reduced as a result of heavy machinery usage (compaction of the humus and *cambic* horizons). These soils are vulnerable to water stagnation.

Two possible sources of soil organic carbon should be considered in alluvium-derived soils: autochthonous (*in situ* biomass production and decomposition) and allochthonous (redeposited organic matter). The analysed soils are characterised by widely differing amounts of organic carbon (OC). The most OC-rich are pedons within the pre-regulation level (Table 2, Profile 1) and adjacent former river channels (Tables 5 and 7, Profiles 2 and 3). The lowest OC amounts are typical of sandy soils within the post-regulation level (Profile 4). Soils of the former inter-bar channels have significant organic carbon (OC) amounts to a depth of approximately 100 cm (Tables 5 and 7, Profiles 2 and 3). This is due to the conditions in local depressions being favourable to both *in situ* biomass production (high fertility and humidity of soils) and allochthonous organic matter accumulation (relatively high frequency of inundation, and deposition of OC-rich, fine-grained alluvia). The ***Humic*** supplementary qualifier was used to emphasise the high amounts of OC (weighted average of OC≥1%) to a depth of 50 cm from the soil surface (Profiles 2 and 3). The vertical distribution of OC is quite different in soils of higher elevated parts of the flooded zone (Profiles 1 and 4). A downward decrease in OC content is typical for soils of the pre-regulation level (Table 2, Profile 1), while pedons of the post-regulation level reveal an irregular decrease in organic carbon with depth (Table 9, Profile 4). Various pedo-sedimentological (characteristics of sediments) and biological conditions (land-use history) during soil formation appear to be crucial factors in explaining the lateral variability of OC stocks.

Soils within the flooded zone are influenced by different types of water regime. They are under influence both of surface water (floods and precipitation) and of the capillary fringe. Various types of surface water movement influence the dynamics of sedimentation processes and hydrological conditions. Soils are under the influence of both sheet flow (Profiles 1–4) and channel flow (Profiles 2 and 3). In the description of the hydrological regime of soils in various topographic positions, the duration of water stagnation should be considered. Pedons in higher topographic positions are inundated less often than those in local depressions. Even in the phase of a flood cessation, soils of former inter-bar channels are influenced by surface water for much longer than those in higher elevated parts of the flooded zone. Characteristics of water flow and stagnation (flow speed and duration of inflow-outflow cycles) are crucial in interpreting the hydromorphic features of floodplain soils. Alternating processes of oxidation and reduction, which are connected with water stagnation (rainfall water, flood water), are recorded as a mantle of oxi- and reductimorphic mottles (*stagnic properties* and *reducing conditions*). The distinction between *stagnic* and *gleyic* properties is difficult to manage in the soils of local depressions (Profiles 2 and 3). A clear vertical distinction (depth function) between *stagnic* and *gleyic properties* seems to be difficult to make without detailed micromorphological studies. Excluding the influence of surface water dynamics it seems that the hydromorphic features of these pedons are mostly the effect of capillary fringe (Fig. 2., Profiles 2 and 3). Soils developed from fine-grained sediments (Profile 1) present in higher topographic positions reveal weakly developed *stagnic properties.* The presence of weakly developed features revealing water stagnation was expressed by the ***Protostagnic*** qualifier. *Stagnic properties* are not present or are very weakly developed (only in fine-grained layers) in soils of the post-regulation level. This is because of their high permeability (Profile 4). In these pedons, the influence of the gleyzation process is weakly expressed morphologically at a depth of >50 cm from the land surface (supplementary qualifier ***Endogleyic***).

A characteristic feature of the presented soils is a stratification that is visible morphologically (to the naked-eye) or "chemically". This feature can be indicated in the classification of a soil using the ***Geoabruptic*** supplementary qualifier, which expresses an *abrupt textural difference* (very sharp increase in clay content). It was applied in soils within the post-regulation level (Table 8, Profile 4) and adjacent, more highly elevated parts of the former river channels (Table 6, Profile 3). Typical for alluvium-derived soils is also the presence of layers rich in organic matter below the A or B horizons, which emphasise stratification. These OC-enriched deposits can be found at a depth of up to 100 cm or even deeper (Dąbkowska-Naskręt, 1990; Laskowski, 1986; Michalski, 2013). These are crucial criteria for distinguishing *fluvic material* in the WRB system (IUSS Working Group WRB, 2014). Not all studied soils meet the criteria.

The highest degree of (morphologically visible) soil material alteration is typical of the highest elevated, relatively flat parts of the pre-regulation level. They are covered by moderately developed pedons (Fig. 2, Profile 1) that are classified as **Phaeozems**. The features typical of young, alluvium-derived soil are not present in these pedons. The stratification is highly disturbed and weakly or not visible up to 150 cm. These soils have an Apg–Bwg–Cg horizon sequence, which reveals the relative stability of the land surface during pedogenesis. Humus horizons are well developed and rich in organic matter. They fulfil all the criteria typical of a *mollic horizon* (e.g. organic carbon content, colour, structure, thickness) (Table 2, Profile 1). The content of organic carbon decreases with depth, confirming favourable conditions for classic, top-down pedogenesis. Hence, this profile does not meet the criterion of *fluvic material.* A disturbance of stratification is present just below the A horizon. The degree of parent material alteration is well expressed in the *cambic horizon.* The reasons for the disturbance are surely bioturbation (visible, open or infilled root and earthworm channels, also with worm casts; *krotovinas*) and agricultural practices (regular deep ploughing). The presence of a *cambic* horizon was emphasised by the ***Cambic*** qualifier. Weakly expressed hydromorphic features caused by water stagnation were indicated by the ***Protostagnic*** qualifier. The studied **Phaeozems** are characterised by a very high base saturation (Table 3, Profile 1). The ***Eutric*** qualifier is not used in this case because a high base saturation is a typical property of **Phaeozems** (IUSS Working Group WRB, 2014).

Moderate alteration is also typical of soils within former inter-bar channels (Profiles 2 and 3). The soils reveal highly expressed *gleyic properties* throughout the whole profiles. This allows them to be classified as **Gleysols** with a typical A(h)l–Cl–Cr horizon sequence. Those of them that occupy bottoms of depressions (Fig. 2, Profile 2) represent "geochemical sinks". Not only organic matter (the presence of well developed *mollic horizons*), but also other nutrients (e.g. calcium carbonates), are accumulated in these pedons (Table 5, Profile 2). The presence of significant amounts of calcium carbonates (>2%) in almost the whole profile (excluding the Ahl horizon) is emphasised by the ***Calcaric*** qualifier. Soils which occupy the slopes of the local depressions represent transitional pedons between pre- and post-regulation levels (Fig. 2, Profile 3). They are still classified as **Gleysols**, but reveal a feature typical of weakly developed alluvial soils – visible stratification. The presence of *fluvic material*, which still shows stratification, was indicated by the ***Fluvic*** qualifier (Fig. 2, Profile 3). Base saturation in the presented **Gleysols** is decidedly higher than 50% (pH-H_2O values >6 indicate high base saturation; IUSS Working Group WRB, 2014), which permits the use of the ***Eutric*** qualifier.

Soils of the post-regulation level are weakly developed and were classified as **Fluvisols**. Their profiles present an ACp–C–Cl sequence with distinct stratification. Primeval sedimentological features are very well-preserved, as was emphasised by the ***Pantofluvic*** qualifier. Disturbance of sedimentary structures (layering) is present only in the upper parts of the soil profiles (the presence of ACp horizons). The vertical variability of texture and chemical properties (e.g. OC content) reflects the dynamics of a pedo-sedimentary environment. The extremely high base saturation (≥90% in the whole profile) meets the requirements for the ***Pantoeutric*** qualifier. It reveals still-active alteration of pedogenesis and sedimentation of fresh alluvia (lithogenesis) on the land surface. Alluvium-derived soils covering the post-regulation level of the floodplain (Profile 4) have weakly developed properties of *reducing conditions* present only in the deeper parts of the profiles, as emphasised by the ***Bathgleyic*** qualifier.

Soil sequence

All described pedons have a somewhat similar lithogenesis. They are formed from alluvial deposits (sands or silt loams). The main differences responsible for the various pathways of the soil-forming processes are associated with the microrelief of the floodplain, plant cover history and the influence of surface water (flood water, precipitation) and ground water. A crucial role is also played by distance from the active river channel and the patterns of sediments input to the land surface. The spatial arrangement of pedons represents the soil maturity sequence (Fig. 2). The typical indicators of alluvial soils' maturity seem to be: (i) presence of a horizonation (development from AC–C–C(l) to A–Bw–C(g) sequence) and the degree of primeval stratification disturbance, (ii) pedogenic structure formation and biological activity and (iii) chemical alteration (e.g. leaching of carbonates, decrease in pH values).

Considering soil maturity stages within the analysed flooded zone, three main factors should be considered: (i) stability or instability of land surface (frequency of fresh alluvia input by floods and their chemical characteristics), (ii) position in the microrelief and (iii) agricultural human activity (plant cover history and agricultural practices). Other factors seem to be dependent variables.

The presented transect (Fig. 2) reveals a simplified pattern in the lateral variability of soil development. This shows the crucial role that distance from the river channel plays as a main factor explaining the spatial variability of soil cover. Put more simply, the greater the distance from the channel, the higher the degree of land surface stability and the lower the frequency of sediments input by floods. This can be confirmed by the similar altitudes of the analysed levels – the pre-regulation level (Fig. 2, Profile 1) and the post-regulation level (Fig. 2, Profile 4). The post-regulation level was formed over a period of approximately 150–170 years, which means that sedimentation rates were much higher within this area than they were on the pre-regulation level (Michalski, 2014). The zone between these levels (former river channels) should be considered a specific accumulation area (Profiles 3 and 4 as "geochemical sinks").

The studied soils can be described as weakly or moderately developed. Weakly developed pedons classified as ***Pantoeutric Pantofluvic*** **Fluvisols** occupy only the post-regulation level of the flooded zone. These are areas of former river bars adjacent to the present-day river channel. These soils developed in conditions of rapid, human-induced sedimentation (regulation of the river channel, the construction of river groynes). In such conditions, periods of land surface stability were relatively short. Processes of sedimentation (and to some degree also of erosion) dominated over pedogenesis. The previous studies carried out within the right-bank floodplain of the lower Vistula river (Michalski, 2014) reveal that post-regulation level is the most "geo-sedimentologically active" area with distinct accumulation of fresh alluvia (e.g. crevasse splays) and erosional processes (e.g. crevasse channels). In such unstable conditions soil-forming processes cannot completely evolve. These soils present the initial phase of parent material alteration. In alluvium-derived soils this stage is characterised by well-preserved stratification and a lack of – or weakly-developed – humus horizons (***Ochric*** qualifier) (A(AC)–C sequence). The pedogenesis can be briefly described as the formation of a humus horizon and the oxidation of gleyed layers. Due to their stratification (e.g. the presence of sandy layers of significant thickness) the presented **Fluvisols** have weakly developed humus horizons with weakly developed soil structure. The studied soils still contain significant amounts of calcium carbonates, probably due to the input of nutrients with freshly deposited alluvia. Previous studies (Michalski, 2014) have revealed that fine-grained flood sediments can contain relatively high amounts of calcium carbonates (4.1–8.9%). In ploughed soils these deposits are incorporated into A horizons, influencing their physical and chemical properties. Fine-grained, OC-rich layers present in these soils reveal that they experienced relatively high biological activity (bioturbations, well-developed pedogenic structure) in the past when they occupied the land surface.

Soils of the inter-level areas (classified as ***Eutric*** [***Calcaric*** or ***Fluvic***] ***Mollic*** **Gleysols**) formed in favourable hydrological conditions. They have *mollic* horizons with well-developed structure (common bioturbations). The soil profiles were deepened due to the lowering of the ground water table after river regulation works. As a result, the layers below the humus horizon have been transformed by pedogenesis to varying extents (pedogenic structure formation, disturbance of stratification). Their chemical, physical and biological properties (high biological activity) emphasise their specific position in the landscape. They still play a role as "geochemical sinks" (accumulation of organic matter and nutrients). They can be considered as moderately developed. Processes of carbonates leaching are not chemically visible, due to the high frequency of flooding and the input of nutrients with fresh deposits. These soils are still strongly influenced by ground water, but they present pedogenic transformation (oxidation processes and formation of pedogenic structure both in the upper and the middle parts of profiles).

The relatively flat surfaces of the pre-regulation level are covered with moderately developed ***Cambic Protostagnic*** **Phaeozems** (Fig. 2, Profile 1). These areas present favourable conditions in which pedogenesis can evolve. As a result, soils with distinct horizonation appear (with the presence of diagnostic *mollic* and *cambic* horizons). They are relatively well-drained and are biologically active. Hence they have a well-developed pedogenic structure. The primeval lamination is not present or is very weakly expressed. These soils still reveal weakly visible features of *gleyic* properties in deeper parts of profiles (a relict of a higher groundwater table in the past), but the present gleyzation is mainly caused by water stagnation (agricultural activity).

All the studied soils are ***Eutric*** and present extremely high base saturation, relatively high calcium carbonates contents and high pH values. This confirms that they are chemically very young, and processes of chemical alteration (concerning the presented data) are weakly expressed. Within analysed flooded zone, lithogenesis still operates, with its variable rate influencing pathways of pedogenesis.

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Volcanic soils of the Kremnické vrchy Mountains, Slovakia

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Fig. 1. Location

Kremnické vrchy Mountains are volcanic mountains located in the central part of Slovakia. They are one of the neovolcanic mountains of the Slovak Central Highlands (*Slovenské stredohorie* in Slovak) in the Western Carpathians. The Kremnica Mountains were formed by volcanic activity in the Neogene period. The geological structure is based on lava bodies. The originally highly aligned mountain surface was deformed by geomorphological processes at the end of the Neogene period. A massive vault was formed in the eastern part, which was divided by rivers into long river banks, while an old plateau in the western part was less deformed when it was erected.

Lithology and topography

The highest part of the mountains with the exposed vault is located in the eastern part with the highest peak – Flochová (1317 m a.s.l.). The remaining part of the old plateau is at the maximum altitude of 800–900 m a.s.l. in some places, but mostly at 550–600 m a.s.l. At the interface between the high vault in the east and the plateau in the west, andesites are enriched with silica from hot waters released through geological faults. This led to the formation of roundish hills over the Kremnica town, as well as the cliff relief – Skalka (1232 m a.s.l.).

Vegetation

The original vegetation cover in most of the Kremnické vrchy Mountains was fir-beech forests (*Abies alba, Fagus sylvatica*). Nowadays, woody vegetation alternates in many places with grassland (meadows and pastures), less frequently with arable land. Beech (*Fagus sylvatica*) with admixture of maple (*Acer*) and elm (*Ulmus*) trees dominate in forest, mainly on the high vault, while the yew (*Taxus baccata*) occurs in the lower location. The herbaceous vegetation is relatively homogeneous; more heterogenous flora occurs only in marginal parts, and mountain herbaceous species occur more regularly only under the main ridge.

Climate

The region is located in the snow climate, fully humid precipitation with warm summer (Kottek et al., 2006). According to Climatogeographical types of Slovakia (Tarábek, 1980) this region is characterized by mountainous, cold climate with little temperature fluctuation and very wet. Mean air temperature per year is 2 – 4 °C and mean rainfall amount per year is 1 200 until 1 600 mm.

Profile 1 – Dystric Katoskeletic Umbric **Andosol** (Fulvic, Loamic, Thixotropic)
Localization: Kremnica – Skalka, S slope with inclination 13°, maple - beech forest, 1 259 m a.s.l., **N** 48°44'18.42'', **E** 18°59'51.837''

Morphology:

Olf – 2–0 cm, slightly decomposed material;

Ah – 0-10 cm, *umbric* and *fulvic* horizon, sandy loam, common stones, black (10YR 2/1), moist, fine subangular blocky structure, common roots, clear and smooth boundary;

ABw – 10–35 cm, sandy loam, common stones, very dark brown (10YR 2/2), moist, medium subangular blocky structure, thixotropy, common roots, clear and smooth boundary;

Bw1 – 35–55 cm, sandy loam, common stones, very dark greyish brown (10YR 3/2), moist, medium subangular blocky structure, thixotropy, few roots, gradual and smooth boundary;

Bw2 – 55–80 cm, sandy loam, dominant stones, dark brown (10YR 3/3), moist, medium to coarse subangular blocky structure, few roots, gradual and smooth boundary;

BC – 80–(110) cm, sandy loam, abundant stones, dark yellowish brown (10YR 3/4), moist, coarse subangular blocky structure, very few roots.

Table 1. Texture and melanic index

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm			Textural class	Bulk density [g·cm^{-3}]	Melanic index (MI)
		2 – 0.05	0.05 – 0.002	<0.002			
Ah	0–10	59	30	11	SL	0.42	2.62
Bw2	55–80	66	30	4	SL	0.65	2.24
BC	80–(110)	69	25	6	SL	0.82	2.31

Table 2. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	N_t [g·kg^{-1}]	C:N	pH	
					H_2O	KCl
Ah	0–10	127	9.2	14	4.3	4.0
Bw2	55–80	78	-	-	4.5	4.3
BC	80–(110)	59	-	-	4.6	4.5

Table 3. Content of selected forms of iron and aluminium

Horizon	Depth [cm]	Fe_o	Fe_d	Al_o	Al_d
		[g·kg^{-1}]			
Ah	0–10	10.1	18.1	31.5	27.3
Bw2	55–80	10.1	16.9	20.2	20.7
BC	80–(110)	11.4	19.4	30.2	30.2

Profile 2 – Dystric Umbric **Andosol** (Fulvic, Epiloamic, Endoarenic, Thixotropic)

Localization: Kremnica – Skalka, NE slope with inclination 38°, maple – beech forest, 1 226 m a.s.l., **N** 48°44’25.026’’, **E** 18°59’53.804’’

Morphology:

Olf – 3–0 cm, slightly decomposed organic material;

Ah – 0–20 cm, *umbric*and *fulvic* horizon, sandy loam, few stones, black (10YR 2/1), moist, finesubangular blocky structure, common roots, abrupt and smooth boundary;

ABw – 20–35 cm, sandy loam, few stones, very dark brown (10YR 2/2), moist, medium subangular blocky structure, thixotropy, common roots, clear and smooth boundary;

Bw1 – 35–55 cm, sandy loam, few stones, very dark brown (10YR 3/2), moist, medium to coarse subangular blocky structure, thixotropy, few roots, clear and smooth boundary;

Bw2 – 55–85 cm, loamy fine sand, few stones, very dark brown (10YR 3/3), moist, coarse subangular blocky structure, thixotropy, very few roots, clear and smooth boundary;

BC – 85–(130) cm, loamy fine sand, abundant stones, dark yellowish brown (10YR 3/4), moist, coarse subangular blocky structure, thixotropy, very few roots.

Table 4. Texture and melanic index

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm			Textural class	Bulk density [g·cm^{-3}]	Melanic index (MI)
		2 – 0.05	0.05 – 0.002	<0.002			
Ah	0–20	65	25	10	SL	0.31	2.25
Bw2	55–85	76	20	4	LFS	0.37	2.38

Table 5. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	N_t [g·kg^{-1}]	C:N	pH	
					H_2O	KCl
Ah	0–20	160	14.2	11	3.95	3.72
Bw2	55–85	59	8.1	7	4.62	4.42

Table 6. Content of selected forms of iron and aluminium

Horizon	Depth [cm]	Fe_o	Fe_d	Al_o	Al_d
		[g·kg^{-1}]			
Ah	0–20	13.0	20.0	29.3	26.9
Bw2	55–85	21.4	30.0	27.0	35.5

Profile 3 – Dystric Endoskeletic **Cambisol** (Loamic, Ochric)
Localization: Kordíky, SE slope with inclination 6°, permanent grassland, 783 m a.s.l.,
N 48°46'44.076'', **E** 19°2'3.743''

Morphology:

A – 0–20 cm, humus horizon, sandy loam, few stones, dark yellowish brown (10YR 4/4), moist, fine subangular blocky structure, common roots, abrupt and smooth boundary;

AB – 20–40 cm, sandy loam, few stones, yellowish brown (10YR 5/4), moist, subangular blocky structure, common roots, clear and smooth boundary;

Bw – 40–65 cm, *cambic* horizon, sandy loam, many stones, yellowish brown (10YR 5/6), moist, medium to coarse subangular blocky structure, few roots, clear and smooth boundary;

BC – 65–(90) cm, loam, abundant stones, brownish yellow (10YR 6/6), moist, coarse subangular blocky structure, very few roots.

Table 7. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm			Textural class	Bulk density [g·cm^{-3}]
		2 – 0.05	0.05 – 0.002	<0.002		
A	0–20	54	37	9	SL	-
Bw	40–65	55	35	10	SL	-
BC	65–(90)	51	37	12	L	-

Table 8. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	N_t [g·kg^{-1}]	C:N	pH	
					H_2O	KCl
A	0–20	34.2	2.6	13	5.08	4.08
Bw	40–65	10.1	0.8	13	5.50	4.38
BC	65–(90)	6.2	0.5	12	5.68	4.39

Table 9. Exchangeable cations

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^+	Na^+	Al
		[%]				[mg·kg^{-1}]
A	0–20	80.12	7.75	2.01	1.20	5.64

Profile 4 – Dystric Skeletic **Cambisol** (Ochric, Siltic)
Localization: Banská Bystrica - Radvaň, SE slope with inclination 9°, permanent grassland, 708 m a.s.l.,
N 48°46’45.457’’, **E** 19°2’9.424’’

Morphology:

A – 0–20 cm, humus horizon, silt loam, few stones, dark yellowish brown (10YR 4/4), moist, fine subangular blocky structure, common roots, abrupt and smooth boundary;

AB – 20–36 cm, silt loam, few stones, very dark brown (10YR 4/6), moist, medium subangular blocky structure, common roots, clear and smooth boundary;

Bw – 36–80 cm, *cambic* horizon, silt loam, many stones, yellowish brown (10YR 5/6), moist, medium to coarse angular blocky structure, few roots, clear and smooth boundary;

BC – 80–(105) cm, transitional horizon loam, abundant stones, yellowish brown (10YR 5/8), moist, coarse angular blocky structure, very few roots.

Table 10. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm			Textural class	Bulk density [g·cm^{-3}]
		2 – 0.05	0.05 – 0.002	<0.002		
A	0–20	36	54	10	SiL	-
AB	20–36	24	61	15	SiL	-
Bw	36–80	22	60	18	SiL	-
BC	80–(105)	33	42	25	L	-

Table 11. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	N_t [g·kg^{-1}]	C:N	pH	
					H_2O	KCl
A	0–20	41.6	3.8	11	4.72	3.93
AB	20–36	11.0	1.4	8	5.28	4.12
Bw	36–80	8.3	0.8	10	5.34	4.14
BC	80–(105)	-	-	-	5.63	4.58

Table 12. Exchangeable cations

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^+	Na^+	Al
		[%]				[g·kg^{-1}]
A	0–20	60.55	23.61	1.19	0.33	26.64

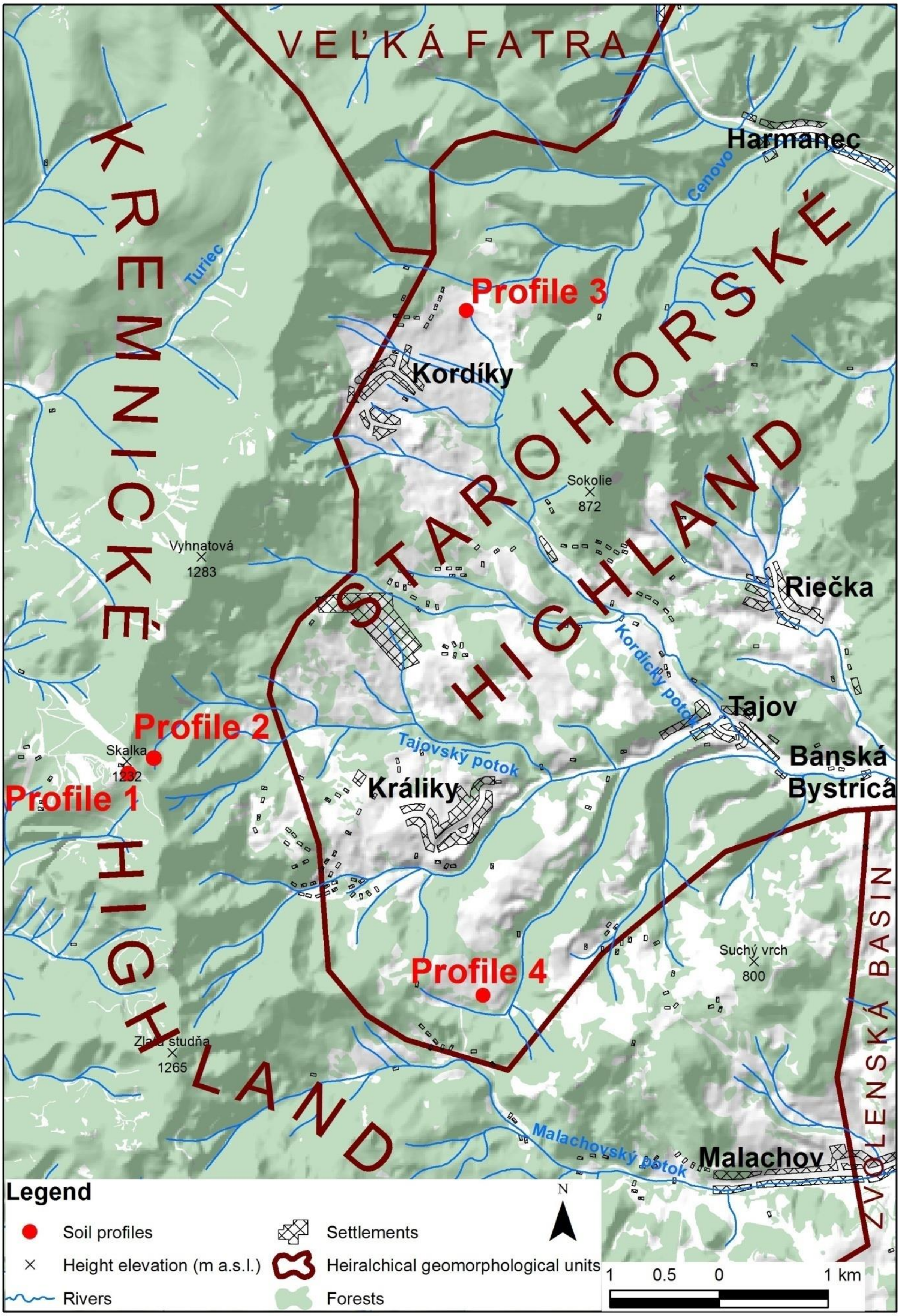

Fig. 2. Localization of soil profiles

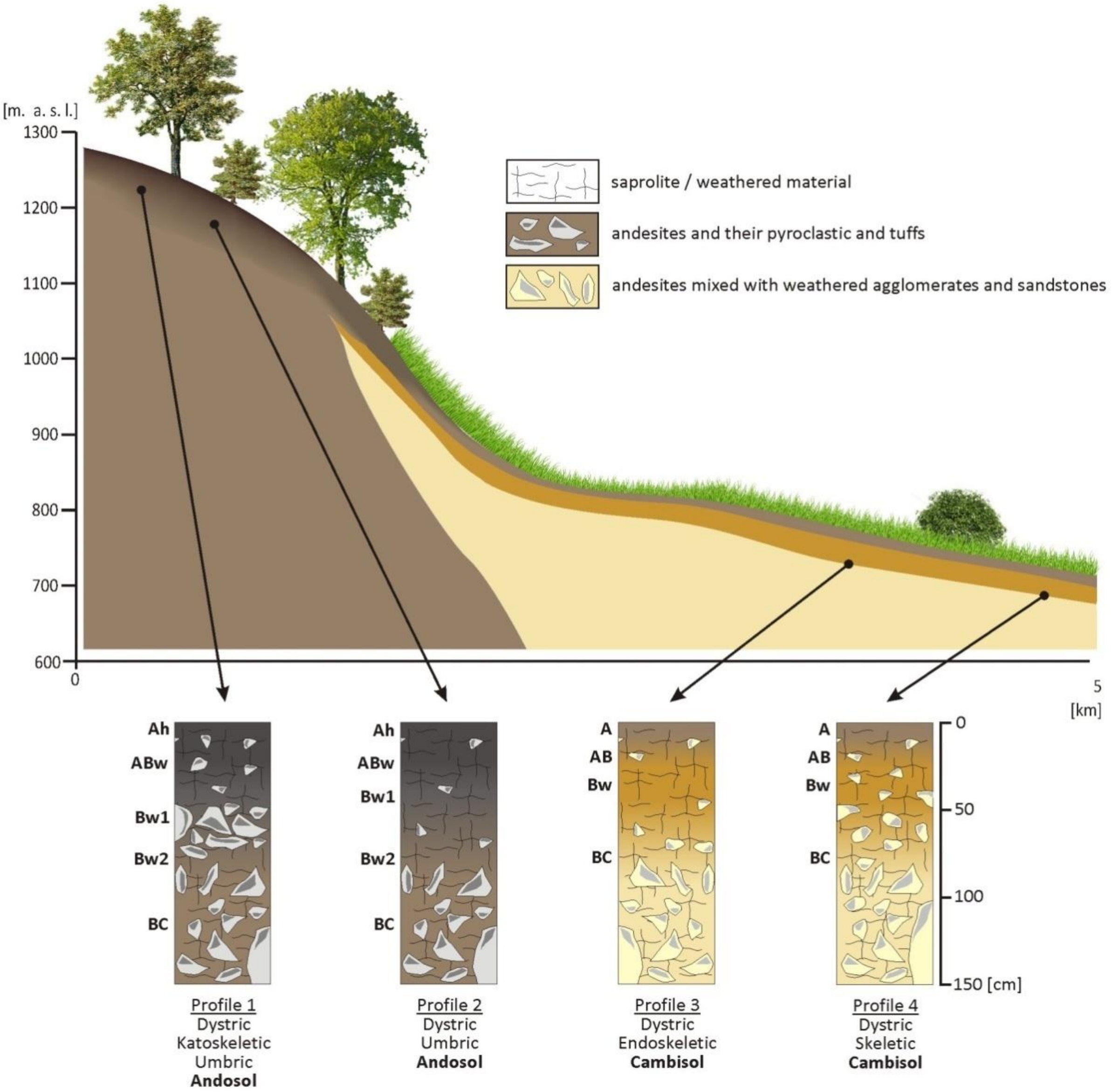

Fig. 3. Sequence of soil profiles

Soil genesis and systematic position

The first two soil profiles were classified as **Andosols** (IUSS Working Group WRB, 2015). These typically dark soils of volcanic landscapes encompasses units that develop in glass-rich volcanic ejecta (ash, tuff, pumice, cinders, but also andesite and others). The main features to the RSG Andosols are: 1) the presence of *andic* properties ≥ 30 cm within ≤ 100 cm of the soil surface and starting ≤ 25 cm from the soil surface and 2) no *argic*, *ferralic*, *petroplinthic*, *pisoplinthic*, *plinthic* or *spodic* horizon, unless buried deeper than 50 cm from the mineral soil surface. *Andic* properties result from moderate weathering of mainly pyroclastic deposits. The presence of short-range-order minerals and/or organo-metallic complexes is characteristic for *andic* properties. **Andosols** have an *umbric* horizon, which is a relatively thick, dark-coloured surface horizon with a low base saturation and a moderate to high content of organic matter, therefore ***Umbric*** principal qualifiers were applied. These soils have also ***Thixotropic*** and ***Fulvic*** supplementary qualifiers. ***Thixotropic*** means the presence of a material in a certain layer within ≤ 50 cm from the soil surface, which changes under pressure or by friction from a plastic solid state into a liquefied state and back into a solid state. ***Fulvic*** is used for soils having a *fulvic* horizon starting ≤ 30 cm from the soil surface. The *Fulvic* horizon is a thick, dark coloured horizon at or near the soil surface, which is typically associated with short-range-order minerals (commonly allophane) or with organo-aluminium complexes. It has a low bulk density and contains highly humified organic matter that shows a lower ratio of humic acids to fulvic acids compared with the *melanic* horizon. ***Loamic*** (Profiles 1–3) means having a texture class of loam, sandy loam, sandy clay loam or silty clay loam in a ≥ 30 cm thick layer within ≤ 100 cm from the mineral soil surface. Profile 1 has the principal qualifier ***Katoskeletic***, which means having ≥ 40% (by volume) of coarse fragments (andesites) between > 0 and < 50 cm of the (mineral) soil surface, with the lower limit ≥ 100 cm from the (mineral) soil surface, and no such horizon or layer occurs < 1 cm from the (mineral) soil surface. **Andosol** has sandy loam only in the upper part and a higher content of the sand fraction in the lower section of the profile so ***Epiloamic*** and ***Endoarenic*** qualifiers were used.

Profiles 3 and 4 were classified as **Cambisols** according to WRB (2015). These are soils that have developed on volcanic rocks (mostly andesites) mixed with weathered agglomerates and sandstones with at least incipient subsurface soil formation. Humus horizons in these pedons are less developed compared to previously described Andosols and meet only the criteria of the ***Ochric*** qualifier. **Cambisols** are characterized by slight or moderate weathering of parent material and the absence of considerable quantities of illuviated clay and organic matter. These soils are characterized by the presence of the *cambic* horizon starting at ≤ 50 cm from the soil surface and having its lower limit at ≥ 25 cm from the soil surface. The *Cambic* horizon is a subsurface horizon showing evidence of pedogenetic alteration that ranges from weak to relatively strong. The principal qualifier ***Dystric*** should be used for both profiles, because they have an effective base saturation of < 50%. Profile 3 has horizons with sandy loam, and loam texture classes, hence ***Loamic*** should be used as a supplementary qualifier. Profile 4 is characterized by a higher content of silt fraction (silt loam texture from 0 to 80 cm), which is expressed by the ***Siltic*** qualifier and ≥ 40% (by volume) of coarse fragments averaged over a depth of 100 cm from the soil surface, thus ***Skeletic*** should also be used as the principal qualifier.

Soil sequence

Andosols occurs in the neovolcanic part of the Western Carpathians only occasionally. These soils are situated on volcanic rocks, mainly pyroclastic deposits with vitric components mostly under forest in humid areas. They are represented by very dark brown to black soils (10YR 2/1- 2/2), humus (often more than 10% of organic carbon), and acid to very acid (pH/KCl mostly between 3.5–4.5). **Andosols** are extended to volcanic, mainly pyroclastic deposits often with the dominance of vitric components. It is possible to distinguish soils with more or less developed *andic* properties, mostly from the Andic (Vitric) **Cambisols** to **Andosols** sequence, mainly in the forest landscape.

The main part of the Kremnica Mountains is created by neovolcanites (mostly by andesites and their pyroclastic and tuffs). Andesites of the second volcanic phase are pyroxenes, ascending together with tuffs, in which smaller fragments were created as remnants of streams. They are mostly characteristic for the top part of the mountain ridge of the Kremnické vrchy **(Profiles 1 and 2).**

Andic layers have more or less different characteristics, depending on the type of dominant weathering process affecting the soil material. They may exhibit thixotropy, i.e. soil material changing under pressure or friction. In perihumid climates (in the conditions of the Kremnické vrchy

Mountains, soil profiles 1 and 2 are situated over 1000 m above sea level), humus-rich andic layers may contain more than twice as much water as oven-dried and rewetted (hydric characteristics) samples.

The presence of allophanes and *andic* properties were also identified using the sodium fluoride field test described by Fieldes and Perrott (1966). Also pH in NaF of 9.5 and more indicates the presence of allophanes in all soil profiles, which was confirmed in the described soil profiles of **Andosols**.

The Melanic Index (MI) was not identified under 1.7 in any of the Slovakian **Andosols** (Balkovič, 2005), which was also confirmed. In addition, the *fulvic* horizon is characteristic for Slovakian Andosols, resp. Andic soils, which was confirmed by higher values of the melanic index (MI > 1.7) (Kobza, 2008, 2017a, b).

Volcano eruptions caused andesite outpourings parallel with a large amount of ash and boulders (pyroclastics). This material was erupted and transported into the surroundings. The admixture of Eocene agglomerates and sandstones, often occurring on the soil cover surface in the environs of the Kremnické vrchy Mountains (in the zone of Králiky – Kordíky in this case), is the parent rock of Cambisols **(Profiles 3** and **4)**. A colder and more humid climate in the upper parts of the mountains slowed down the weathering processes. This made it possible to preserve the *andic* properties in the volcanic rocks located on the summits of the Kremnické vrchy Mountains.

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Diversity of soils derived from the Magura Nappe rocks (the Western Outer Carpathians, Poland) – the case study of soil cover of Mt Luboń Wielki

Tomasz Zaleski, Bartłomiej Kajdas, Ryszard Mazurek

Samples were collected from Mt Luboń Wielki (1022 m a.s.l.), which is located in the Outer Carpathians in the western part of the Beskid Wyspowy (the Island Beskids) mountain ridge, S Poland (Fig. 1). Mt Luboń Wielki is the most prominent peak in the Beskid Wyspowy mountain ridge. All streams flowing from the Luboń Wielki massif feed the Raba river or its tributary – the Smugawka. The Luboń Wielki massif rises almost 500 m above the valleys of these rivers.

Fig. 1. Location

Lithology and topography

In terms of geology, it is part of the Rača subunit of the Magura Nappe (Fig. 2). Large synclines dominate in the Beskid Wyspowy (Klimas, Szczebel, Luboń Wielki, Lubogoszcz, Śnieżnica, Ćwilin and Łopień) and form isolated "island mountains" (Konon 2001). This "islandic" type of morphology results from relief inversion of the lithostratigraphic succession of the Rača subunit – the youngest thick-bedded Magura Sandstones (the Upper Eocene-Oligocene) in the cores of synclines are much more resistant compared to the older thin-bedded Hieroglyphic Beds (Middle-Upper Eocene) and Variegated Shales (Lower-Middle Eocene) in the outer part.

Land use

In 1970, the Luboń Wielki inanimate nature reserve was established in the upper part of Mt Luboń Wielki and on its S-E slopes. The aim of the reserve is to protect the largest flysch landslide in the Beskid Wyspowy together with the landslide rock formations such as a landslide tongue, debris and boulder fields and chasms. The boulder field on Mt Luboń Wielki is treeless and surrounded by natural beech forest (*Dentario glandulosae-Fagetum*), and fir and spruce forest (*Abieti-Piceetum*). Lower parts of Mt Luboń Wielki are agriculturally used (Rąkowski et al. 2007).

Climate

The region of the Beskid Wyspowy mountain ridge is located in the zone of warm-summer humid continental climate according to the Köppen-Geiger climate classification (Kottek et al. 2006). It is a typical mountain climate. Vertical climat zones are present – moderately warm with mean temperature ranging from +6°C to +8°C up to 750 m a.s.l. and moderately cool with mean temperature from +4°C to +6°C above the altitude of 750 m a.s.l. Mean annual precipitation ranges from 800 to 900 mm (Orębska-Starklowa et al. 1995).

Profile 1 – Dystric Endoskeletic Leptic **Cambisol** (Ochric, Siltic)
Localization: Flattening under the Luboń Mt. top; Carpathian beech forest, inclination 8º, 993 m a.s.l.,
N 49°39′06.3″ **E** 19°59′40.4″

Morphology:

Oi – 3–0 cm, poorly decomposed organic material containing mainly beech leaves;

Ah – 0–5 cm, humus horizon, silt loam, moist, brownish black (7.5YR 2/2), medium strong granular structure, common sandstone fragments, common roots, clear boundary;

Bw – 5–20 cm, silt loam, yellowish brown (10YR 5/6), fine strong blocky subangular structure, moist, many sandstone fragments, common roots, gradual boundary;

BC1 – 20–40 cm, silt loam, yellowish brown (10YR 5/6), fine strong blocky subangular structure, moist, abundant sandstone fragments, common roots, gradual boundary;

BC2 – 40–60 cm, silt loam, yellowish brown (10YR 5/6), fine strong blocky subangular structure, moist, abundant sandstone fragments, common roots, clear boundary;

R –60–(80) cm, *continuous rock*, firm Magura fm. Sandstone.

Table 1. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm									Textural class
		> 2.0	2.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
Ah	0–5	20	3	1	5	24	22	22	18	5	SiL
Bw	5–20	30	1	2	5	28	18	24	14	9	SiL
BC1	20–40	45	1	3	6	24	18	24	16	8	SiL
BC2	40–60	70	1	1	5	21	14	24	19	15	SiL

Table 2. Chemical and physicochemical properties

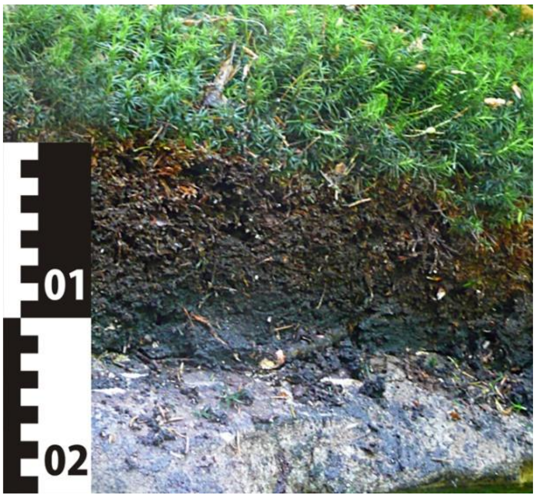
Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
Ah	0–5	38.6	1.92	20	4.1	3.3	-
Bw	5–20	2.61	0.16	16	4.3	3.4	-
BC1	20–40	-	-	-	4.3	3.4	-
BC2	40–60	-	-	-	4.5	3.7	-

Table 3. Sorption properties

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	HA	CEC	CEC_{clay}	BS
		[cmol(+)·kg^{-1}]								[%]
Ah	0–5	8.25	1.62	0.84	6.09	8.55	21.75	30.30	-	28
Bw	5–20	4.34	2.57	1.58	1.30	5.45	23.44	28.89	-	19
BC1	20–40	6.57	3.76	1.25	0.87	5.89	22.25	28.14	-	21
BC2	40–60	3.73	2.04	1.38	0.87	4.29	21.75	20.92	-	16

Profile 2 – Dystric Lithic **Leptosol**

Localization: On the surface of sandstone boulder on the Luboń Wielki Mt. slope, moss, 915 m a.s.l., **N** 49°39′06.3″ **E** 19°59′40.4″



Morphology:

Oi – 6–0 cm, poorly decomposed organic material containing mainly beech leaves;

Ah – 0–6 cm, humus horizon, sandy loam, moist, brownish black (7.5YR 2/2), medium strong granular structure, common sandstone fragments, common roots, clear boundary;

R –6–(20) cm, *continuous rock*, firm Magura fm. Sandstone.

Table 4. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm									Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.002	< 0.002	
Oi	6–0	-	-	-	-	-	-	-	-	-	-
Ah	0–6	0	2	4	6	8	39	16	21	4	SL
R	6–(20)	-	-	-	-	-	-	-	-	-	

Table 5. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
Oi	6–0	166	6.33	26	3.5	2.6	-
Ah	0–6	7.91	0.37	21	3.8	3.1	-
R	6–(20)	-	-	-	-	-	-

Table 6. Sorption properties

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	HA	CEC	CEC_{clay}	BS [%]
		[cmol(+)·kg^{-1}]								
Oi	6–0	231.4	83.72	40.94	52.25	408.31	281.32	689	-	59
Ah	0–6	87.41	34.61	17.42	13.07	152.51	241.93	394	-	39
R	6–(20)	-	-	-	-	-	-	-	-	-

Profile 3 – Dystric Hyperskeletic **Leptosol** (Ochric)
Localization: Soil developed below stone run on the slope of Luboń Wielki Mt.;
semi-decidous forest with beech, fir and spruce, 887 a.s.l.,
N 49°38′59″ **E** 19°50′35″

Morphology:

Oi – 3–0 cm, poorly decomposed organic material containing mainly beech leaves and fir needles;

Ah – 0–6 cm, humus horizon, sandy loam, moist, brownish black (10YR 2/3), medium strong granular structure, dominant sandstone fragments, common roots, clear, wavy boundary;

AC – 6–30 cm, transitional horizon, (in sandstone crack), sandy loam, moist, yellowish brown (2.5Y 5/6), medium moderate blocky subangular structure, dominant sandstone fragments, common roots;

R – 30–(50) cm, *continuous rock*, firm Magura fm. Sandstone.

Table 7. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm									Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.002	< 0.002	
Ah	0–6	5	0	0	1	3	56	15	20	5	SL
AC	6–30	30	2	5	5	5	26	21	28	8	SL
R	30–(50)	-	-	-	-	-	-	-	-	-	

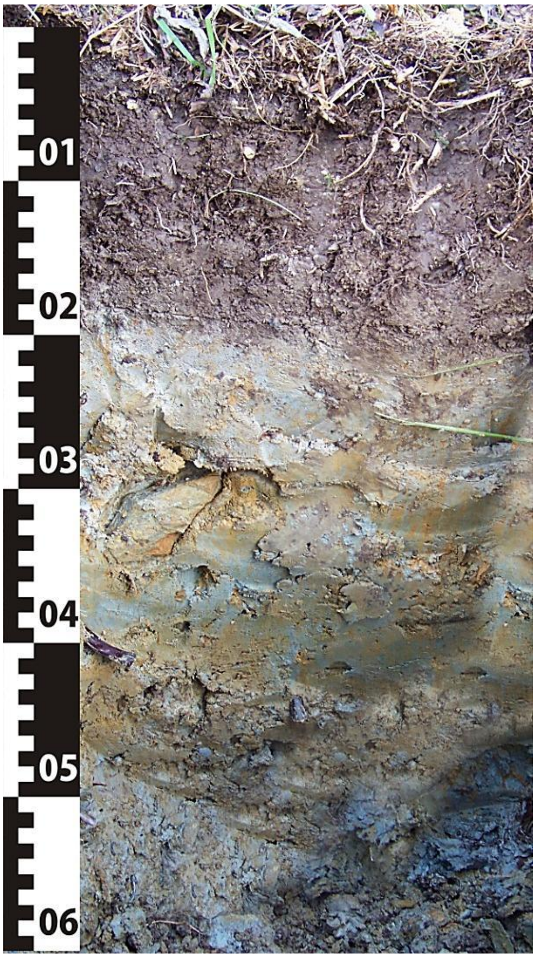
Table 8. Chemical and physicochemical properties

Horizon	Depth [cm]	OC $[g\cdot kg^{-1}]$	Nt $[g\cdot kg^{-1}]$	C/N	pH		$CaCO_3$ $[g\cdot kg^{-1}]$
					H_2O	KCl	
Ah	0–6	93.3	7.10	13	3.3	2.9	-
AC	6–30	13.6	1.30	10	4.0	3.6	-
R	30–(50)	-	-	-	-	-	-

Table 9. Sorption properties

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	HA	CEC	CEC_{clay}	BS [%]
		$[cmol(+)\cdot kg^{-1}]$								
Ah	0–6	45.34	10.97	2.69	2.11	61.11	425.36	486	-	13
AC	6–30	37.80	11.92	2.14	0.68	52.54	171.64	224	-	23
R	30–(50)	-	-	-	-	-	-	-	-	-

Profile 4 – Eutric Mollic **Gleysol** (Loamic)
Localization: Marsche, inclination 3º, 679 m a.s.l.
N 49°38′33.7″ **E** 19°59′41.8″



Morphology:

Ahl – 0–20 cm, loamy sand, wet, brownish black (2.5Y 3/2), medium strong granular structure, common roots, clear boundary;

Bl1 – 20–35 cm, loam, wet, grayish olive (7.5Y 4/2) with gleyic properties, massive, few roots, gradual smooth boundary;

Bl2 – 35–60 cm, clay loam, wet, olive (5Y 5/4) with gleyic properties, massive, very few roots; gradual smooth boundary;

Cl – 60–(80) cm, clay loam, very wet, gray (10Y 5/1) with gleyic properties, massive.

Table 10. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm									Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.002	< 0.002	
Ahl	0–20	0	0	1	3	7	68	11	7	3	LS
Bl1	20–35	0	0	2	4	7	19	17	31	20	L
Bl2	35–60	5	1	1	4	5	13	16	32	28	CL
Cl	60–(80)	90	1	2	3	5	11	18	27	33	CL

Table 11. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
Ahl	0-20	74.6	7.3	10	4.8	4.1	-
Bl1	20-35	4.00	0.4	10	5.3	4.2	-
Bl2	35-60	2.10	0.4	5	5.8	4.6	-
Cl	> 60	6.90	-	-	5.9	4.7	-

Table 12. Sorption properties

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	HA	CEC	CEC_{clay}	BS [%]
		[cmol(+)·kg^{-1}]								
Ahl	0-20	470.3	57.53	2.39	3.89	534.14	573.30	1071	-	50
Bl1	20-35	106.6	17.21	1.76	1.83	127.41	46.64	174	-	73
Bl2	35-60	231.0	40.34	2.09	2.83	276.30	42.91	319	-	87
Cl	> 60	257.2	59.72	1.98	3.29	322.18	35.45	358	-	90

Profile 5 – Eutric Endoskeletic Leptic **Cambisols** (Loamic, Raptic)
Localization: Semi-decidous forest with beech and fir, inclination 15-18º, 662 m a.s.l.,
N 49°38′52.8″ **E** 19°59′28.6″

Morphology:

Oi – 3–0 cm, highly decomposed organic material; black (7.5YR 1.7/1), moist, very few sandstone fragments, many roots, clear smooth boundary;

A – 0–7 cm, sandy loam, moist, dark brown (10YR 3/3), medium strong granular structure, few sandstone fragments, many roots, clear irregular boundary;

AB – 7–25 cm, sandy loam, moist, yellowish brown (10YR 5/6), fine strong blocky subangular structure, many sandstone fragments, common roots, gradual boundary;

Bw – 25–45 cm, sandy loam, moist, yellowish brown (10YR 5/6), fine strong blocky subangular structure, abundant flat sandstone fragments, few roots, clear boundary;

2C – 45–90 cm, silty loam, moist, yellowish brown (2.5Y 5/3), fine moderate blocky subangular structure, abundant sandstone and shale fragments, very few roots, gradual boundary;

2R – 90–(134) cm, silty loam, moist, yellowish brown (2.5Y 5/3), broken sandstone and shale layers, very few roots, gradual boundary.

Table 13. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm									Textural class
		> 2.0	2.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
Ah	0–7	35	3	5	9	26	25	20	4	8	SL
AB	7–25	50	2	4	10	28	23	21	3	10	SL
Bw	25–45	70	6	9	15	19	17	16	10	9	SL
2C	45–90	80	2	2	2	28	11	16	27	12	SiL
2R	90–(134)	-	-	-	-	-	-	-	-	-	

Table 14. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		CaCO$_3$ [g·kg^{-1}]
					H$_2$O	KCl	
Ah	0–7	11.49	0.57	20	3.5	2.7	-
AB	7–25	0.95	0.05	19	3.6	2.7	-
Bw	25–45	0.33	0.04	8	4.9	3.2	-
2C	45–90	-	-	-	5.2	3.2	-
2R	90–(134)	-	-	-	-	-	-

Table 15. Sorption properties

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	TEB	HA	CEC	CEC$_{clay}$	BS [%]
		[cmol(+)·kg^{-1}]								
Ah	0-7	6.17	2.31	0.93	0.43	9.85	8.25	18.10	-	54
AB	7-25	9.20	5.99	3.04	2.61	20.84	41.56	62.40	-	33
Bw	25-45	7.26	5.19	2.97	3.48	18.90	42.75	61.65	-	31
2C	45-90	86.44	43.95	3.15	3.91	137.09	7.88	144.96	-	95
2R	90-(134)	-	-	-	-	-	-	-	-	-

Profile 6 – Eutric Calcaric **Planosol** (Humic, Episiltic, Endoloamic, Cambic)
Localization: meadow on the foothill of Luboń Wielki Mt., inclination 5º, 561 m a.s.l.,
N 49°38′09″ **E** 19°59′49″

Morphology:

A – 0–20 cm, silt loam, moist, olive brown (2.5Y 4/3), fine strong blocky angular structure, abundant rocks fragments, common roots, clear gradual boundary;

Bw – 20–45 cm, silt loam, moist, dark olive brown (2.5Y 3/3), medium strong blocky angular structure, abundant rocks fragments, clear gradual boundary;

Bwg – 45–60 cm, silty clay loam, moist, gray (7.5Y 5/1), massive coherent structure, abundant fragments of sandstone with calcite veins, common roots, clear gradual boundary;

2Cgk – 60–(90) cm, silty clay loam, moist, gray (7.5Y 4/1), massive coherent structure, many calcareous sandstone fragments, common roots, moderately calcareous.

Table 16. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm									Textural class
		> 2.0	2.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
A	0–20	10	3	4	10	15	15	19	25	9	SiL
Bw	20–45	20	6	2	4	12	15	21	15	25	SiL
Bwgk	45–60	30	2	2	2	2	3	15	36	38	SiCL
2Cgk	60–(90)	30	2	2	1	2	1	16	36	40	SiCL

Table 17. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
A	0–20	29.5	1.30	23	5.6	4.6	-
Bw	20–45	3.12	0.27	11	6.6	5.4	-
Bwgk	45–60	3.02	0.23	13	6.6	5.7	51.7
2Cgk	60–(90)	-	-	-	7.0	6.8	65.8

Table 18. Sorption properties

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	HA	CEC	CEC_{clay}	BS [%]
		[cmol(+)·kg^{-1}]								
A	0–20	32.04	9.56	5.74	4.35	51.69	25.34	77.03	-	67
Bw	20–45	20.48	19.62	3.25	7.83	51.18	2.63	53.81	-	95
Bwgk	45–60	28.91	26.41	2.83	3.91	62.07	0.94	63.00	-	99
2Cgk	60–(90)	24.87	34.28	3.23	13.48	75.86	1.50	77.36	-	98

Profile 7 – Eutric Cambic Hyperskeletic **Leptosol** (Loamic, Ochric)
Localization: Meadow on the foothill of Luboń Wielki Mt., inclination 10º, 490 m a.s.l.,
N 49°37′56″ **E** 19°59′42″

Morphology:

A – 0–20 cm, loam, dry, dull reddish brown (2.5YR 4/3), fine strong blocky angular structure, common fragments of weathered shale, many roots, gradual boundary;

Bw – 20–60 cm, *cambic* horizon, loam, dry, dull reddish brown (2.5YR 4/3), dominant fragments of weathered red and green variegated shale, many roots, gradual boundary;

R – 60–(80) cm, dominant fragments of weathered red and green variegated shale, few roots.

Table 19. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm									Textural class
		> 2.0	2.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
A	0–20	10	8	7	9	15	6	27	10	18	L
Bw	20–60	75	9	3	2	23	13	16	13	22	L
R	60–(80)	-	-	-	-	-	-	-	-	-	

Table 20. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
A	0–20	19.8	1.8	11	4.8	3.6	-
Bw	20–60	6.4	0.7	9	4.9	3.4	-
R	60–(80)	-	-	-	-	-	-

Table 21. Sorption properties

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	HA	CEC	CEC_{clay}	BS [%]
		[cmol(+)·kg^{-1}]								
A	0–20	63.83	20.04	6.49	3.91	94.27	5.06	99.34	-	95
Bw	20–60	24.41	28.20	2.83	2.17	57.61	9.38	66.99	-	86
R	60–(80)	-	-	-	-	-	-	-	-	-

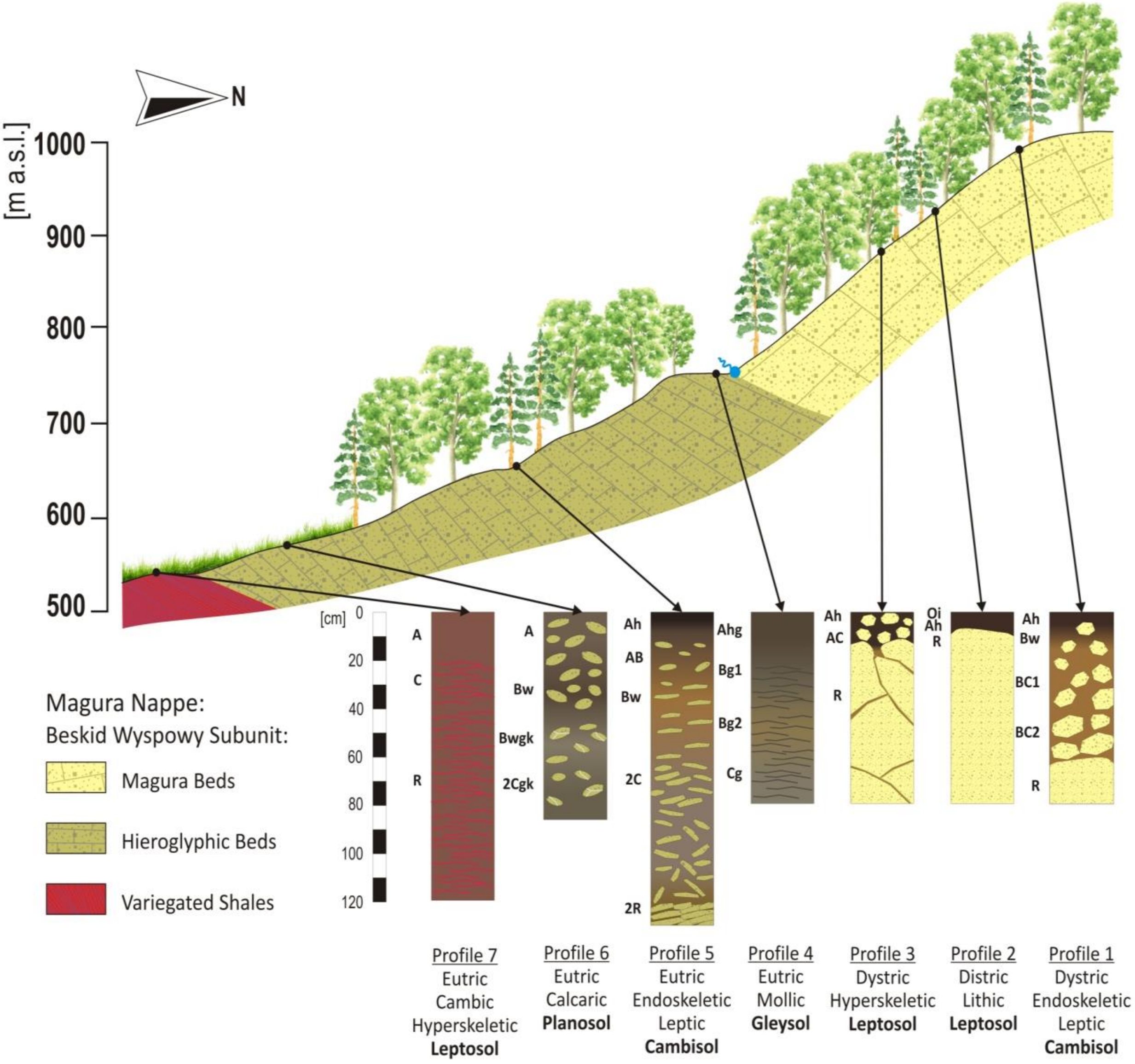


Fig. 2. Lithotoposequence of soils derived from the Magura Nappe rocks

Soil genesis and systematic position

The studied soils represent most important types of soils found along the transect from the mountain feet – the Raba river valley to the peak in the altitudinal gradient from 500 m a.s.l. to 1022 m a.s.l.

Profile 1 represents soils typical of the flattening situated several metres below the mountain peak. The soil developed *in situ* from the weathered mantle of vertical layers of thick-bedded sandstone Magura fm. Mostly ***Dystric Endoskeletic Leptic*** **Cambisols** with a diagnostic *cambic* horizon occur in this part of Mt Luboń Wielki. Mineral horizons are loamy and the content of rock fragments increases with the depth of soil (Table 1). The soils show acid reaction in the whole profile (Table 2) and the low level of base saturation (Table 3). Gradual horizon boundaries are typical for ***Dystric*** **Cambisols** from the Carpathians. Similar soils are found across the Outer Flysch

Carpathians, especially over the Magura Nappe (Eastern Outer Flysch Carpathians) in the lower and upper montane zone.

***Dystric Lithic* Leptosol** – profile 2 is situated on the largest flysch landslide in the Beskid Wyspowy. It represents shallow soils, less than 20 cm deep. On Mt Luboń Wielki, such soils are found at rock ledges, on the outcrops of thick-bedded sandstone of Magura fm. These soils contain mainly an ectohumic horizon with *folic* properties, while humic horizons with *mollic* properties are rather scarce. Weathered mineral horizons are almost non-existing between solid rock and organic horizons. Such soils are formed in damp and shady locations as a result of accumulation and slow mineralization of organic matter, manly of moss origin. Because of the nature of organic matter, this type of soil has highly acidic reaction (Table 5).

Brown soils like ***Dystric Hypersceletic* Leptosol *(Ochric)*** (profile 3) are the product of thick-bedded sandstone of Magura fm weathering. This type of soils can be found on the slope, where stabilized boulder colluviums or bedrock outcrops occur. Such soils usually consist of a few centimetres thick organic *ectohumic* horizon, a few centimetres of a *humic* horizon and parent material (Table 7). In thicker soils – more than 30 cm deep, a *cambic* horizon is common. Such Leptosols usually show acid reaction and loamic texture with a high content of coarse rock fragments, mainly stones and boulders (Tables 8 and 9). In the Luboń Wielki (LW) transect, the depth of weathering mantles and the amount of rock fragments increase with decreasing altitude of the terrain.

Eutric Mollic* Gleysols *(Loamic) (profile 4) and ***Leptic* Histosols** are found in the contact zone between thick-bedded sandstones of the Magura formation (above) and thin-bedded sandstones and shales of Hieroglyphic beds (below) as well as on small (less than 0.5 ha) terrain flattenings. The occurrence of gleyic soils is a result of continuous water leaching from the contact zone between permeable Magura sandstone and impermeable shales of Hieroglyphic fm. These soils are characterised by the presence of a histic horizon of up to 40 cm in thickness. The mineral parent material has mainly clay loam texture with a small amount of coarse fraction (Table 10). The content of organic matter is usually about 20%, but in some cases is may be higher. These are mesotrophic or eutrophic habitats with acid reaction at the upper horizons (Table 11). The lower part of these soils is usually more base saturated (Table 12).

Morphological and chemical properties of soils on Mt Luboń Wielki depend to a large extent on the colluvial material present in the soil profile, both the percentage of coarse rock fragments and their lithology (sandstones, carbonate-bearing sandstones or shales). Therefore, shallow ***Dystric Hyperskeletic* Leptosols** are found in the higher part of Mt Luboń Wielki, while ***Eutric Endoskeletic Leptic* Cambisols *(Loamic, Endoraptic)*** (profile 5) or ***Distric Endoskeletic Leptic* Cambisols** are found on a deeper colluvium. These soils are characterised by a very distinct lithological discontinuity between the solifluction cover and weathered parent material ***(Endoraptic).*** A smaller amount of coarse rock fragments and a larger amount of sand fraction are found in the upper horizons compared to lower horizons (Table 13). This discontinuity is also expressed in the diversification of chemical properties (Tables 14 and 15), especially in Cation Exchange Capacity (CEC) and Base Saturation (BS).

In the lower part of Mt Luboń Wielki, layers of thin-bedded sandstones (Hieroglyphic beds) densely cut with secondary calcite veins covered with noncarbonate colluvic material displaced in the process of solifluction or when the soil creeps from the upper part of the slope, are classified as ***Eutric Calcaric* Planosols** (profile 6). Similarly to profile 5, less clay fraction and larger amounts of sand and silt fraction ***(Episiltic)*** are found in the upper horizons compared to the lower horizons ***(Endoloamic)***

(Table 16). Those soils show a characteristic two-part nature and clear differences in chemical properties, especially in reaction, CEC and BS (Tables 17 and 18).

Eutric Endoskeletic **Cambisols** ***(Loamic)*** and ***Eutric Cambic Hyperskeletic*** **Leptosols** ***(Loamic, Ochric)*** (profile 7) occur at the foot of Mt Luboń Wielki, on weathered mantles of variegated shales. Variegated shales were exposed while the Raba river was cutting its channel through soft, liable rocks. These soils are adjacent to ***Eutric Calcaric*** **Planosols** (profile 6) and both soil types are used for agricultural purposes as arable land, meadows and pastures.

Soil sequence

Differentiation in the soil cover of Luboń Wielki Mt is a result of differences in lithological and morphological diversity. The soils present in the LW transect were classified into various soil units. The LW transect may also be typical of the Outer Carpathians, an example of soil type diversification depending on the slope position. It features different stages of mineral soil development, depending on the relief and thickness of the weathering mantle.

At the lower part of the slope, soils are deep, with clayey or loamic textural classes and many to abundant large rock fragments. The abundance of rock fragments increases with the depth of less than 50–60 cm, while only few rock fragments are present at the upper part of the soils. On steep slopes of Luboń Wielki Mt, shallow and loamy soils with abundant rock fragments (over 50% of stones and boulders) are most common.

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Topoclimatic soil gradient in the Karkonosze Mountains

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Fig. 1. Location

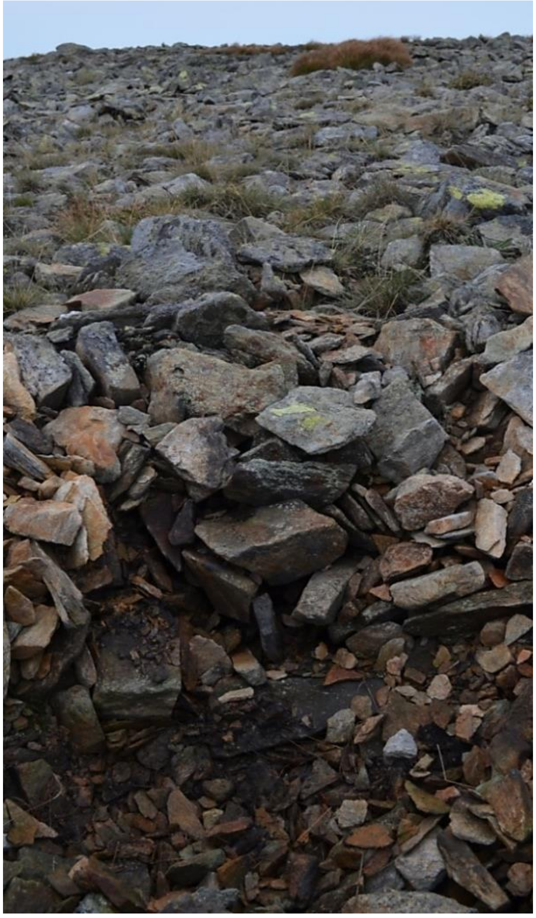
The spatial diversity of soil cover in mountain areas depends on a variety of factors, including (1) the parent rock that generally controls the macro- and micronutrient availability and fluxes, and (2) topography that may modify the intensity of erosion/accumulation phenomena and local water regime (Migoń and Kacprzak, 2014; Szopka et al., 2010; Waroszewski et al., 2016). However, elevation plays a crucial role in mountain landscapes, as it is correlated with climatic factors, and especially with air temperature, precipitation and water balance. Altitude and climate may therefore influence soil development both indirectly – through the intensity of physical and chemical weathering, water fluxes and balance in soil profile, and profile distribution of elements (Jenny, 1994; Lesovaya et al., 2012; Egli et al., 2014), and directly – through vegetation cover, biological activity and processes in soils, including organic matter decomposition and cycling (Bojko and Kabala, 2016, 2017; Drewnik 2006; Gutiérrez-Girón et al., 2015; Johnson et al., 2011; Labaz et al., 2014; Smith et al., 2002; Vucetich et al., 2000). As a result, on a mountain slope a clear spatial soil zonality may develop that is closely related to the altitude-climate-vegetation zones (Álvarez Arteaga et al., 2008; Dahlgren et al., 1997; Schawe et al., 2007; Yimer et al., 2006). The Karkonosze Mountains, the highest range of the Sudeten Mountains, are characterised by a zonation of climate conditions and vegetation cover that is typical of a temperate climate. The relatively homogeneous parent rock in the northern slopes allows the altitude- and climate-related soil differentiation to be tracked.

Lithology and topography

The Karkonosze Mountains (with the highest peak – Mount Śnieżka, 1,602 m a.s.l.) are on the border with the Czech Republic (Fig. 1). The northern (Polish) part of the range is developed from Carboniferous granites, upraised mainly during the Variscan orogeny. The granite massif is surrounded by Palaeozoic metamorphic rocks, including gneisses, schists, dolomites, and greenstones (Aleksandrowski et al., 2013). The highest peak, Mount Śnieżka, consists of hornfels, a metamorphic rock that is particularly hard and resistant for weathering and which developed at the contact of granite and Palaeozoic cover. Despite a homogeneous bedrock, the land surface is highly variable, and was modelled mainly in the Pleistocene period by local glaciers and slope processes in the periglacial zone (Traczyk and Migoń, 2003). Glacial cirques and moraines, stone/boulder covers, patterned grounds, solifluction lobes, etc. are typical geomorphological forms in the upper mountain zone. Pleistocene-Holocene stratified cover-beds featuring textural differentiation and high content of (sub)angular rock fragments are the most common parent material for soils in all elevation zones; however, autogeneous granite regoliths are also locally preserved.

Profile 1 – Dystric Hyperskeletic **Leptosol** (Protic)

Localization: upper part of slope, inclination 20-30°, exposition NE, sparse alpine vegetation, 1510 m a.s.l., **N** 50°44'20.7" **E** 15°44'33.6"



Morphology:

(A)C – 0–8 cm, discontinuous layer with fine-earth infilling in some fissures between hornfels fragments; pH of infilling (in water): 4.5-5; flat or angular stones locally are sorted and form various kinds of patterned grounds (relics of periglacial conditions); more intense alpine vegetation cover (*Festuca airoides, Juncus trifidus, Huperzia selago, Hieracium alpinum, Carex bigelowii* etc.) may develop in places where larger accumulation of fine earths or plant litter has accumulated; the cover is extremely drained; however, stones are often moist due to common occurrence of clouds and fog;

C – 8–(100) cm, open-work structure built of hornfels platy gravels and angular stones/boulders, unsorted, non-weathered and free of silt/clay caps; fine-earth infilling makes <1% of the layer volume; in some places organic accumulations may also be present.

Profile 2 – Dystric Nudilithic **Leptosol** (Humic)

Localization: steep rock walls in the upper part of mountain slope, exposition N, sparse vegetation (mosses, grass, blueberry) on the rock shelves, 1390 m a.s.l.,
N 50°44'19.7" **E** 15°43'54.8"

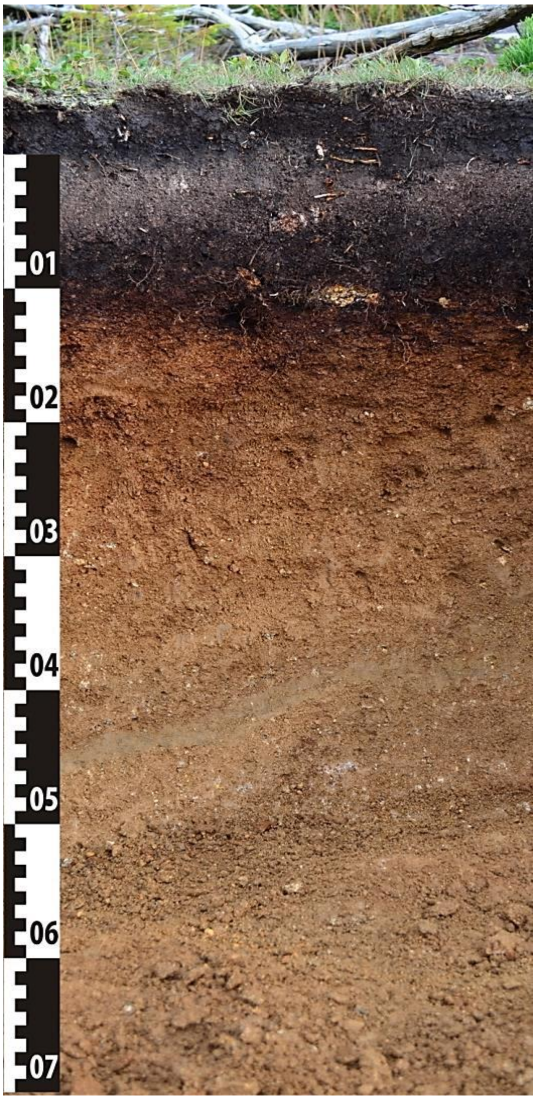
Morphology:

(A)**R** – 0–2(5) cm, discontinuous layer of initial accumulation of mineral fine earths and organic matter from plant litter (initially of lichens and mosses), inly on rock shelves and in rock fissures; pH of mineral-organic accumulations (in water): 4-5; accumulation zones cover <5% of the rock wall;

R – 2(5)+ cm, granite hard rock.

Profile 3 – Skeletic Leptic Albic **Podzol** (Arenic)

Localization: gently undulating summit of the mountain ridge, inclination 2-5°, no stones/boulders on the surface, vegetation: mountain pine shrubs, blueberry, grasses , 1370 m a.s.l., **N** 50°44'24.5" **E** 15°43'23.6"



Morphology:

Oe – 6–5 cm, litter layer, partly decomposed needles of mountain pine and grass tissues;

Oa – 5–0 cm, litter layer, highly decomposed plant residues, black (10YR 2/2);

E – 0–5(3–7) cm, eluvial horizon, *albic* material, gray (7.5YR 6/2 moist), loamy coarse sand, abundant fine gravels (angular granite fragments), weak blocky subangular structure, many fine roots, gradual boundary;

Bh – 5–10 cm, *spodic* horizon, dark brown (7.5YR 3/2), coarse sandy loam, abundant fine and medium gravels, weak blocky subangular structure, many fine roots, gradual boundary;

Bhsm – 10–18 cm, *spodic* horizon, reddish brown (5YR 4/6), coarse sandy loam, abundant fine gravels, strong platy-angular structure, partly cemented with iron, few fine roots, gradual boundary;

Bs – 18–36 cm, illuvially Fe-enriched horizon, brown (7.5YR 5/5), loamy coarse sand, abundant fine and medium gravels (angular granite fragments), dry, medium angular structure, no roots, gradual boundary;

C – 36–60 cm, granite regolith, yellow (7.5YR 6/4), loamy coarse sand, abundant fine and medium gravels (angular granite fragments), dry, rock-inherited structure, no roots, gradual boundary;

R – 60–(80) cm granite hard rock, cracked.

Table 1. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
E	0–5	42	8	19	18	20	8	11	12	2	2	LCS
Bh	5–10	46	8	16	15	17	11	11	13	6	3	CSL
Bhsm	10–18	44	8	17	16	15	7	13	16	5	3	CSL
Bs	18–36	55	10	22	18	19	6	8	11	3	3	LCS
C	36–60	67	12	22	16	16	7	13	11	2	1	LCS

Table 2. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		Feo	Alo	Alo+1/2Feo
					H_2O	KCl	[%]		
Oa	5–0	303	10.8	28	4.04	3.39	n.d.	n.d.	-
E	0–5	14.5	0.42	35	4.24	3.49	0.05	0.08	0.11
Bh	5–10	32.7	1.08	30	4.33	3.61	0.23	0.44	0.55
Bhsm	10–18	12.9	n.d.	-	4.59	3.93	0.87	0.70	1.14
Bs	18–36	6.21	n.d.	-	4.76	4.15	0.40	0.54	0.74
C	36–60	3.48	n.d.	-	4.79	4.19	0.15	0.22	0.30

Table 3. Base cations and base saturation

Horizon	Depth [cm]	AE	Al^{3+}	Ca^{2+}	Mg^{2+}	K^+	Na^+	BC	ECEC	BS
		[cmol(+)kg^{-1}]								[%]
E	0–5	4.24	4.09	0.80	0.45	0.06	0.08	1.39	5.47	25
Bh	5–10	8.10	8.00	0.80	0.44	0.05	0.07	1.37	9.36	15
Bhsm	10–18	5.10	5.05	0.72	0.39	0.04	0.07	1.22	6.27	19
Bs	18–36	1.96	1.92	0.64	0.40	0.03	0.06	1.13	3.05	37
C	36–60	1.86	1.82	0.72	0.41	0.03	0.06	1.22	3.04	40

Profile 4 – Katoskeletic Histic Albic **Podzol** (Loamic, Oxyaquic, Placic)

Localization: gently undulating summit of the mountain ridge, inclination 1-3°, the edge of mountain peatbog, no stones/boulders on the surface, 1425 m a.s.l.,
N 50°44'20.9" **E** 15°42'25.6"

Morphology:

He – 0–15 cm, *histic* horizon, partly decomposed fibrous peat (*hemic*), very dark brown (2.5Y 3/3), wet, common grass roots, gradual boundary;

Ha – 15–25 cm, *histic* horizon, highly decomposed peat (sapric), black (2.5Y 2.5/1, moist), wet, many grass roots, sharp and smooth boundary;

E – 25–28 cm, eluvial horizon, *albic* material, gray (7.5YR 6/2, moist), coarse loamy sand, many fine gravels (angular granite fragments), moist, weak blocky subangular structure, few fine roots, gradual boundary;

Bh – 28–35 cm, *spodic* horizon, greyish brown (7.5YR 4/2, moist), coarse sandy loam, many fine and medium gravels (angular granite fragments), moist, weak blocky subangular structure, very few fine roots, abrupt smooth boundary;

Bhsm – 35–39 cm, *spodic* horizon starting with *placic* - Fe-cemented layer, 2 mm thick, impermeable for water and roots, reddish brown (5YR 4/4, moist), coarse sandy loam, abundant fine and medium gravels (angular granite fragments), dry (below placic), strong platy-angular structure, no roots below placic, gradual boundary;

BC – 39–(60) cm, transition to granite regolith, yellowish brown (10YR 5/5, moist), coarse sandy loam, abundant fine and medium gravels (angular granite fragments) and granite subangular stones, dry, medium angular structure, no roots.

Table 4. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
E	25–28	15	21	15	22	16	9	3	9	3	2	LCS
Bh	28–35	15	18	7	14	16	4	13	19	5	4	CSL
Bhsm	35–39	40	19	8	11	14	2	15	22	6	3	CSL
BC	39–(60)	45	17	9	12	11	4	13	22	9	3	CSL

Table 5. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		Feo	Alo	Alo+1/2Feo
					H_2O	KCl	[%]		
He	0–15	461	n.d.	-	3.4	2.7	n.d.	n.d.	n.d.
Ha	15–25	434	n.d.	-	3.3	2.6	n.d.	n.d.	n.d.
E	25–28	15.3	n.d.	-	3.6	3.0	0.004	0.081	0.08
Bh	28–35	45.3	1.12	40	3.8	3.1	0.021	0.453	0.46
placic	35–35.2	n.d.	n.d.	-	n.d.	n.d.	5.681	0.658	3.50
Bhsm	35–39	21.7	0.84	26	4.2	3.6	1.033	0.545	1.06
BC	39–(60)	8.9	n.d.	-	4.3	3.7	0.487	0.385	0.63

Table 6. Base cations and base saturation

Horizon	Depth [cm]	AE	Al^{3+}	Ca^{2+}	Mg^{2+}	K^+	Na^+	BC	ECEC	BS
		[cmol(+)kg^{-1}]								[%]
He	0–15	22.4	18.2	1.75	0.68	0.28	0.18	2.89	21.1	14
Ha	15–25	43.2	39.2	1.20	0.36	0.20	0.15	1.91	41.1	5
E	25–28	3.60	3.29	0.35	0.12	0.04	0.03	0.54	3.83	14
Bh	28–35	8.80	8.44	0.36	0.14	0.05	0.04	0.59	9.03	7
Bhsm	35–39	11.2	10.8	0.30	0.10	0.10	0.09	0.59	11.4	5
BC	39–(60)	4.00	3.68	0.28	0.09	0.10	0.09	0.56	4.24	13

Profile 5 – Skeletic Albic **Podzol** (Arenic, Endodensic, Oxyaquic)

Localization: Upper part of mountain slope, variable inclination 5-25°, exposition N, surface coverage with stones/boulders 40-70%, vegetation: spruce forest (locally degraded), blueberry, grasses, mosses in the forest floor, 1170 m a.s.l.,
N 50°45'17.9" **E** 15°42'28.5"

Morphology:

Oe – 8–2 cm, litter layer, partly decomposed needles of mountain pine and grass/blueberry/mosses tissues;

Oa – 2–0 cm, highly decomposed plant residues, peaty-like, black (10YR 2/2);

Ah – 0–10 cm, humus horizon, black (7.5YR 2/2 moist) with whitish sand/gravel particles, coarse sandy loam, rich in humus, many fine angular gravels (granite), weak blocky subangular structure, moist, many fine roots, clear wavy boundary;

Eg – 10–13 cm, eluvial horizon, *albic* material, gray (7.5YR 5/1 moist), coarse sandy loam, many fine angular gravels (granite), weak blocky subangular structure, moist, clear irregular boundary;

Bhsm – 13–20 cm, *spodic* horizon, brown (7.5YR 4/3), coarse loamy sand, abundant fine gravels, angular structure, partly cemented with iron, thin iron pan (*placik*) present at lower boundary, wet above *placik*, abrupt boundary;

Bs – 20–30 cm, *spodic* horizon, strong brown (7.5YR 5/6 moist), loamy coarse sand, abundant fine and medium gravels, dry, angular structure, no roots, gradual boundary;

BC – 30–50 cm, transition to regolith, yellow (10YR 6/4, moist), loamy coarse sand, abundant angular medium gravels, dry, platy/angular structure, no roots, gradual boundary;

C – 50–(80) cm, massive slope cover, hiperskeletal with loamy sand infilling.

Table 7. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
Ah	0–10	20	8	17	18	14	9	18	11	2	3	CSL
Eg	10–13	45	10	20	15	12	7	13	13	5	5	CSL
Bhsm	13–20	50	13	28	19	12	6	8	9	2	3	LCS
Bs	20–30	60	16	23	18	11	9	5	10	2	6	LCS
BC	30–50	80	17	23	15	10	11	4	11	4	5	LCS

Table 8. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		Feo	Alo	Alo+1/2Feo
					H_2O	KCl	[%]		
Oe	8–2	460	11.1	41	3.91	3.32	n.d.	n.d.	-
Oa	2–0	370	12.3	30	3.84	3.23	n.d.	n.d.	-
Ah	0–10	45.0	1.71	26	4.08	3.43	0.23	0.22	0.33
Eg	10–13	15.0	n.d.	-	4.20	3.49	0.20	0.18	0.28
Bhsm	13–20	8.11	n.d.	-	4.44	3.70	0.36	0.66	0.84
Bs	20–30	6.95	n.d.	-	4.48	3.73	0.41	0.45	0.66
BC	30–50	0.58	n.d.	-	4.58	3.85	0.30	0.35	0.50

Table 9. Base cations and base saturation

Horizon	Depth [cm]	AE	Al^{3+}	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	BC	ECEC	BS [%]
		[cmol(+)kg^{-1}]								
Ah	0–10	5.07	4.85	1.55	0.49	0.16	0.11	2.31	7.16	32
Eg	10–13	4.25	4.11	1.42	0.35	0.10	0.08	1.95	6.06	31
Bhsm	13–20	2.93	2.82	1.25	0.32	0.09	0.07	1.73	4.55	38
Bs	20–30	2.26	2.13	0.93	0.28	0.08	0.05	1.34	3.47	39
BC	30–50	2.04	1.98	0.82	0.30	0.10	0.05	1.27	3.25	39

Profile 6 – Eutric Katoskeletic **Cambisol** (Katoarenic, Epiloamic, Ochric)

Localization: Lower part of mountain slope, inclination 5-15°, exposition N, surface coverage with boulders 30-50%, beech forest (110 y) with admixture of larch, 850 m a.s.l.,
N 50°45'46.5" **E** 15°44'41.5"

Morphology:

Oi – 3–1 cm, undecomposed forest litter – beech leaves;

Of – 1–0 cm, partly decomposed forest litter;

Ah – 0–5 cm, humus horizon, black (10YR 3/1 moist), coarse sandy loam, few fine angular gravels (granite), dry, fine moderate granular structure, abundant fine roots, no redoximorphic features, clear smooth boundary;

Bw1 – 5–30 cm, *cambic* horizon, yellowish brown (10YR 5/6, moist), coarse sandy loam, many fine angular gravels (granite), dry, fine moderate subangular structure, abundant fine roots, no redoximorphic features, gradual boundary;

Bw2 – 30–60 cm, *cambic* horizon, pale brown (10YR 5/4, moist), loamy coarse sand, many fine and medium angular gravels (granite), dry, fine moderate subangular structure, many fine roots, no redoximorphic features, gradual boundary;

BC – 60–(120) cm, transitional horizon, yellowish brown (10YR 6/4, moist), loamy coarse sand, abundant angular and rounded gravels, stones and boulders (granite), dry, fine moderate subangular structure, few fine roots, no redoximorphic features.

Table 10. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
Ah	0–5	15	21	15	16	10	9	8	13	4	4	CSL
Bw1	5–30	30	25	16	12	10	8	10	11	4	4	CSL
Bw2	30–60	40	23	16	12	13	10	10	10	3	3	LCS
BC	60–(120)	60	24	17	14	12	10	9	9	3	2	LCS

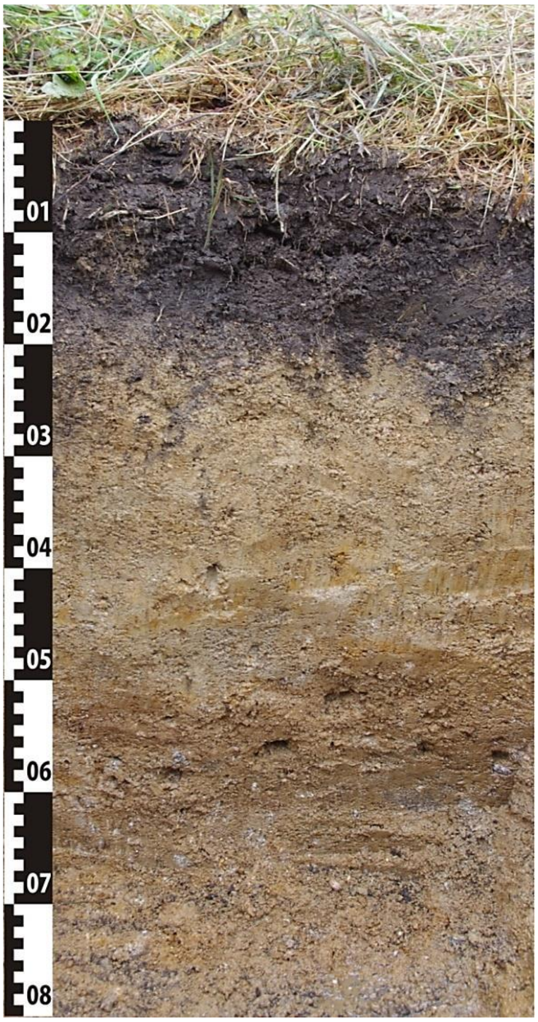
Table 11. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		Feo	Alo	Alo+1/2Feo
					H_2O	KCl	[%]		
Oe	1–0	420	15.0	28	4.13	3.21	n.d.	n.d.	-
Ah	0–5	130	7.20	18	4.01	3.25	0.45	0.54	0.77
Bw1	5–30	21.0	0.95	22	4.81	4.15	0.47	1.12	1.35
Bw2	30–60	10.5	n.d.	-	4.87	4.21	0.42	1.03	1.24
BC	60–(120)	7.12	n.d.	-	5.01	4.26	0.42	1.00	1.21

Table 12. Base cations and base saturation

Horizon	Depth [cm]	AE	Al^{3+}	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	BC	ECEC	BS
		[cmol(+)kg^{-1}]								[%]
Ah	0–5	8.72	7.89	2.23	0.55	0.14	0.11	3.03	10.9	28
Bw1	5–30	1.93	1.87	1.15	0.38	0.12	0.06	1.71	3.58	48
Bw2	30–60	1.32	1.28	1.12	0.32	0.10	0.11	1.65	2.93	56
BC	60–(120)	1.42	1.37	1.32	0.39	0.11	0.13	1.95	3.32	59

Profile 7 – Endoskeletic Albic Stagnic **Luvisol** (Aric, Cutanic, Endoloamic, Ochric, Episiltic, Endoraptic)
Localization: Footslope, inclination 5-10°, exposition N, pasture (formerly arable), grass vegetation, 660 m a.s.l., **N** 50°46'00.4" **E** 15°45'27.5"



Morphology:

Ap – 0–20 cm, plough layer (humus horizon), dark grey (10YR 4/2, moist), silt loam, few fine gravels (granite), fine-medium moderate granular structure, abundant fine roots, clear irregular boundary;

Eg1 – 20–38 cm, eluvial horizon, pale brown (10YR 7/3 moist), silt loam, few fine gravels, fine blocky subangular structure, many fine roots; few redoximorphic features; gradual boundary;

Eg2 – 38–50 cm, eluvial horizon, yellowish brown (10YR 6/4 moist), silt loam, few fine gravels, fine blocky subangular structure; many redoximorphic features (stagnic properties), including Fe-Mn fine soft accumulations; gradual and smooth boundary;

Btg – 50–73 cm, *argic* horizon, brown (7.5YR 5/5 moist), loam, many fine and medium gravels, medium blocky angular structure, many clay cutans on aggregates, few fine roots, many redoximorphic features (stagnic properties), gradual and smooth boundary;

2BCg – 73–(110) cm, transitional horizon, light brown (7.5YR 6/4 moist), sandy loam, abundant fine and medium gravels (granite), medium blocky angular and platy structure, few clay cutans, weak redoximorphic features, no roots.

Table 13. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
Ap	0–20	12	2	8	9	11	16	27	21	4	2	SiL
Eg	20–50	16	3	7	9	10	15	25	20	5	6	SiL
Btg	50–73	40	5	6	8	8	15	23	19	5	11	L
2BCg	73–(120)	80	8	9	9	14	16	17	13	4	10	SL

Table 14. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		CaCO$_3$ [g·kg^{-1}]
					H$_2$O	KCl	
Ap	0–20	26.8	1.41	19	4.77	3.93	-
Eg	20–50	8.76	0.38	23	5.27	4.34	-
Btg	50–73	4.13	n.d.	-	5.55	4.56	-
2BCg	73–(120)	1.68	n.d.	-	5.71	4.79	-

Table 15. Base cations and base saturation

Horizon	Depth [cm]	AE	Al^{3+}	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	BC	ECEC	BS
		[cmol(+)kg^{-1}]								[%]
Ap	0–20	3.09	2.96	1.52	0.43	0.08	0.08	2.11	5.07	42
Eg	20–50	1.82	1.78	2.00	0.38	0.07	0.09	2.53	4.31	59
Btg	50–73	1.00	0.97	2.56	0.52	0.06	0.10	3.23	4.20	77
2BCg	73–(120)	0.40	0.37	2.72	0.57	0.08	0.09	3.46	3.83	90

Profile 8 – Haplic **Luvisol** (Aric, Cutanic, Loamic, Ochric, Endoraptic)

Localization: Foot slope, inclination 6-12°, exposition N, meadow (formerly - arable field), grass vegetation, 620 m a.s.l., **N** 50°46'25.8" **E** 15°46'09.6"

Morphology:

Oi – 3–0 cm, grass litter, fibrous, undecomposed or partly decomposed;

Ap1 – 0–10 cm, upper plough layer (humus horizon), dark brown (10YR 3/3 moist), silt loam, few fine gravels (granite), dry, fine moderate granular structure, abundant very fine and fine roots, clear smooth boundary;

Ap2 – 10–26 cm, bottom plough layer (humus horizon), greyish brown (10YR 4/3 moist), silt loam, few fine gravels (granite), dry, fine moderate blocky subangular structure, many fine roots, clear smooth boundary;

Bt1 – 26–60 cm, *argic* horizon, brown (10YR 5/6 moist), loam, few fine gravels (granite), dry, medium blocky subangular/angular structure, many clay cutans on aggregates, few fine roots, no redoximorphic features, gradual and smooth boundary;

Bt2 – 60–76 cm, *argic* horizon, yellowish brown (10YR 6/5 moist), loam, few medium gravels (granite), dry, medium blocky angular structure, many clay cutans on aggregates, few fine roots, no redoximorphic features, clear wavy boundary;

2BC – 76–(100) cm, transitional horizon, yellowish brown (10YR 5/5 moist), sandy loam, many fine and medium gravels (granite), dry, medium blocky angular and platy structure, few clay cutans, no redoximorphic features, no roots.

Table 16. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
Ap1	0–10	9	3	8	8	8	14	28	21	6	4	SiL
Ap2	10–26	10	3	7	9	8	15	27	22	5	4	SiL
Bt1	26–60	12	4	6	10	8	16	24	20	4	8	L
Bt2	60–76	14	5	8	10	11	12	22	19	4	9	L
2BC	76–(100)	26	8	10	9	14	18	13	11	5	12	SL

Table 17. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
Ap1	0–10	25.2	1.20	21	5.53	4.19	-
Ap2	10–26	21.1	0.92	23	5.78	4.38	-
Bt1	26–60	11.8	n.d.	-	5.94	4.53	-
Bt2	60–76	5.08	n.d.	-	6.12	4.75	-
2BC	76–(100)	2.17	n.d.	-	6.13	5.15	-

Table 18. Base cations and base saturation

Horizon	Depth [cm]	AE	Al^{3+}	Ca^{2+}	Mg^{2+}	K^+	Na^+	BC	ECEC	BS
		[cmol(+)kg^{-1}]								[%]
Ap1	0–10	1.95	1.84	1.52	0.51	0.12	0.09	2.24	4.08	55
Ap2	10–26	1.27	1.22	2.48	0.53	0.11	0.10	3.22	4.44	73
Bt1	26–60	0.54	0.52	3.20	0.45	0.09	0.10	3.83	4.35	88
Bt2	60–76	0.43	0.41	2.88	0.55	0.09	0.09	3.60	4.01	90
2BC	76–(100)	0.15	0.12	3.76	1.01	0.13	0.13	5.02	5.12	98

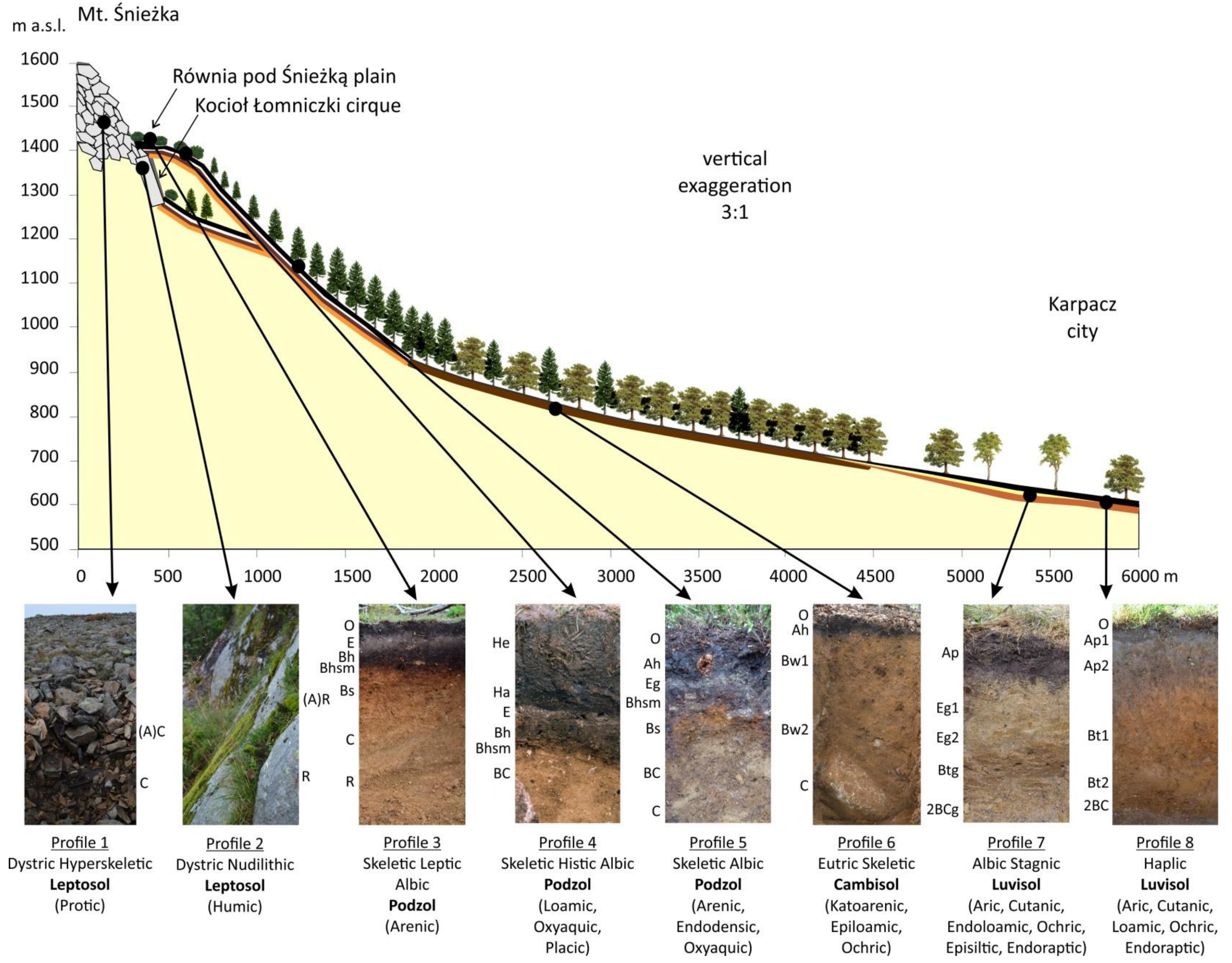


Fig. 2. Topoclimatic soil sequence in the northern slopes of the Karkonosze Mountains

Climate

Mean annual air temperature decreases from 7.9 °C at the foothills to 0.4 °C on Mt Śnieżka. The decrease in temperature with elevation is 0.59 °C per 100 m of altitude (on average). The mean annual precipitation increases from 700-750 mm in the foothills to approx. 1500 mm in the highest parts. July is the warmest and the moist month of the year, January – the coldest one. The duration of the snow cover period varies from 60-65 days in the foothills, up to 180-200 days in the upper forest zone (Sobik et al., 2013).

Land use

Five natural climate-induced vertical vegetation zones, which are typical of mid- and high mountains of Central Europe, are recognisable in the Karkonosze Mts; however, land and forest management have strongly influenced the species composition in all zones. Natural broadleaf forests in the sub-mountain (foothill) zone (<500 m a.s.l.), presumably *Galio–Carpinetum* and *Luzulo–Quercetum* communities, are preserved fragmentarily due to the common agricultural use of land at this altitude (Danielewicz et al., 2013). The lower mountain forest zone (500–1,000 m a.s.l.), potentially a habitat for *Luzulo–Fagetum* and *Abieti–Piceetum* communities, is in a large part covered by human-introduced mono-species Norway spruce stands. The upper mountain forest zone (1,000–1,250 m a.s.l.) is, due to its climate, naturally dominated by a *Calamagrostio villosae–Piceetum* community with Norway spruce as the prevailing tree species. The sub-alpine zone (1,250–1,450 m a.s.l.) is a mosaic of phytocenoses with shrubs of mountain pine (*Pinetum mugo sudeticum*) and matgrass–meadows (*Carici–Nardetum*), with several unique communities on bogs and in glacial cirques. The alpine zone (1,450–1,603 m a.s.l.) covers only small areas around the highest peaks and is represented by herbaceous communities such as "sparse meadows" with mountain rush (*Carici–Festucetum airoidis*). As a result of a so-called ecological disaster, thousands of hectares of spruce stands in the Sudeten Mountains were damaged in the 1970s–80s.

Soil genesis and systematic position

The soil profiles included in the sequence illustrate the spatial diversity of soils in the northern slopes of the Karkonosze Mountains, which developed under the join influences of parent material, topography, climate, vegetation, and land use.

Profile 1 is located in the upper slope of the highest peak – Mt Śnieżka – which is covered with a thick layer of hornfels rock debris (a "stone sea"). The original regolith has been deeply leached from fine-earth particles (possibly by subsurface suffosion), and thus the present-day cover has an open-work structure (lack of fine earths in the spaces between stones). There is no horizontal differentiation down to a depth of 100 cm, and the soil was thus classified as ***Hyperskeletic* Leptosol** with the supplementary qualifier ***Protic***. The incidental mineral infilling, where present, has an acidic reaction (***Dystric*** qualifier). The stone cover is relatively stable due to the lack of "plastic" infilling and its low water capacity, thus the locally recognisable segregation of the rock fragments was possible probably under periglacial conditions, when densified snow infilled the stone cover and allowed the specific liquefaction, i.e. the liquid-like flow of non-liquid materials (Traczyk and Migoń, 2003). In conjunction with the harsh climate of the alpine zone, ***Dystric Hyperskeletic* Leptosols** that developed from stone/boulder covers in the Karkonosze Mountains (both on hornfels and on granite bedrocks) create a particularly unfriendly habitat for vegetation and for any land use. The upper parts of the stone/boulder covers are sparsely covered with only a few species of lichens, grasses and other plants. The vegetation cover is thicker only in the isolated sites of fine-earth accumulation. Additionally, in the lower zone of the "stone sea", where the accumulation of fine earths and organic residues is more intense and the climate less harsh, the mountain pine shrubs form a typical vegetation (Żołnierz and Wojtuń, 2013) and soils often have the ***Folic*** qualifier, or may even transform to ***Hyperskeletic Folic* Histosols** (Kabała et al., 2013).

"Micro-profile" 2 was situated in the upper part of granite walls at an altitude of ca. 1,400 m a.s.l. Rock walls are uncommon in Variscian orogens, which are considered relatively old mountains and more "smooth" as compared to Alpine orogens (Traczyk and Migoń, 2003). The rock walls in the Karkonosze Mts were developed during the Pleistocene period: the steep, high and continuous walls were excavated by mountain glaciers in large glacial cirques, while the discontinuous rock walls were created in so called "nival niches" or smaller cirques. The walls have been subjected to physical (frost) weathering and still maintain "fresh" (chemically un-weathered) surfaces. The steep walls have regularly been "cleaned" of finer particles by rain and melting waters, and thus only a little volume of sandy regolith and organic debris may accumulate in cracks or concave shelves, as a layer of a few centimetres thick (**Leptosol**), while hard rock is predominantly exposed at the wall surface (***Nudilithic*** qualifier). The acidic reaction of the accumulated soil justified the ***Dystric*** qualifier, while its enrichment with organic residues warranted the ***Humic*** supplementary qualifier.

Soil profile 3 was situated on a gently undulating summit plain (Równia pod Śnieżką, 1,370 m a.s.l.) created by the intense removal of older saprolites, possibly by the Pleistocene mountain glaciers (Traczyk and Migoń, 2003). Presently, the plain is formed of relatively thin, highly skeletal regolith, and allogenic additions (e.g. aeolian silt) are absent or insignificant. The soil profile is developed typically for **Podzols**, i.e. has a litter layer underlain by a light-grey eluvial horizon (***Albic*** qualifier), and a thick illuvial horizon, subdivided into three subhorizons: Bh – dark brown, dominated by humus illuviation; Bhsm – strong brown, enriched with organic matter and Fe/Al, partly cemented (specifically, as numerous very thin [<1 mm] iron pans instead of massive *ortstein*); and Bs – a rusty brown subhorizon with prevailing Fe and Al accumulation and relatively insignificant enrichment with humus (Table 2). At least the Bh and Bhsm layers meet the morphological and chemical criteria for a *spodic* horizon, which is crucial for **Podzol** identification. The soil is developed from granite regolith and is highly skeletal (42–67%) throughout the profile (***Skeletic*** qualifier) down to the hard rock present at a depth of ca 60 cm (***Leptic*** qualifier). The soil also has the typical physicochemical properties for the granite-derived Podzols of the subalpine zone: acidic reaction (pH 4.0–4.8) and low base saturation (15–40%) throughout the profile, both increasing with depth; low sum of base cations (<1.4 cmol[+] kg^{-1}), but with high exchangeable acidity and exchangeable aluminium that were both highest in the topsoil and rapidly decreased below the Bhsm horizon (table 2).

The summit plains in the Karkonosze Mts are locally (in flat depressions) covered with peatbogs. Histosols prevail in the central part of the bog, where the peat thickness exceeded 40 cm (*hemic*) or 60 cm (*fibric* material); by contrast, various transitional soils have developed at the edge of peatbog. The soil in profile 4 has an organic layer (peat) of 25 cm thick that allows a ***histic*** horizon (and qualifier) to be identified, but is not enough to classify the soil as Histosol. The soil has an illuvial B horizon consisting of two subhorizons: greyish brown Bh (organic matter accumulation prevails over Fe/Al accumulation) and brown Bhs (significant accumulation of Fe and Al). Both subhorizons meet the morphological and chemical criteria for a *spodic* horizon, which allowed the soil to be classified as a **Podzol**. ***Spodic*** is overlain by a thin, grey, eluvial horizon consisting of ***albic material*** (***Albic*** qualifier). The soil is developed from relatively homogeneous material – the regolith is of granite, and has a prevailingly sandy loam texture (***Loamic*** supplementary qualifier) and a high content of fine/medium angular granite fragments (***Katoskeletic*** qualifier). Only the topsoil layer (eluvial horizon) consists of coarser sandy and less skeletal material, which was possibly accumulated in the course of local fluvial processes before the peatbog started to grow. The unique feature of **Podzols** represented by profile 4 is the presence of a thin iron pan at the contact between the Bh and Bhs subhorizons. This *placic* layer is impermeable to roots and water, and thus the soil above the *placic* is wet, whereas the material below it is dry and free of redoximorphic features. The E and Bh horizons, even if permanently wet and covered with peat, do not meet the criteria for stagnic or gleyic properties required by the WRB classification (IUSS Working Group WRB, 2015) due to coarse sandy texture or high content of ("masking") humus. Therefore, the ***Oxyaquic*** qualifier was added. It is still unclear whether the peat started to grow first, which accelerated Fe leaching and *placic* formation, or, conversely, whether the climate moistening led first to enhanced soil leaching and *placic* formation, which resulted in permanent water stagnation at the soil surface, which in turn allowed peatbog development. Palynological and geochemical analysis of sediments from the nearby Wielki Staw lake suggests an early Holocene development of **Podzols** and then climate moistening and peatbog formation (Malkiewicz et al., 2016). However, this finding does not explain the age of the *placic* layers.

Similarly, the upper forest zone has a cold and wet climate that induces overmoistening of topsoil and accumulation of undecomposed litter, as exemplified in profile 5 from 1,170 m a.s.l. Poor granite bedrock, moist climate and spruce forests favoured the podzolisation process that led to diversification of the profile into an eluvial layer (consisting of *albic material*, thus justifying the **Albic** qualifier) and illuvial Bhs/Bs layers that meet the criteria of a *spodic* horizon, which is diagnostic for **Podzols**. The near-surface overmoisture could result either from (partial) cementation of the *spodic* horizon with Fe compounds, or from mechanical compaction of the subsoil, which in both cases creates a barrier to water and plant roots (***Endodensic*** qualifier). Due to the same reasons as in profile 4, stagnic or gleyic properties are not evident despite prolonged water saturation, and thus the ***Oxyqauic*** qualifier was added. The soil has a high content of angular granite gravels and stones (***Skeletic*** qualifier) and a prevailing loamy sand texture (***Arenic*** qualifier) that is astonishing when juxtaposed with its compactness (in the subsoil). Podzols in the upper forest zone have not developed from autogeneous granite regolith (as profiles 3 and 4), but from slope cover beds, as exemplified by: the large density (compactness) of the subsoil (which is considered to be a solifluction layer); the predominance of angular, unweathered rock fragments; and the lack of granite regolith (lack of groat-like structure).

Soils in the lower slopes are also developed from granite; however, the climate is not so harsh, and broadleaf (beech) forests prevail instead of spruce stands, which resulted in a weaker soil leaching and uncommon podzolisation. Thick subsurface B horizons in the soils of this zone, as exemplified in profile 6, have a sandy loam texture, well developed blocky subangular structure, and more saturated colour chroma than the subsoil. The presence of the above justified the *cambic* horizon, the lack of mollic/umbric topsoil horizon, and lack of illuvial spodic/argic diagnostic horizons being classified as **Cambisols**. The soil has a prevailing high base saturation (>50%) down to a depth of 100 cm (***Eutric*** qualifier), high content (>40%) of granite fragments (***Katoskeletic*** qualifier) and sandy loam texture over the loamy sand (***Epiloamic*** and ***Katoarenic*** qualifiers, respectively). The topsoil humus layer has variable thickness of 5–10 cm, but averaged organic carbon content over the upper 10 cm justified the ***Ochric*** qualifier. The additional confirmation of the high biological activity of these ***Eutric*** **Cambisols** is the mull humus, featuring thin Oi and Oe layers, lack of Oa layer, and fine-granular structure in A horizon. Locally, the soil surface is 20–40% covered with granite boulders. The angular shapes of boulders indicate their periglacial origin and confirm the importance of slope mass-movement in the formation of slope cover beds.

Profiles 7 and 8, from the lower part of the northern slope (foothill), have a finer texture – silt loam over loam or sandy loam, probably due to large-scale erosion/accumulation phenomena and possible addition of aeolian silt (Waroszewski et al., 2015, 2016). The parent material of these soils is not a "regolith", but a stratified cover bed formed in the course of various geomorphological processes. It is unclear whether all such cover beds meet the criteria of colluvium as defined in the WRB classification (IUSS Working Groups WRB, 2015), so the qualifier Colluvic has not been applied to these soils. A moist mountainous climate and broadleaf forest vegetation led to subsurface clay translocation in loamy soils situated on gently inclined slopes, where water may infiltrate the soil profile. Profile 7 has a "completely" developed (and preserved) sequence of horizons: humus layer thickened up to 20 cm by ploughing, eluvial and illuvial horizons. The illuvial layer has >8% of clay and abundant clay cutans on structural aggregates (*argic* horizon). The presence of *argic* and high base saturation (>50%) prevailing down to a depth of 100 cm allow soil classification as **Luvisols**. An eluvial layer is depleted of clay and is lighter in colour (***Albic*** qualifier) and has redoximorphic features, in particular in its lower part (***Stagnic*** qualifier). These features are present also in Btg and 2BCg horizons; however, the intensity of the redoximorphic mosaic is not large enough in the upper 50 cm to classify the soil as a Stagnosol. The soil has a high content of rock fragments below a depth of 50 cm (***Endoskeletic*** qualifier), and a silt loam texture above the loam and sandy loam (***Episiltic*** and ***Endoloamic*** qualifiers, respectively). An abrupt change in soil texture, skeleton content and shapes of rock fragments was identified at a depth of 73 cm (***Endoraptic*** qualifier). Although rich in organic carbon (ca. 2.7%), the topsoil humus layer, which is ploughed down to 20 cm (***Aric*** qualifier), is not enough dark to meet the criteria for an umbric horizon (thus the ***Ochric*** qualifier).

The **Luvisol** in profile 8 has an "incomplete" sequence of horizons: a humus layer thickened by ploughing is directly underlain by an illuvial horizon, whereas the eluvial layer is missing. Such A–B–C order makes them similar to Cambisols, and many of these soils have previously been classified as "brown soils". However, the subsurface B layer has abundant clay cutans on structural aggregates, ≥8% of clay fraction and a thickness of at least 50 cm, i.e. it meets the criteria for an *argic* horizon. Taking into account the high base saturation (>50%) throughout the profile, the soil may be classified as a **Luvisol**. The lack of eluvial horizon justifies the ***Haplic*** qualifier. Unlike other soils in the catena, profile 8 has too low a content of rock fragments for the ***Skeletic*** qualifier. The prevailing texture is loam over sandy loam (***Katoloamic*** qualifier), while silt loam is present in the 26-cm-thick topsoil only, which is too thin to indicate a different texture class. The abrupt change in soil texture, skeleton content and shapes of rock fragments was identified at a depth of 76 cm (***Endoraptic*** qualifier). Although rich in organic carbon (>2%), the topsoil humus layer, which is ploughed down to 26 cm (***Aric*** qualifier), is not enough dark to meet the criteria for a mollic horizon (thus the ***Ochric*** qualifier).

The mountain Luvisols represented by profiles 7 and 8, although acidic, have a texture and physicochemical properties that for many crops are beneficial (including high base saturation and narrow C:N ratio), and have been farmed since at least the 18th century, as slope inclination and low skeleton content allowed. Some intensely farmed soils on steeper slopes (profile 8) have been eroded and have an "incomplete" sequence of genetic horizons (Świtoniak et al., 2016). Presently, many of these soils are abandoned and reforested, or used as extensive pastures and "ecological" meadows.

Soil sequence

The sequence of soil profiles in the northern slopes of the Karkonosze Mountains shows a typical altitude- and climate-related soil zonality that influences the direction and intensity of geomorphological processes and vegetation cover. Thus, the altitude and climate influence the soil development both directly and indirectly. Profiles 1 – ***Hyperskeletic*** **Leptosol** and 2 – ***Nudilithic*** **Leptosol** are located in the highest, alpine zone of the Karkonosze Mts, where the low temperatures eliminate protective vegetation cover, while high precipitation accelerates the removal of weathering products. The soils are permanently at the initial stage of development. The subalpine zone and upper forest zone have a climate that is cold and moist, but not as extreme as in the alpine zone, and this allowed coniferous forests or shrubs to grow and the podzolisation process to develop. This altitude zone is therefore dominated by **Podzols**, whose morphology and properties depend on local topography and moisture accumulation. ***Albic*** **Podzols** (profile 3) predominate in well drained positions on the summit plain, whereas ***Histic*** **Podzols** (profile 4) are present in local depressions and the transitional zones to peatbogs. The ***Albic*** **Podzols** (profile 5) on the slopes, which developed on compacted cover beds, have impermeable subsoil and an ***Oxyaquic*** characteristic in the topsoil. The lower forest zone – populated by climate-controlled mixed or beech forests, giving less favourable conditions for podzolisation – is dominated by **Cambisols** (profile 6). The foothill zone with a climate that is moist, but not as cold as in upper zones, was originally covered by broadleaf forests, including beech stands. The moist climate and native vegetation led to the leaching of base cations and clay from the topsoil of the loamy and silty soils, and the development of **Luvisols**. Extensively used ***Albic*** **Luvisols** (profile 7) comprise a complete sequence of genetic horizons (A–E–Bt–C), often with stagnic properties, while the intensely farmed soils lost the eluvial layer (presumably due to sheet erosion) and have the sequence of horizons Ap–Bt–C typical of ***Haplic*** **Luvisols** (profile 8). Therefore, the altitude-, climate-, and topography-related large-scale vertical zonality in the northern slopes of the Karkonosze Mountains comprises the following soil groups: **Leptosols** – **Podzols** – **Cambisols** – **Luvisols**.

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Forest areas within a sandy glaciolacustrine plain of the middle course of the Nemunas river, Lithuania

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The study area is situated on a glaciolacustrine plain of the Late Weichselian glaciation, Baltija stage, South Lithuanian Phase (Basalykas, 1965; Guobytė, 2011). The investigated soil parent material, i.e. glaciolacustrine sediments, were formed close to the edge of an ice-meltwater lake that was dammed from the southeast by ridges of marginal glacial deposits (Baltija Highlands) of the last glacial maximum and from northwest by a glacier in the Middle Lithuanian phase of the same glaciation.

Fig. 1. Location

Lithology and topography

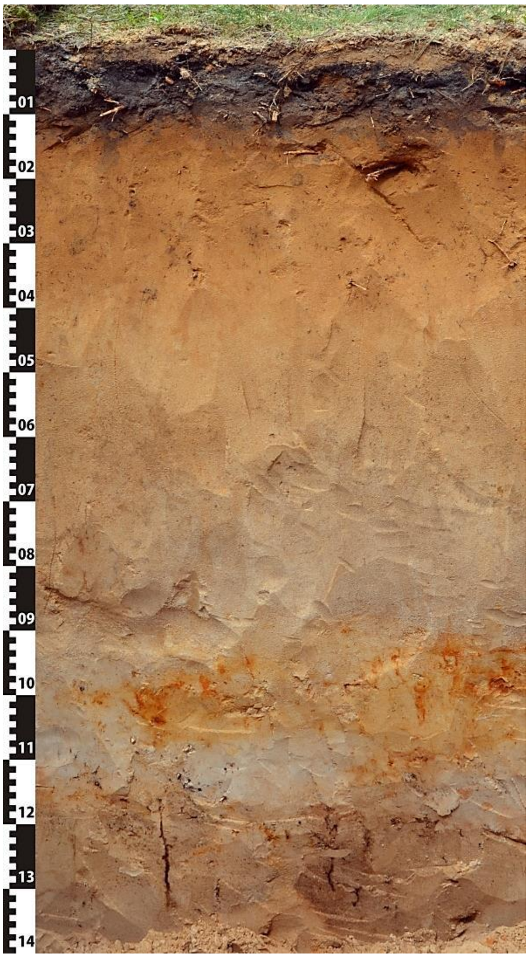
The small and shallow ice-melting (72–85 m a.s.l.) lake deposits are dated from 14,600 to 12,000 years BP and consist of fine sand in the upper layer turning to very fine-grained sand with depth. The relatively coarse texture on the top of the sediments indicates that an ice-dam position existed not very far to the east, and therefore the formation of the fine grained melt-lake deposits was impacted at times by fluvial, and later by aeolian processes (Basalykas, 1965).

The primary glaciolacustrine relief developed later, during the Holocene – the plain surface was carved by small flows and light valleys appeared as a result, while wet depressions were covered by peat. The present relief of the investigated area could be described as an undulating plain, characterised by almost flat, low hummocks of up to 2 m high, and could be attributed to the particular geomorphological micro-region of the Garliava glaciolacustrine sandy plain (Guobytė, 2013).

Land use

At the time of writing, (2018) the investigated area belongs to the Public Institution Dubrava Experimental-Training Forest Enterprise (established in 1957). After returning part of forests to previous owners, the Dubrava Forest Enterprise currently administers 13,613 ha of state forests in an area of 58,000 ha (0.68 percent of the country's territory) on the left bank of the Nemunas river. The large diversity of the soil in the territory of the forest enterprise allowed the formation of different types of stands. The forest enterprise with all the species at its disposal in some way reflects the diversity of the entirety of Lithuania's forests (Kulbokas et al., 2018; Lietuvos miškų ūkio statistika, 2017). Even so, the area is dominated by coniferous stands, which occupy 70% of the total stands (respectively, 42% for pine and 28% for spruce stands). Birch (11%) and black alder (11%) predominate among soft deciduous trees, while the other softwood species make up a rather small percentage (about 4%).

Profile 1 – Dystric Brunic **Arenosol** (Ochric, Raptic, Protospodic, Endogleyic)
Localization: Dubrava, sandy glaciolacustrine plain, summit-inclination 0,5°, coniferous forest, 73 m a.s.l.,
N 54°49'30.50" **E** 24°03'41.00"



Morphology:

O – 8–0 cm, organic horizon, divided into 3 subhorizons (Oi, Oe, Oa);

AE – 0–10 cm, humic horizon, fine sand, dark gray (10YR 4/1), fine subangular weak structure, few roots, clear and wavy boundary;

Bs – 10–15 cm, illuvial horizon, fine sand, dark yellowish brown (10YR 4/6), fine subangular weak structure, pH 5, few roots, clear and wavy boundary;

Bw – 15–40 cm, *in-situ* accumulation horizon, fine sand, reddish yellow (7.5YR 6/8), single grain structure, many sesquioxides coatings on coarse fragments, very few roots, gradual and wavy boundary;

BC – 40–90 cm, transitional horizon, fine sand, very pale brown (10YR 7/4), single grain structure, clear and wavy boundary;

2Cl – 90–115 cm, parent material with gleyic properties, very fine sand, very pale brown (10YR 7/3) with mottling 10 % - yellowish red (5YR 5/8), single grain structure, very few roots, common concentrations of soft iron concretions, clear and wavy boundary;

2Cl2 – 115–(145) cm, parent material with gleyic properties, very fine sand, light yellowish brown (10YR 6/4), single grain structure, few soft iron-manganese concretions.

Table 1. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
O	8–0	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.	-
AE	0–10	0	4	4	21	65	4	1	1	0	0	FS
Bs	10–15	0	1	2	18	70	7	1	1	0	0	FS
Bw	15–40	0	0	0	8	82	7	1	1	1	0	FS
BC	40–90	0	0	1	25	70	3	1	0	0	0	FS
2Cl	90–115	0	0	1	3	55	34	2	2	2	1	VFS
2Cl2	115–(145)	0	0	0	1	76	20	1	1	1	0	VFS

Table 2. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
O	8–0	357	13.3	27	3.6	3.1	-
AE	0–10	26.6	1.18	22	4.2	3.5	-
Bs	10–15	-	-	-	5.0	4.3	-
Bw	15–40	-	-	-	5.1	4.7	-
BC	40–90	-	-	-	5.5	5.0	-
2Cl	90–115	-	-	-	5.0	4.8	-
2Cl2	115–(145)	-	-	-	5.0	4.8	-

Profile 2 – Albic **Podzol** (Arenic, Drainic, Bathygleyic)

Localization: Dubrava, sandy glaciolacustrine plain, summit-inclination 0,5°, coniferous forest, 72 m a.s.l.
N 54°49'27.02" **E** 24°03'34.60"

Morphology:

O – 6–0 cm, forest litter;

Ah – 0–8 cm, humus horizon, very fine sand, dark gray (10YR 4/1), weak subangular fine structure, abrupt and smooth boundary;

E – 8–25 cm, *albic* material, very fine sand, light gray (10YR 7/1), weak subangular fine structure, gradual and wavy boundary;

EB – 25–35 cm, transitional horizon, very fine sand, brown (7.5YR 4/3), weak subangular fine structure, gradual and smooth boundary;

Bhs – 35–45 cm, *spodic* horizon, very fine sand, yellowish red (5YR 4/6), moderate subangular fine structure, iron-organic coatings, gradual and smooth boundary;

Bs – 45–70 cm, illuvial horizon, very fine sand, weak subangular fine structure, strong brown (7.5YR 4/6), iron coatings, diffuse boundary;

BC – 70–95 cm, transitional horizon, very fine sand, brownish yellow (10YR 6/6), single grain structure, diffuse boundary;

C – 95–125 cm, parent material, very fine sand, light reddish brown (2.5YR 6/4) single grain structure, diffuse boundary;

Cl – 125–(160) cm, very fine sand, light reddish brown (2.5YR 6/4), parent material with gleyic properties, single grain structure, illuvial lamellae.

Table 3. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
O	6–0	-	-	-	-	-	-	-	-	-	-	-
Ah	0–8	0	6	9	20	55	5	2	1	1	1	FS
E	8–25	0	0	1	17	70	8	1	1	1	1	FS
EB	25–35	1	0	1	21	69	5	1	1	1	1	FS
Bhs	35–45	0	1	1	31	61	4	1	1	0	0	FS
Bs	45–70	0	0	0	30	68	1	1	0	0	0	FS
BC	70–95	0	0	0	14	80	5	1	0	0	0	FS
C	95–125	0	0	0	17	81	2	0	0	0	0	FS
Cl	125–(160)	0	0	0	11	84	4	1	0	0	0	FS

Table 4. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [$g \cdot kg^{-1}$]	Nt [$g \cdot kg^{-1}$]	C/N	pH		$CaCO_3$ [$g \cdot kg^{-1}$]
					H_2O	KCl	
O	6–0	457	16.8	27	4.0	3.5	-
Ah	0–8	104	04.9	21	3.7	2.8	-
E	8–25	-	-	-	4.5	3.6	-
EB	25–35	-	-	-	4.4	3.6	-
Bhs	35–45	-	-	-	4.7	4.1	-
Bs	45–70	-	-	-	4.9	4.5	-
BC	70–95	-	-	-	4.9	4.5	-
C	95–125	-	-	-	5.1	4.5	-
Cl	125–(160)	-	-	-	4.9	4.5	-

Profile 3 – Folic Albic **Podzol** (Arenic, Bathygleyic)
Localization: Dubrava, sandy glaciolacustrine plain, summit-inclination 0.5°, coniferous forest, 71 m a.s.l.,
N 54°49'30.00" **E** 24°03'35.60"

Morphology:

O – 10–0 cm, pH 4.0, very dark brown (10YR 2/2), clear and smooth boundary;

A – 0–15 cm, fine sand, black (10 YR 2/1), weak subangular fine structure, dry, very few roots, clear and smooth boundary;

E – 15–25 cm, *albic* material, fine sand, light brownish gray (10YR 6/2), single grain structure, dry, clear and smooth boundary;

Bhs – 25–65/37 cm, spodic horizon, fine sand, dark reddish brown (5YR 3/4), single grain structure, slightly moist, clay and humus common coatings, iron organic matter cementation, gradual and wavy boundary;

Bs1 – 65/37–92 cm, *spodic* horizon, fine sand, strong brown (7.5YR 4/6), single grain structure, slightly moist, few sesquioxides coatings and bridges between sand grains, broken iron cementation, gradual and smooth boundary;

Bs2 – 92–125 cm, fine sand, light yellowish brown (2.5Y 6/4), single grain structure, moist, few sesquioxides coatings and bridges between sand grains, broken iron cementation, gradual and wavy boundary;

Bl – 125–137 cm, very fine sand, oxymorphic – brown (7.5YR 5/3), reductomorphic – light brownish gray (2.5Y 6/2), single grain structure, wet, gradual and smooth boundary;

Cl1 – 137–160 cm, parent material with gleyic properties, fine sand, pale brown (10YR 6/3), single grain structure, wet, gradual and smooth boundary;

Cl2 – 160–(175) cm, parent material with gleyic properties, fine sand, yellowish brown (10YR 5/4), single grain structure, very wet.

Table 5. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
O	10–0	-	-	-	-	-	-	-	-	-	-	-
A	0–15	0	5	7	17	57	9	2	1	1	1	FS
E	15–25	0	1	2	14	64	13	2	2	1	1	FS
Bhs	25–65/37	0	1	3	17	63	10	2	2	1	1	FS
Bs1	65/37–92	0	0	0	17	80	2	1	0	0	0	FS
Bs2	92–125	0	0	0	2	85	8	2	1	1	1	FS
Bl	125–137	0	3	8	6	55	18	3	3	2	2	FS
Cl1	137–160	0	0	0	0	87	3	1	0	0	0	FS
Cl2	160–(175)	0	0	1	40	57	1	1	0	0	0	FS

Table 6. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
O	10–0	429	15.3	28	3.9	3.0	-
A	0–15	71.5	3.1	23	3.7	3.1	-
E	15–25	-	-	-	4.4	3.4	-
Bhs	25–65/37	-	-	-	4.3	3.9	-
Bs1	65/37–92	-	-	-	4.7	4.5	-
Bs2	92–125	-	-	-	4.7	4.7	-
Bl	125–137	-	-	-	4.7	4.2	-
Cl1	137–160	-	-	-	4.9	4.7	-
Cl2	160–(175)	-	-	-	4.9	4.7	-

Profile 4 – Dystric Rheic Epifibric Amphihemic **Histosol** (Endoarenic)
Localization: Dubrava, sandy glaciolacustrine plain, summit-inclination 0,5°, mixed forest, 70 m a.s.l.,
N 54°49'35.40" **E** 24°03'28.30"

Morphology:

Hi – 0–10 cm, *histic* horizon, slightly decomposed *fibric* organic material, moist, common roots, clear boundary;

He – 10–40 cm, *histic* horizon, moderately decomposed hemic organic material, moist, few roots, gradual boundary;

Ha – 40–70 cm, *histic* horizon, highly decomposed sapric organic material, moist, very few roots, clear boundary;

2Cr – 80 – (120) cm, fine sand, single grain structure, pH 4.5, clear boundary, reducing conditions, water table.

Table 7. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		CaCO$_3$ [g·kg^{-1}]
					H_2O	KCl	
Hi	0–10	45.151	1.65	27.4	3.9	3.0	-
He	10–40	47.475	1.72	27.6	3.9	2.8	-
Ha	40–80	42.94	1.81	23.7	4.1	3.0	-

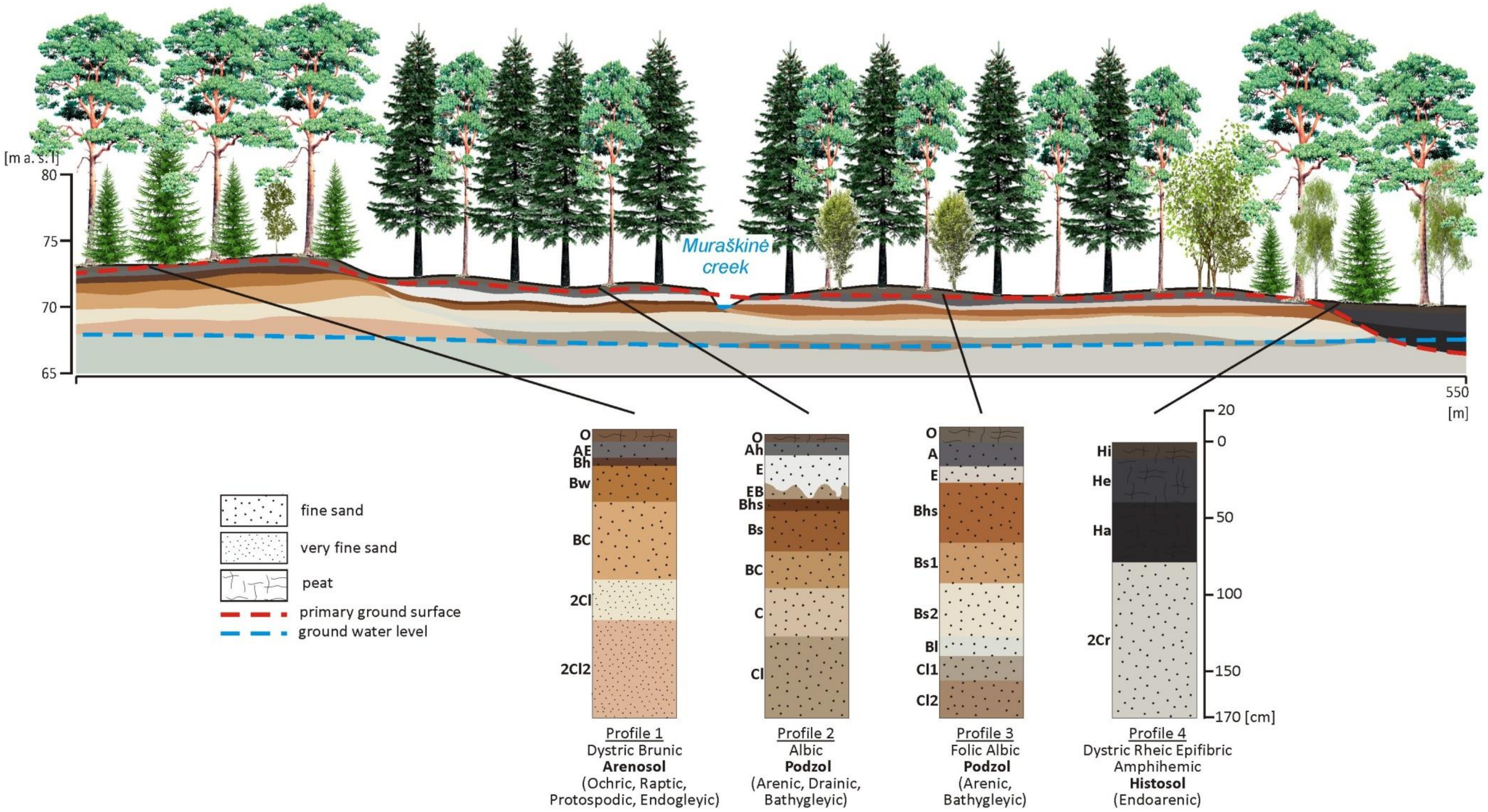


Fig. 2. Hydrotoposequence of soils within a sandy glaciolacustrine plain of the middle course of the Nemunas river

Hardwood grows in an area of 394 ha (3.2%), among which oak trees predominate. As any other Lithuanian forest enterprise, the Dubrava Forest Enterprise performs usual forestry activities in its administered forests: restoring, planting and felling forest, growing young stands, maintaining forest plantations and protecting from animals, and forest pest insects and diseases across an area of 400 ha, and performing sanitary and fire protection not only in all state forests, but also in private forests that fall under the territory controlled by the Forest Enterprise. Alongside routine forestry works, specific activities typical only of experimental and training forest enterprises are performed in Dubrava forests (Girios prie Nemuno slėnio, 2007).

Climate

The study area belongs to Vidurio žemumos (Middle Lowland) climatic region and the Nemumo žemupio (Nemunas river middle course) sub-region (Bukantis, 2016). The average annual temperature is 7.1–7.4 °C. The average temperature of the coldest months (January and February) is -3.6– -3.1 °C, while the warmest month is July (18.0–18.1 °C). Mean annual amount of precipitation is about 600–640 mm. Snow cover persists is 65–80 days, meanwhile, the sunshine duration is close to the average of Lithuania – about 1870 hours.

Soil genesis and systematic position

The soil cover of the southern part of the Baltic area is very diverse and complex. Stratigraphy, calcareousness, topography, vegetation and human activity are the main factors in this soil variety. Climatic conditions in the southern part of the Baltic area are favourable to many processes of soil formation, such as the forming process of brown soils, lessivation, podzolisation, pseudo-podzolisation, gleyification and bogging. In 1959, wider investigations focused especially on forest soils while carrying out cartographical work. It was elucidated at that time that the genesis of many soils is not clear. However, it was found that morainic drifts, glaciofluvial deposits and rocks without tills of glaciolacustrine origin are the most widespread parent rocks, while alluvial, aeolian and organogenic rocks occur significantly less (Vaičys, 1975).

Profile 1 is from an upper part of the inclined glaciolacustrine undulating sandy plain. This soil formed in a forest landscape in a comparatively wet and cold climate. The upper part of the soil is affected by aeolian processes. Although this is not clearly visible in the soil profile morphology, it does, however, present traces of >2 mm sand fraction in the 0–40 cm layer. Since the texture class coarser than loamy sand was detected to a depth of 100 cm from the mineral soil surface, the investigated soil profile was classified as an **Arenosol** (IUSS Working Group WRB, 2015). At a depth of 15–40 cm, the material has a texture class of sand, a pedogenetic structure, and alteration of colour (reddish compared to the directly underlying layer), and does not form part of another diagnostic horizon or plough layer. Taking into account all the above considerations, the ***Brunic*** qualifier was used. The pH values measured within 100 cm were at levels low enough to indicate that the soil could have low base saturation (<50%) and therefore the ***Dystric*** qualifier was also added to RSG.

The effect of groundwater on this soil formation is minimal. This is evidenced not only by the morphology of the soil (profile 3) but also by the growth of conifer forest (predominantly pines and also some spruce). However, there are obvious previous aeolian processes that led to the land area rising. Since the soil is formed at a higher elevation, groundwater may not significantly affect the leaching of iron oxides to the deeper horizons or layers. Automorphism determines the occurrence of iron oxidation only in the upper part of the soil, the accumulation of three-valent iron oxides and the formation of the Bw horizon. Since the soil is formed at a higher elevation, groundwater may not significantly affect the leaching of iron oxides to the deeper horizons or layers. Only in the lower part of the soil profile, where the fraction of small sand prevails are hydromorphic features and some iron concentration visible.

However, since this soil (profile 1) formation was going for a long time in comparatively dry conditions and under coniferous forest, the podzolic processes are very scarce and only visible in the AE horizon. The slow soil formation is visible at the relatively thin O horizon – of 8 cm (in Lithuanian climatic conditions the O horizon thickness may be 20–30 cm).

Profiles No. 2 and No. 3 illustrate how, in one case (profile 2), optimal water content in acid sandy deposits promotes the podzolic process, and in another case (profile 3), when there is an excess of ground water, it stops podzolic processes. These profiles are in the central part of the catena, which is gradually lowering. These profiles have no signs of aeolian processes, and in profile 2, in the upper part of the soil, the amount of >2-mm sand fraction is attributable to the processes of limonitisation and formation of persistent ferrous units because of a podzolic process. The fact that soil profile 2 gets more moisture and groundwater is involved in the soil formation, tells us that coniferous forest dominated by mature spruce grew here. Also at a depth of 110 cm in the soil there are ferrous-humus microfibers, which show short-term groundwater level fluctuations. This is a characteristic **Podzol** (a *spodic* horizon is present starting at the depth of 35 cm) showing that intensive and long-term podzolic processes occur in this place. The intensity is shown in the pretty well expressed Bhs–Bs–Bs1–Bs2 soil horizons, while the long-term influence is visible in the very thick (20–50 cm) E–EB horizons. The high amount of OC (10.5 %) is associated with higher moisture content, because of the relatively shallow depression in the terrain. To reflect the ≥1-cm-thick layer of light-coloured material from which organic matter and free iron oxides have been removed, and the fact that it starts ≤100 cm from the mineral soil surface, the ***Albic*** qualifier was used.

Soil profile 3 also fulfils the main requirements of **Podzols** (IUSS Working Group WRB, 2015). This is an another example of soil that was formed in the same forest and the same relief topo-system. However, profile 3 is situated in the lower part of the terrain and has therefore been influenced by intensified groundwater flow. This soil profile illustrates how excess moisture stops podzolic processes while in the lower part of the soil profile lower (from 125 cm) hydromorphic properties begin and soil formation is driven by reducing conditions. Despite the fact that the Bhs–Bs1–Bs2 part of the profile is thick and fairly well differentiated, in order to decide on the intensive podzolic processes, the E soil horizon is very thin compared with profile 2. This suggests that the impact of groundwater is influencing podzolic processes and impedes the leaching down of products. Soil profile 3, as with profile 2, was classified as an ***Albic*** **Podzol**. Since the organic matter layer (O) on the top of mineral material has a thickness of ≥10 cm, the ***Folic*** qualifier was added.

Profile 4 of the investigated catena is characterised by a comparatively cold humid climate and lower terrain position in slightly undulating sandy, gentle glaciolacustrine lowlands, and is an integral part of a hydrolithotoposequence. The investigated **Histosol** is formed in a shallow lowland (peat layer thickness up to 100 cm), on fine and silty glaciolacustrine sand. Its fineness increases the migration of water and creates a local hydromorphism – waterproof and aqueous conditions – which becomes the basis for Histosol formation. It is natural, and not drained. This is evidenced by the Histosol morphology. The upper layers are typical of slightly decomposed peat. This shows that the peat has a sufficient moisture regime from drying out and mineralisation. For Histosol layers, gradual peat decomposition going deeper down is typical; this shows that the Histosol evolved consistently and naturally without any significant anthropogenic impact. From the deeper, older, more decomposed peat, rising up, there is a change to younger, less decomposed peat.

Soil sequence

Soil hydrotoposequence analysis (Fig. 2) illustrates the evolution of soil sand plains into a forest landscape. This catena clearly shows the impact of terrain and groundwater on the main soil-forming processes, especially on podzolic process. Investigation of the catena reveals a genetic relationship between **Arenosols**, **Podzols** and **Histosols** formed in a cold and wet climate. The Podzolic process is predominantly zonal in sandy soil parent material formations of Lithuania. The lack or excess of moisture inhibits the podzolic process. The most favourable conditions for the podzolic process and formation of **Podzols** are found on acid sands in flat and lower areas in which groundwater is involved in soil formation. Weak gleyification (hydromorphism) and coniferous vegetation (especially – spruce) promotes the podzolic process (Vaičys, 2001).

In the presence of moisture deficiency, on the slightly undulating higher terrain locations in sandy deposits **Arenosols** are formed. Meanwhile, in lower areas where groundwater is close to the surface, the excess water will lead to peat formation. As a consequence this also leads to the formation of **Histosols**.

Summing up, it can be stated that the investigated hydrolithotoposequence catena illustrates soil complex series that are typical of sandy, slightly undulating, gentle glaciolacustrine plains, and express its development depending on the prevailing soil-formation factors. The given catena revealed that in those lowlands, the humidity and position of relief has a significant effect on the interaction between zonal and azonal soil-formation processes, whereas the transformation of **Arenosols** to **Podzols** and **Histosols** takes place in the landscape depressions.

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Soil sequence on sands filling the karst sinkhole in the north of the East European Plain

Maria Smirnova, Maria Gerasimova

Belomorsko-Kuloy Plateau on the northern periphery of the East European Plain is composed in its southeastern part by karsting rocks – Permian limestone, dolomite, anhydrite, gypsum (Spiridonova, 2007). The diversity of rocks subject to continuous dissolution in the course of time is responsible for the diversity of karst landforms (Goryachkin, Shavrina, 1997). Most common among them are sinkholes, their shape being conical, cup- or saucer-like; they have abrupt edges and symmetrical slopes with slope gradients ranging from 10° to 35°; their mean dimensions are: 15-25 m in diameter and 2-5 m in depth (Smirnova, Gennadiev, 2011). A particular feature of the area is that the karstland is covered by glacial sediments of the last glaciation (Valdai – Würm – Vistula; Goryachkin et al, 2003), and the overlying sediments in the research area are sands and loams. A slope of the karst sinkhole filled with sands was chosen as study object because of contrasting combination of soil parent material and underlying rock in the area with cold humid climate and coniferous forests.

Fig. 1. Location

Lithology and topography

Formation and evolution of karst topography in the study area was strongly affected by the series of Pleistocene glaciations, and by the Late Valdai glaciation and its subsequent degradation, specifically (Nikolaev, 1987, Malkov et al., 2001). The cover of Quaternary sediments testifies to its simultaneous (or subsequent) development with karst landforms (Goryachkin, Shavrina, 1997). Sands, presumably of glaciofluvial origin, are sometimes mixed with till derived of red Permian rocks. At the depth of more than 5 m, anhydrites and gypsum are interstratified with dolomites, red calcareous sandstones and siltstones of the Sotka suite of the Permian (Structure and dynamics…, 2000; Spiridonova, Goryachkin, 2011).

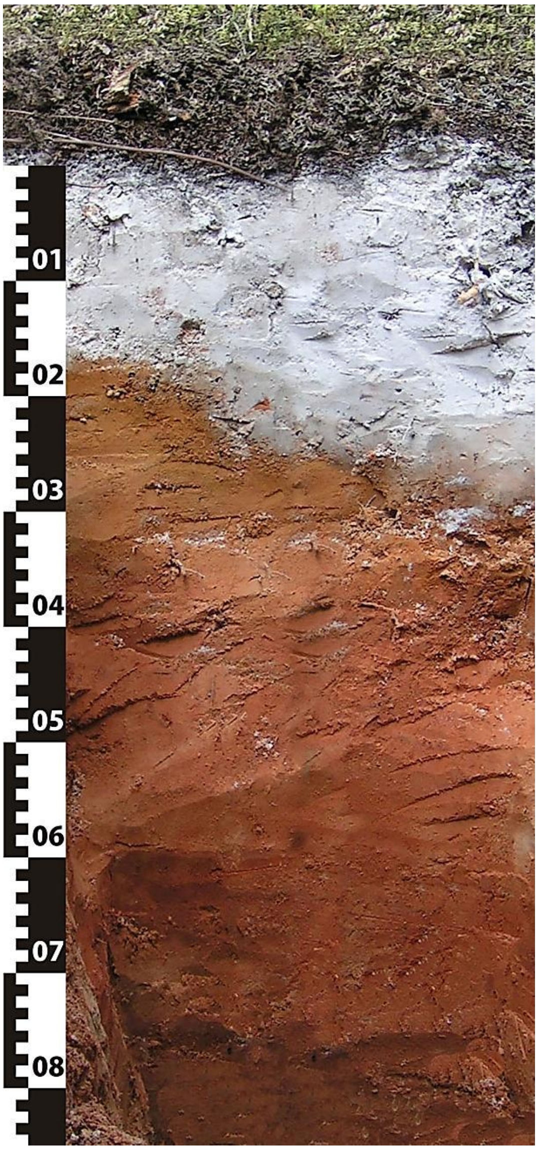
The sinkhole with soil sequence under study has a conical shape, and symmetrical even slopes 29° steep, which permits to qualify the sinkhole as a subsidence doline (Waltham et al., 2005, Ford, Williams, 2007). The length of the slope is 18 m, depth of the sinkhole – 9 m, diameter – 18 m.

Land use

The sinkhole is located in Pinega Natural Reserve arranged in 1972. Therefore, it is not possible to perform any economic activity there; moreover, it would be hardly possible because of well pronounced karst landscape. The inter-sinkhole areas with a thick sand cover (up to 5 m) are occupied by pine forests (*Pinus sylvestris),* often with admixture of birch and/or aspen (*Betula pendula* and *Populus tremula*, respectively); the ground cover mostly consists of green mosses, lichens and *Vaccinium* species. The sinkhole slopes are covered with blueberry (*Vaccinium myrtillus*), lichens (*Cladonia arbuscula* and *Cladonia rangiferina*) and green mosses (mostly *Pleurozium schreberi*).

Profile 1 – Folic Albic **Podzol** (Arenic, Chromic)

Location: subhorizontal inter-sinkhole surface 137 m a.s.l.; pine forest with spruce regrowth and few juniper bushes; lichens with green mosses, blueberry.
N 64°33'56.1" **E** 43°15'35.9"



Morphology:

O – 10–0 cm, loose organic layer, composed of weakly decomposed residues of mosses, lichens, pine needles and fine roots, pierced by roots, weakly moist to dry, clear and wavy boundary;

E – 0–25 cm, *albic* material, coarse sand, almost white (10 YR 8/1), weakly moist to dry, friable, single grain structure, few fine fragments of igneous rocks, few roots, abrupt wavy boundary;

Bsm1 – 25–32 cm, *spodic* horizon, coarse sand, yellowish red (5 YR 5/8), weakly moist, weak slightly angular crumbly structure, rather firm, common iron-manganic segregations: concretions, mottles some of them weakly cemented; few fine fragments of igneous rocks up to 5 mm in diameter, few fine roots, gradual boundary;

Bsm2 – 32–60 cm, coarse sand, reddish yellow (5 YR 6/6), weakly moist, massive structure, friable and slightly firm, few fine fragments of igneous rocks up to 12 mm in diameter, few fine roots, gradual boundary;

BC – 60–(80) cm, coarse sand, reddish yellow (5 YR 5/6) with pinkish gray mottles (5 YR 6/1) several cm in size, weakly moist, massive structure, friable and slightly firm, few fine fragments of igneous rocks up to 15 mm in diameter.

Table 1. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
E	0–25	3	1	33	48	3	2	6	4	1	2	CS
Bsm1	25–32	2	1	22	42	3	9	9	8	3	2	CS
Bsm2	32–60	3	1	25	41	3	7	6	13	1	3	CS
BC	60–(80)	3	3	27	38	4	6	10	9	2	1	CS

Table 2. Chemical and physicochemical properties

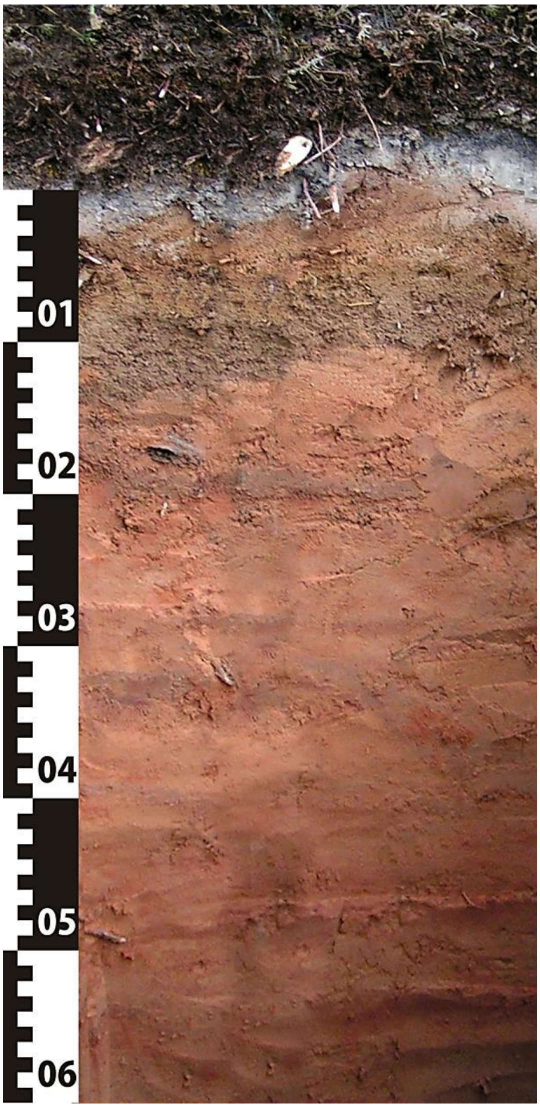
Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH H_2O
O	10–0	-	-	-	4.0
E	0–25	12.3	0.63	20	3.9
Bsm1	25–32	18.1	0.65	28	4.2
Bsm2	32–60	-	-	-	4.2
BC	60–(80)	-	-	-	4.5

Table 3. Elemental composition

Horizon	Depth [cm]	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	MnO	TiO_2	K_2O	P_2O_5
		[%]								
E	0–25	94.95	2.80	0.22	0.11	0.10	0.01	0.12	1.41	0.03
Bsm1	25–32	88.38	6.54	0.86	0.15	0.39	0.01	0.19	1.64	0.11
Bsm2	32–60	89.25	5.69	0.90	0.15	0.33	0.01	0.17	1.53	0.06
BC	60–(80)	91.31	5.21	0.88	0.17	0.28	0.01	0.15	1.59	0.08

Profile 2 – Folic Albic **Podzol** (Areninovic) over Rubic Brunic **Arenosol** (Colluvic)

Location: upper tier of the sinkhole slope – 3 m below the edge and 15 m down to the bottom (135 m a.s.l.), even slope surface with gradient of 29°; single young spruce trees, blueberries, lichen – green moss discontinuous cover
N 64°33'56.1" **E** 43°15'35.9"



Morphology:

Oi – 12–6 cm, loose organic layer composed of weakly transformed residues of mosses, lichens, pine needles and roots, weakly moist to almost dry, gradual boundary;

Oe – 6–0, loose organic layer composed of weakly and moderately transformed organic residues, weakly moist, densely pierced by roots, clear and wavy boundary;

E – 0–4 cm, *albic* material*,* coarse sand, light gray (7.5 YR 7/1), weakly moist, loose and friable, single grain structure, few fine fragments of igneous rocks, very few roots, gradual and wavy boundary;

Bs – 4–9 cm, *spodic* horizon, coarse sand, yellowish red (5YR 5/6), weakly moist, weak angular crumbly structure, firm, common iron-manganic soft concretions, few fine fragments of igneous rocks up to 5 mm in diameter, common fine roots of varying size, clear and wavy boundary;

2Ahb – 9–19 cm, buried humus horizon, coarse sand, light reddish brown (5YR 6/3), weakly moist, weak crumbly structure, rather firm, few brown ocherous mottles, few fine fragments of igneous rocks up to 10 mm in diameter, few fine roots, clear and wavy boundary;

2C – 19–(60) cm, buried colluvium, coarse sand, reddish yellow (5YR 6/6) with subhorizontal partly discontinuous layers with diffuse boundaries, about 1.5 cm thick, with 10-15 cm between them - loamy sand, reddish gray (5YR 5/2), weakly moist, massive, friable to weakly compact, few fine fragments of igneous rocks up to 15 mm in diameter.

Table 4. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
E	0–4	2	3	38	44	3	2	4	3	2	1	CS
Bs	4–9	3	2	25	36	5	8	7	10	4	3	CS
2Ahb	9–19	2	1	31	38	4	6	8	7	3	2	CS
2C	19–(60)	3	2	26	35	7	7	8	8	4	3	CS

Table 5. Chemical and physicochemical properties

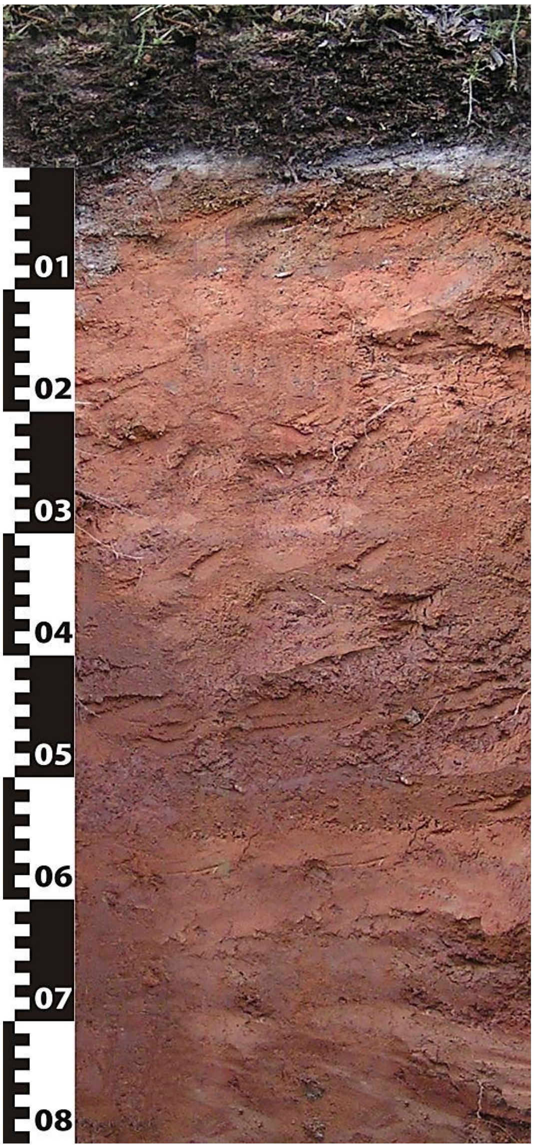
Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH H2O	FeO [g·kg-1]
O	12–6	-	-	-	4.1	-
Oe	6–0	-	-	-	4.0	-
E	0–4	5.0	0.35	14	3.9	1.5
Bs	4–9	8.8	0.59	15	4.0	13.3
2Ahb	9–19	-	-	-	4.2	2.2
2C	19–(60)	-	-	-	4.8	-

Table 6. Elemental composition

Horizon	Depth [cm]	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	MnO	TiO_2	K_2O	P_2O_5
		[%]								
E	0–4	93.25	4.09	0.74	0.15	0.12	0.02	0.21	1.30	0.07
Bs	4–9	85.31	5.46	1.21	0.42	0.22	0.02	0.18	1.47	0.15
2Ahb	9–19	90.4	5.35	0.76	0.16	0.31	0.01	0.15	1.75	0.05
2C	19–(60)	89.31	5.21	0.92	0.21	0.32	0.01	0.16	1.62	0.08

Profile 3 – Dystric Rubic Albic Brunic Folic **Arenosol** (Colluvic, Raptic)

Location: lower part of sinkhole slope – 15 m below the edge and 3 m down to the bottom (130 m a.s.l.), slope gradient 27^{o}, even slope surface; blueberry-green moss community with juniper bushes. **N** 64°33'56.1" **E** 43°15'35.9"



Morphology:

Oe – 12–0, friable organic layer composed of moderately altered residues of mosses, needles and roots, moist, clear and slightly wavy boundary;

E – 0–3 cm, discontinuous layer of *albic material*, coarse sand, light gray (7.5YR 7/1), friable to weakly firm, few fine fragments of igneous rocks, few roots, slightly wavy boundary;

Bsw – 3–8 cm, coarse sand, heterogeneous in colour: 5YR 5/6 (yellowish red) and 5 YR 6/6 (reddish yellow) mottles, weakly moist, weak crumbly structure, rather firm, iron oxides segregations, few fine fragments of igneous rocks up to 5 mm in diameter, few roots of varying diameter, clear and wavy boundary;

2BC – 8–28 cm, coarse sand, reddish yellow (5YR 6/6), moist, friable and slightly firm, massive, few fine fragments of igneous rocks up to 15 mm in diameter, clear transition by texture and consistence, slightly wavy boundary;

3C – 28–(80) cm, medium sand, reddish brown (5YR 5/4), moist, heterogeneous in consistence and texture: firm, weak subangular blocky in the upper part, and friable, rather firm and massive; everywhere – few fragments of igneous rocks up to 20 mm in diameter.

Table 7. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
E	0–3	2	3	37	45	3	2	3	2	3	2	CS
Bsw	3–8	1	2	28	36	5	6	7	8	5	3	CS
2BC	8–28	1	1	31	39	6	4	7	6	5	1	CS
3C	28–(80)	2	2	20	31	8	8	13	8	7	3	MS

Table 8. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH H_2O
Oe	12–0	-	-	-	4.2
E	0–3	10.7	0.79	14	3.8
Bsw	3–8	7.3	0.62	12	4.1
2BC	8–28	-	-	-	4.4
3C	28–(80)	-	-	-	4.6

Table 9. Elemental composition

Horizon	Depth [cm]	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	MnO	TiO_2	K_2O	P_2O_5
		[%]								
E	0–3	93.25	4.09	0.74	0.15	0.12	0.02	0.21	1.3	0.07
Bsw	3–8	85.31	5.46	1.21	0.42	0.22	0.02	0.18	1.47	0.15
2BC	8–28	90.4	5.35	0.76	0.16	0.31	0.01	0.15	1.75	0.05
3C	28–(80)	89.31	5.21	0.92	0.16	0.32	0.01	0.16	1.62	0.08

Climate

The study area is located in the fully humid zone with a long period with snow cover and cool summer (Kottek et al., 2006). Mean annual temperature is +0.2ºC. Cold winter lasts more than half a year (mean temperature in January is -14.5oC, and the absolute minimum registered in Pinega town is -50.2°C); the frost-free period is short: 85-95 days. The depth of soil freezing ranges within 30 – 134 cm; the average snow cover depth is 45-60 cm and the water reserve in the snow makes up 150-200 mm in early spring, and it provides a complete percolation of the soil profile in summer. The summer is short and moderately warm with a mean temperature in June +14.0ºC, and a maximum registered in July: +34.5°C. The mean annual precipitation equals 652 mm. Observations on microclimate confirmed the existence of a vertical temperature gradient in the surface-karst landscape. Thus, summer temperatures in soils at the depth of 20 cm in the bottoms of sinkholes and in the inter-sinkhole areas differ by 5ºC (Structure and dynamics …, 2000).

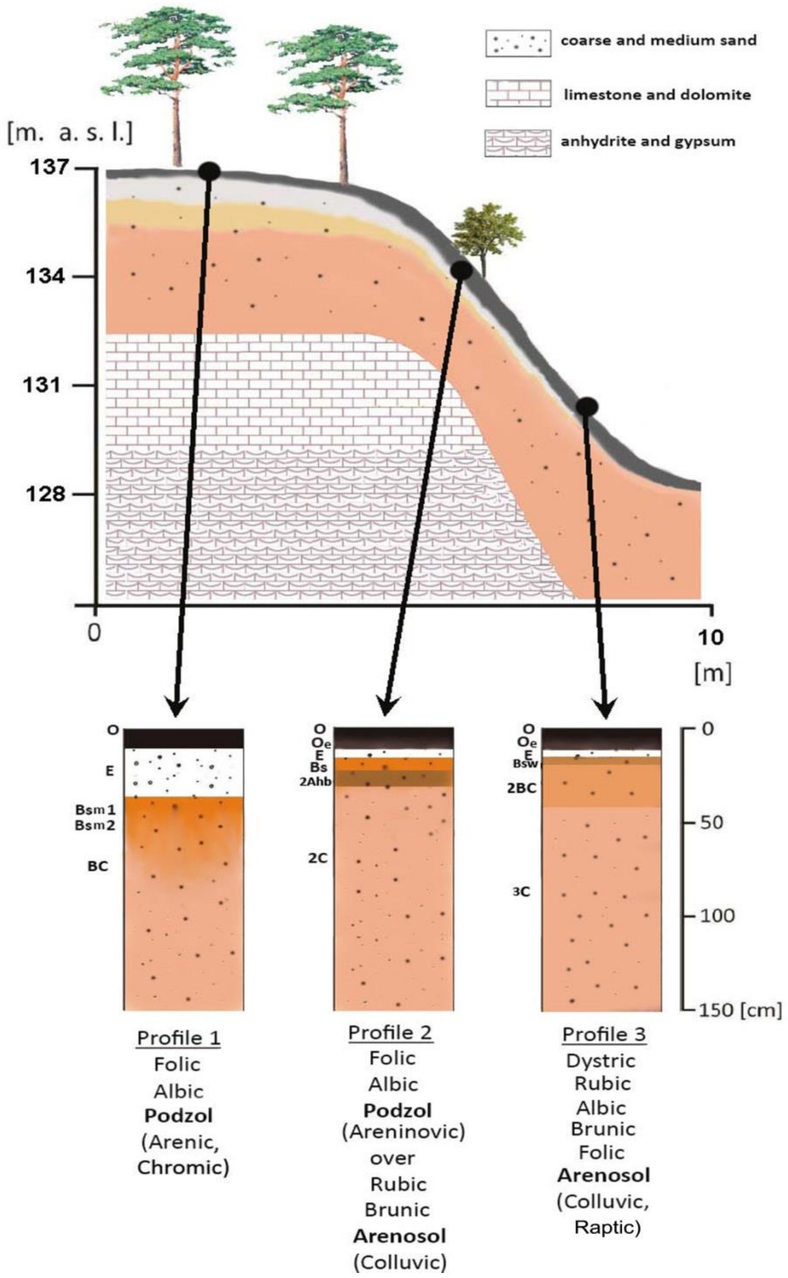


Fig. 2. Toposequence of sandy soils on the slope of karst sinkhole in northern taiga

Soil genesis and systematic position

Soil formation in a karst sinkhole in the taiga zone is expected to be contradictory: calcaric parent material on one hand, and "zonal" trend generating acid soils – **Podzols** (IUSS Working Group WRB, 2015) on sands, and soils with eluvial and argic horizons on loams - **Retisols** (former **Albeluvisols**), on the other hand. All soils of the sinkhole studied are strongly acid with maximum acidity in the eluvial horizon. Steep slopes of the sinkhole provide mass movement within it, while in their lower parts and in the sinkhole bottom the removed material is accumulated. These translocations of diverse materials contribute to rejuvenation of soil profiles, which makes the genetic interpretation more complicated.

Albic **Podzols** are common on deep sands (more than 5 m thick) on the inter-sinkhole surface. The first soil – ***Folic Albic*** **Podzol** ***(Areninovic, Chromic)*** has a rather deep profile with a sharp contrast between the eluvial horizon composed of albic material and reddish thick spodic horizon. Both horizons result of podzolization process, which is active under pine forest; it is also confirmed by analytical data – acid medium, eluvial-illuvial oxides pattern. Under pine forest with lichens in the ground layer, well aerated organic material is accumulated, and ***Folic*** main qualifier is the only possible one in this case. The specific color of the *spodic* horizon may be due to the parent material and fits the ***Chromic*** qualifier, which is not in the list for **Podzols**, therefore, it is the last in the soil name. Weak cementation was noted all over the spodic horizon, although not sufficient to introduce ***Fragic*** qualifier. For a more complete genetic interpretation of profile morphology, it is possible to suppose that the well developed eluvial horizon (almost white and thick albic material) might have originated as due to "normal" vertical flow of acid solutions, so by their lateral outflow, as seen by the inclined lower boundary of eluvial horizon and weakly sloping surface on the photo.

If the first soil has an unambiguous genetic interpretation and systematic position, the other two soils are more difficult to interpret and classify. They are under strong effect of slope processes that have resulted in accumulation of reddish coarse sand interstratified with thin humus-enriched layers. The colluvial material is more or less similar in both soils – reddish coarse sand with few rock fragments (not weathered). However, they differ by manifestations of podzolic pedogenesis.

The second soil of intermediate position was defined as ***Folic Albic*** **Podzol** ***(Areninovic)*** over ***Rubic Brunic*** **Arenosol** ***(Colluvic)***. The thickness of **Podzol** profile is small, although it has a thin spodic horizon below a continuous layer of *albic* material, which testifies to the current podzolization. The ***Folic*** qualifier is the same as in the first soil, but the degree of organic material decomposition is somewhat higher (Oi and Oe sublayers) owing to stronger moistening. The buried soil has a distinct thin upper Ah horizon followed by reddish (***Rubic*** qualifier) coarse sand (**Arenosol**) – result of slope processes, therefore, ***Colluvic*** qualifier was indispensable. It has weak features of pedogenic modifications, not sufficient to attribute a Cambic qualifier: only ***Brunic*** was possible.

The third soil - ***Dystric Rubic Albic Brunic Folic*** **Arenosol** (***Colluvic, Raptic***) is similar to the second one. The RSG is also **Arenosol**, as the two principal qualifiers (***Brunic*** and ***Albic***), the only difference is the discontinuity of albic material, indicating weaker podzolization. The same *Folic* qualifier is "supported" by another one – *Dystric*, since the organic layer is more homogeneous, moist, and composed of medium and even strongly decomposed organic residues. Like the second soil, this one is formed on colluvium, which is less turbated and less homogeneous: elements of stratification may be traced, and the lowermost layer is different in texture and rock fragments admixture (***Raptic*** qualifier).

Soil sequence

The analysis of soil properties shows that podzolization is an essential process in all soils: it is responsible for their high acidity not mitigated by the effect of calcareous rocks in the karst landscape. It produces albic material in all soils starting with the deep one in the main (inter-sinkhole) surface, which, along with distinct *spodic* horizon, permits to identify a true ***Albic* Podzol**. Podzolization becomes weaker downslope being hindered by mass movement in the sinkhole, and this is evidenced either by the lower thickness and discontinuity of albic material layer. Parallel to these changes in soil profiles, the spodic horizon is fading and becomes hardly recognizable in the third soil. These changes are illustrated by the sequence of RSG with due qualifiers: ***Albic* Podzol** → ***Albic* Podzol** over a buried ***Brunic* Arenosol** → ***Albic Brunic* Arenosol.**

All soils have qualifiers for their red color inherited from the parent material – ***Chromic*** or ***Rubic***; their organic horizons were named ***Folic***, although the degree of organic matter transformation and moisture status are changing down slope.

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Intensively used agricultural soils of the Sokal Hills (Western Ukraine)

Waldemar Spychalski, Łukasz Mendyk, Tomasz Kaczmarek

Fig. 1. Location

The study area is located in the western part of the Lviv Oblast, Western Ukraine (Fig. 1). Soil pits were prepared in the area of three raions (counties) comprising the northern border of the Lviv Oblast: Radekhiv (profiles 1 and 4) and Brody (profiles 2 and 3), as well as Sokal (profile 5; Spychalski et al., 2018). According to the geographical regionalization, it is located in the Ukrainian part of the Sokal Hills mesoregion in the Volhynian Upland macroregion (Kondracki 1995).

Lithology and topography

The distribution of surface sediments in the study area is characterised by a typical pattern. In general, the soil parent material consists of loess deposits of varying thickness on the Pre-Quaternary carbonate bedrock (Upper Baden limestone, Cretaceous marl and marl; Kyrylchuk 2014). According to Kyrylchuk (2014), the permafrost zone during the Last Glacial Period contained a continuous loess cover. These sediments were accumulated during several Pleistocene glaciations as the Mazovian Interglacial in loess sections is represented by palaeosols. In the Volhynian Upland, it is represented by a palaeosol of the Sokal (Zavadivka) horizon, observed in the sections Bojanice and Korshiv (Lindner and Marks, 2008). The Studied soil profiles were located at altitudes ranging from 210 m a.s.l. to 248 m a.s.l., which basically corresponds to average heights of the Volhynian Upland (240-250 m a.s.l.).

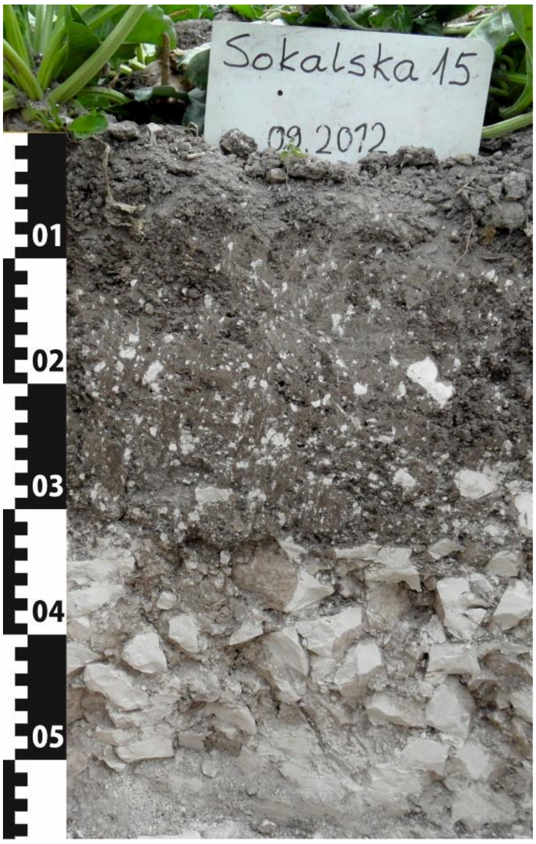
Land use

Nowadays, the study area is intensively used for agricultural purposes. Arable lands dominate the landscape of the study area. The climatic conditions, described in detail below, are suitable for intensive crop production, mainly winter wheat, oilseed rape and sugar beets (Spychalski et al. 2018). The discussed area is located within the Ukrainian forest-steppe zone, which covers an area of about 202,000 km^2 and extends south of Polissya. About two-thirds of this agricultural region is arable land and forests cover only about one-eighth of the area (www.britannica.com/place/Ukraine/Plant-and-animal-life#ref404719).

Climate

According to Kottek et al. (2006), the region is located in the snow climate zone, fully humid with warm summer. The average annual temperature is 8.3˚C. The average temperature of the coldest month (January) is –2.5°C, while the warmest month in the period of 1990–2010 is July – 19.4°C (climatic station at Brody). The average annual sum of precipitation for the same period was 740 mm.

Profile 1 – Skeletic Chernic Rendzic **Phaezoem** (Aric, Pantoloamic, Endodensic)
Localization: middle part of gently slope - inclination 10°, arable land, 233 m a.s.l.
N 50°22'31.6" **E** 24°37'36.6"



Morphology:

Ap – 0–35 cm, plough *chernic* horizon, silty clay loam, grayish brown (10YR 7/1, 10YR 4/1), slightly moist, medium and coarse strong subangular plus fine strong granular structure, many fragments of carbonate bedrock, clear and wavy boundary;

C – 35–(60) cm, parent *calcaric material*, clay loam, light gray (10YR 8/2, 2.5Y 8/1), dry to slightly moist, porous massive structure.

Table 1. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm				Textural class
		> 2.0	2.0-0.05	0.05-0.002	< 0.002	
Ap	0–35	5*	13	56	31	SiCL
C	35–(60)	90*	24	48	28	CL

*examined in the field

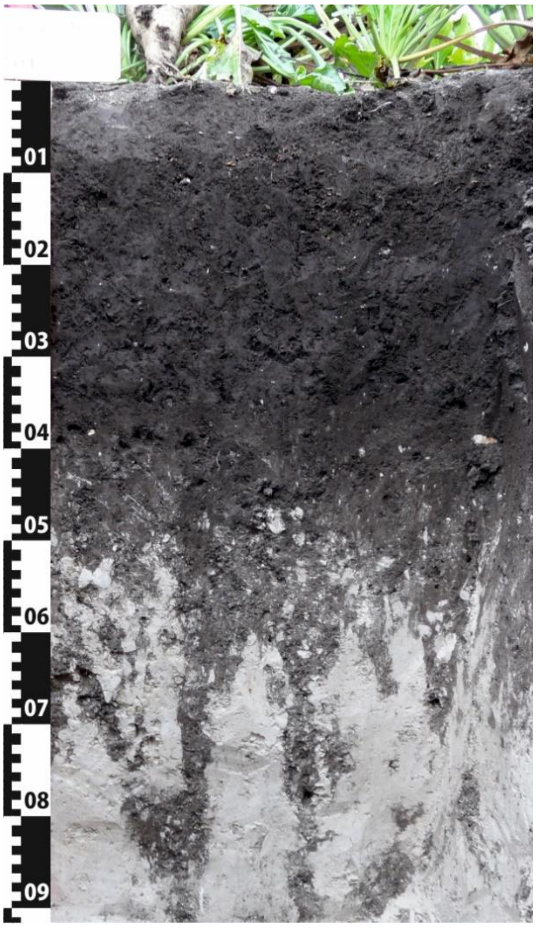
Table 2. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
Ap	0–35	36.3	2.63	14	8.2	7.6	538
C	35–(60)	< 0.01	< 0.01	-	8.5	7.8	490

Table 3. Sorption properties

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	HA	CEC	BS [%]
		[cmol(+)·kg^{-1}]							
Ap	0–35	12.4	3.45	0.41	0.25	16.5	0.55	17.1	96
C	35–(60)	-	-	-	-	-	-	-	-

Profile 2 – Calcaric Chernic **Phaezoem** (Aric, Pantoloamic)
Localization: lower gently slope - inclination 10°, arable land, 248 m a.s.l.,
N 50°01'34.0" **E** 25°09'07.8"



Morphology:

Ap – 0–35 cm, plough *chernic* horizon, loam, dark grayish brown (10YR 4/1, 10YR 3/1), slightly moist, fine strong angular plus medium moderate granular structure, few fragments of carbonate bedrock, clear and smooth boundary;

A – 30–50 cm, humus subhorizon, loam, dark grayish brown (10YR 6/1, 10YR 3/1), slightly moist, very fine strong subangular plus fine moderate angular structure, common fragments of carbonate bedrock, abrupt and irregular boundary;

C – 50–(95) cm, parent soft *calcaric material*, silty clay loam, light gray (10YR 8/1, 10YR 8/2), massive structure, common crotovinas.

Table 4. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm				Textural class
		> 2.0	2.0-0.05	0.05-0.002	< 0.002	
Ap	0–35	-	40	36	24	L
A	35–50	-	29	46	25	L
C	50–(95)	-	17	54	29	SiCL

Table 5. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
Ap	0–35	16.2	2.29	7	8.2	7.5	184
A	35–50	12.5	1.95	6	8.4	7.7	366
C	50–(95)	< 0.01	< 0.01	-	8.6	8.0	707

Table 6. Sorption properties

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	HA	CEC	BS [%]
		[cmol(+)·kg^{-1}]							
Ap	0–35	3.85	0.55	0.17	0.15	4.72	0.40	5.12	92
A	35–50	4.50	0.35	0.11	0.10	5.06	0.30	5.36	94
C	50–(95)	5.50	0.20	0.12	0.10	5.92	0.10	6.02	98

Profile 3 – Endocalcaric Luvic Chernic **Phaeozem** (Aric, Endoloamic, Raptic, Siltic)

Localization: middle slope position, nearly level terrain - inclination 2.5°, arable land, 240 m a.s.l., **N** 50˚01'51.2'' **E** 25˚07'52.1''

Morphology:

Ap – 0–30 cm, plough *chernic* horizon, silt loam, dark grayish brown (10YR 5/2, 10YR 3/2), slightly moist, fine to medium strong granular and angular structure, abrupt and smooth boundary;

AE – 30–45 cm, transitional humus-eluvial horizon, loam, grayish brown (10YR 6/4, 10YR 5/4), slightly moist, medium moderate subangular structure, gradual smooth boundary;

Bt – 45–75 cm, *argic* horizon, silt loam, yellowish brown (10YR 6/4, 10YR 4/4), slightly moist, medium strong angular structure, clay coatings on the ped faces, abrupt and irregular boundary;

2C – 75–(100) cm, *calcaric material*, silty clay loam, very pale brown (10YR 8/2, 10YR 8/4), slightly moist, massive structure.

Table 7. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm				Textural class
		> 2.0	2.0-0.05	0.05-0.002	< 0.002	
Ap	0–30	-	30	55	15	SiL
AE	30–45	-	37	45	18	L
Bt	45–75	-	22	52	26	SiL
2C	75–(100)	-	11	56	33	SiCL

Table 8. Chemical and physicochemical properties

Horizon	Depth [cm]	OC $[g\cdot kg^{-1}]$	Nt $[g\cdot kg^{-1}]$	C/N	pH		$CaCO_3$ $[g\cdot kg^{-1}]$
					H_2O	KCl	
Ap	0–30	16.1	1.42	11	7.8	7.2	trace
AE	30–45	< 0.01	< 0.01	-	7.8	6.7	trace
Bt	45–75	< 0.01	< 0.01	-	7.9	6.8	trace
2C	75–(100)	< 0.01	< 0.01	-	8.7	7.8	681

Table 9. Sorption properties

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	HA	CEC	BS
		$[cmol(+)\cdot kg^{-1}]$							[%]
Ap	0–30	3.85	0.43	0.11	0.30	4.69	1.20	5.89	80
AE	30–45	2.25	0.45	0.14	0.20	3.04	1.50	4.54	67
Bt	45–75	2.15	0.37	0.15	0.15	2.82	0.90	3.72	76
2C	75–(100)	2.75	0.16	0.11	0.10	3.12	0.50	3.62	86

Profile 4 – Lamellic Abruptic **Luvisol** (Aric, Anoloamic, Ochric, Endosiltic)
Localization: nearly level terrain, toe slope - inclination 2°, arable land, 221 m a.s.l.,
N 50°18'57.0" **E** 24°54'01.5"

Morphology:

Ap – 0–33 cm, plough humus horizon, sandy loam, grayish brown (10YR 6/3, 10YR 4/3), slightly moist, fine to medium moderate granular structure, abrupt and wavy boundary;

E – 33–42 cm, eluvial horizon, sandy loam, yellowish brown (10YR 7/6, 10YR 5/6), slightly moist, fine moderate subangular structure, gradual smooth boundary;

Bt – 42–75 cm, *argic* horizon, sandy loam, yellowish brown (10YR 5/3, 10YR 4/4), slightly moist, fine moderate angular structure and fine weak granular structure, clay coatings on ped faces, clear and irregular boundary;

C – 75–(100) cm, silt loam, light yellowish brown (10YR 7/6, 10YR 6/6), slightly moist, coarse weak platy structure.

Table 10. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm				Textural class
		> 2.0	2.0-0.05	0.05-0.002	< 0.002	
Ap	0–33	-	60	37	3	SL
E	33–42	-	70	23	7	SL
Bt	42–75	-	53	29	18	SL
C	75–(100)	-	27	51	22	SiL

Table 11. Chemical and physicochemical properties

Horizon	Depth [cm]	OC $[g\cdot kg^{-1}]$	Nt $[g\cdot kg^{-1}]$	C/N	pH		$CaCO_3$ $[g\cdot kg^{-1}]$
					H_2O	KCl	
Ap	0–33	9.22	0.89	10	6.8	6.4	28
E	33–42	< 0.01	< 0.01	-	7.2	6.0	trace
Bt	42–75	< 0.01	< 0.01	-	7.6	6.8	trace
C	75–(100)	< 0.01	< 0.01	-	6.2	4.3	trace

Table 12. Sorption properties

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	HA	CEC	BS
		$[cmol(+)\cdot kg^{-1}]$							[%]
Ap	0–33	3.40	1.22	0.45	0.12	5.19	0.80	5.99	87
E	33–42	1.60	1.15	0.25	0.30	3.30	0.50	3.80	87
Bt	42–75	2.60	1.25	0.20	0.20	4.25	0.40	4.65	91
C	75–(100)	2.80	1.12	0.09	0.10	4.11	0.30	4.41	93

Profile 5 – Vermic **Chernozem** (Aric, Pantosiltic)

Localization: upper plateau, nearly flat terrain, arable land, 205 m a.s.l.,
N 50°28'13.8" E 24°13'21.0"

Morphology:

Ap – 0–29 cm, plough *chernic* horizon, silt loam, dark grayish brown (10YR 5/2, 10YR 3/1), slightly moist, fine to medium strong granular structure, abrupt and smooth boundary;

ACk – 29–90 cm, transitional horizon, silt loam, grayish brown (10YR 7/3, 10YR 5/3), slightly moist, fine subangular and granular moderate structure, common carbonate concretions, many infilled large burrows and earthworm channels, gradual smooth boundary;

Ck – 90–(110) cm, parent loess material with protocalcic properties, silt loam, yellowish brown (10YR 7/3, 10YR 5/5), slightly moist, common carbonate concretions, coarse platy moderate plus very fine moderate angular structure.

Table 13. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm				Textural class
		> 2.0	2.0-0.05	0.05-0.002	< 0.002	
Ap	0–29	-	15	64	21	SiL
ACk	29–90	-	12	71	17	SiL
Ck	90–(110)	-	14	66	20	SiL

Table 14. Chemical and physicochemical properties

Horizon	Depth [cm]	OC $[g \cdot kg^{-1}]$	Nt $[g \cdot kg^{-1}]$	C/N	pH		$CaCO_3$ $[g \cdot kg^{-1}]$
					H_2O	KCl	
Ap	0–29	16.2	1.48	11	8.0	7.1	trace
ACk	29–90	11.2	0.73	15	8.5	7.5	90.6
Ck	90–(110)	< 0.01	< 0.01	-	8.6	7.8	72.3

Table 15. Sorption properties

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	HA	CEC	BS [%]
		$[cmol(+) \cdot kg^{-1}]$							
Ap	0–29	3.50	1.75	0.18	0.15	5.58	0.80	6.38	87
ACk	29–90	2.75	1.28	0.12	0.11	4.26	0.50	4.76	89
Ck	90–(110)	2.25	1.31	0.11	0.10	3.77	0.40	4.17	90

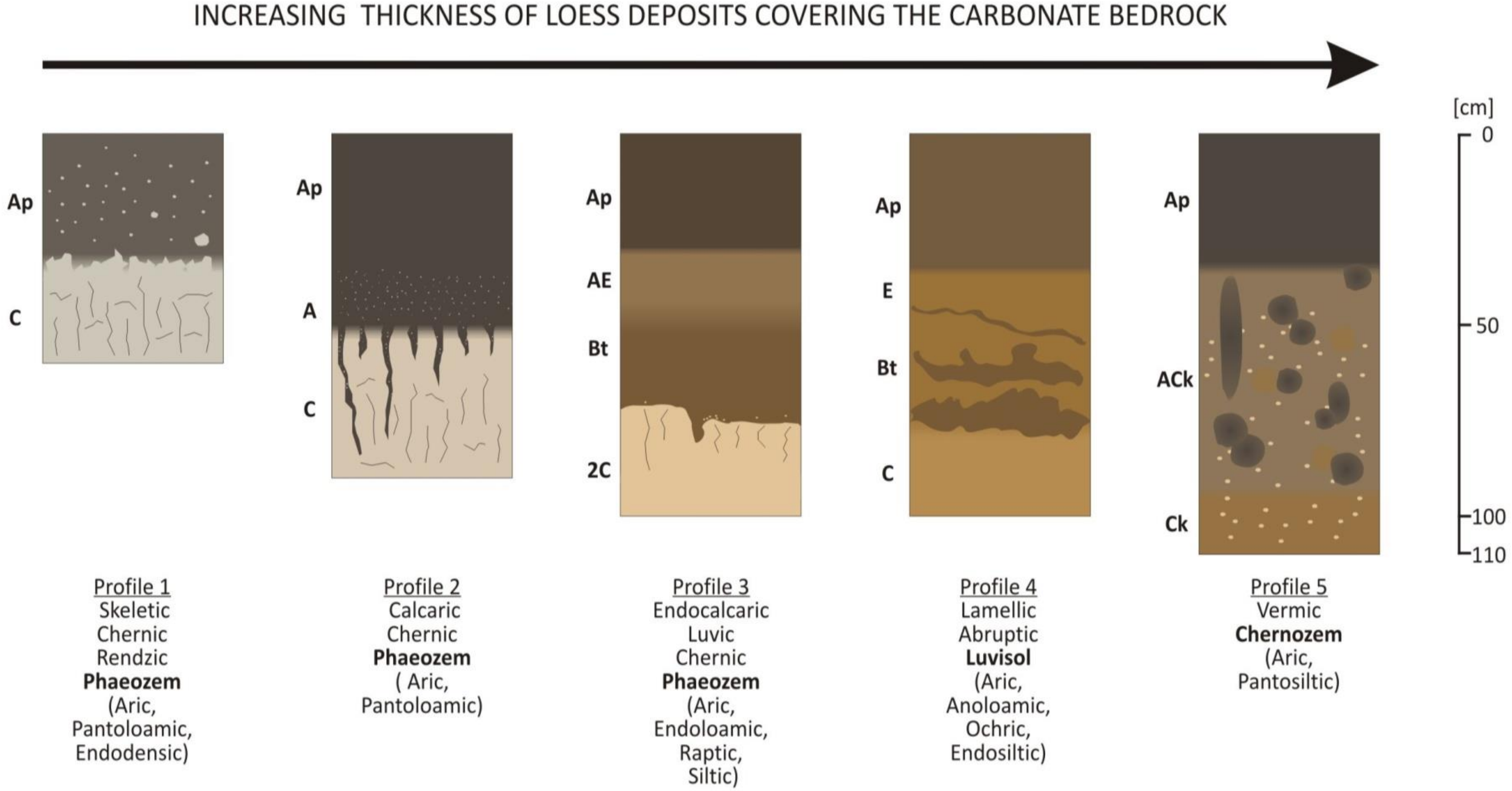


Fig. 2. Lithosequence of soils of the Sokal Hills (Western Ukraine)

Soil genesis and systematic position

The soil cover diversification in the study area is strongly connected with the natural heterogeneity of the surface sediments. In general, the direction of soil forming processes depends on the presence and thickness of loess deposits covering the carbonate bedrock. During the Upper Pleistocene and the Holocene, the soil cover was influenced by changing climatic conditions, resulting in a variety of plant communities with the dominance of trees and grasses (Spychalski et al. 2018).

Profile 1 represents the soil developed from the calcareous rock, probably covered with some admixture of aeolian dust. The most conspicuous morphological feature of this soil profile is a relatively thick, dark humus horizon with a well-developed structure and high content of organic matter (Table 2). As this horizon is characterised by high base saturation (Table 3) and considering the above-mentioned features, the profile meets the criteria for the ***Chernic*** diagnostic horizon. Due to this fact, as well as due to the absence of the ***Calcic*** horizon and the base saturation of more than 50% in the whole soil profile (Table 3), the soil was classified as **Phaeozem** (IUSS Working Group WRB, 2015). The ***Skeletic*** preliminary qualifier was used based on a large amount of coarse fragments and continuous rock (> 40% by volume on average; Table 1). As the ***Chernic*** humus horizon contains more than 40% of calcium carbonates and directly overlies the *calcaric* material (also containing more than 40% of $CaCO_3$), it meets both criteria for the ***Rendzic*** qualifier. The last on the list of preliminary qualifiers used for the description of this profile is ***Chernic.*** It is allowed to be used when the humus horizon in **Phaeozem** contains more than 1% of organic carbon and a well-developed granular or subangular structure, and when it is dark and thick (more than 25 cm) enough to meet the criteria for the ***Chernic*** diagnostic horizon (usually identified in **Chernozems**; IUSS Working Group WRB, 2015). The supplementary qualifiers start with ***Aric.*** This one is used for soils ploughed to a depth of at least 20 cm from the soil surface. Both of the distinguished soil horizons are characterised by loamy texture (Table 1), that is why the ***Pantoloamic*** qualifer is the next one. The **Endodensic** qualifier was applied to express the natural compaction of the soil material starting below the upper 50 cm, which cannot be penetrated by plant roots.

Profile 2 was also classified as **Phaeozem** based on the presence of an even deeper organic carbon-rich humus horizon, which meets the criteria for the ***Chernic*** diagnostic horizon, and high base saturation in the whole soil profile (IUSS Working Group WRB, 2015; Table 6). The calcareous parent material of this soil profile is much softer than in profile 1, which results in the lack of coarse fragments in the very deep humus horizon. The depth of ***Chernic*** could be affected by a large amount of silt deposits but also by higher susceptibility for plant roots and penetration of animals. ***Calcaric*** opens the list of preliminary qualifiers, as the $CaCO_3$ content was more than 2% in all of the distinguished horizons (Table 5). The second one, ***Chernic***, stands for the presence of the above-mentioned humus horizon. Both of the supplementary qualifiers – ***Aric*** and ***Pantoloamic*** – were used for the same reasons as in profile 1 (ploughing and loamy texture).

Profile 3 has developed from 70 cm thick loess deposits covering the carbonate bedrock. This aeolian dust was deep enough for the development of eluvial and illuvial horizons, due to specific climate conditions, plant cover and topographic conditions. In the northern part of the European loess belt, the process of calcium carbonate leaching occurred under forest and/or steppe plant cover during the Late Pleistocene and the Holocene (Jary and Ciszek, 2013). Later, the dissolution of carbonates led to clay leaching and the development of Luvisols. Despite these facts, the profile was classified as **Phaeozem,** due to the presence of the ***Chernic*** diagnostic horizon, additionally emphasised by the ***Chernic*** preliminary qualifier (IUSS Working Group WRB, 2015). The ***Endocalcaric*** primary qualifier was used to express the presence of *calcaric* material starting deeper than 50 cm (Table 8). Due to the presence of the ***Argic*** Bt horizon, the ***Luvic*** qualifier was applied. The ***Aric*** supplementary qualifier was used again, because of ploughing up to a depth of more than 20 cm. The ***Endoloamic*** qualifier provides information on loamy texture starting depper than 50 cm (Table 7). The next one is ***Raptic,*** which can be applied in the case of a *lithic discontinuity* recognized up to a depth of 100 cm from the mineral soil surface (75 cm in this case). The last one – ***Siltic*** – informs us about the silty texture in a layer of at least 30 cm thick , within the upper 100 cm of mineral soil (Ap and Bt horizons in this profile; Table 7).

Profile 4 was classified as **Luvisol** due to the presence of the Bt ***Argic*** horizon. This diagnostic horizon was identified based on the presence of clay coatings on ped faces formed under conditions typical for the *lessivage* process (Quénard et al., 2011; Świtoniak et al. 2016). Due to the fact that this horizon partially consists of several individual lamellas (at least two, more than 2 cm and less than 7.5 cm thick), the ***Lamellic*** preliminary qualifier was applied. The *abrupt textural difference* between eluvial E and iluvial Bt horizons is emphasized by the ***Abruptic*** preliminary qualifier. Similarly to profile 3, this profile was also ploughed deeper than 20 cm (Table 11). Terefore, the qualifer ***Aric*** is also used for this profile. Next one - ***Ochric*** - is used due to the features of the humus horizon (it has at least 0.2% of organic carbon but it does not meet the criteria for ***Mollic, Umbric*** or ***Humic***). Two of the supplementary qualifiers used give us information on the soil texture. Those are ***Anoloamic*** and ***Endosiltic.*** Since these qualifiers were used, we know that the soil profile is characterised by loamy texture, starting from the mineral soil surface and ending somewhere between a depth of 50 cm and 100 cm. Then there is a layer or layers (C horizon in this particular profile) with a silty texture starting deeper than 50 cm (silty loam is regarded as silty; IUSS Working Group WRB, 2015).

The last profile was classified as **Chernozem** due to the presence of the ***Chernic*** surface diagnostic horizon as well as the *protocalcic properties* recognised in ACk and Ck horizons (common soft and hard concretions of secondary calcium carbonates). The only preliminary qualifier – ***Vermic*** – is very important in the description of this profile. It can be used when there is more than 50% (by volume) of worm holes, casts or filled animal burrows in the upper 100 cm of the soil. In fact, we can say that the whole transitional horizon ACk has developed as a result of long lasting activity of soil animals. These were worms, as well as larger animals like rodents. As this soil is also agriculturally used and ploughed deeper than 20 cm, the ***Aric*** supplementary qualifier was applied. ***Pantosiltic*** informs us about the silty texture in the whole analysed soil profile.

Soil sequence

The soil sequence described above is a product of a specific combination of several different soil-forming factors (climate and plant cover in particular), common to this specific part of the European continent. Soil-forming processes are still affected by these factors, overlapping with the natural variability of surface sediments. On the other hand, they are a result of geological and geomorphological processes responsible for the occurrence of specific sedimentary rocks (marls and limestones), often covered with loess deposits of varying thickness. The first two profiles are **Phaeozems,** developed mainly from the carbonate bedrock. Although profile 3 was also classified as **Phaeozem** (due to the features of the humus horizon), together with profile 4 – **Luvisol**, it is strongly affected by the ***lessivage*** process taking place in a relatively thick loess cover. The aeolian dust was originally poor in calcium carbonates compared to carbonate rocks, which led to $CaCO_3$ dissolution and, consequently, clay leaching (Jary and Ciszek, 2013). In some cases, the loess sediments form a deep (acc. to pedological scale) mantle. Carbonates recrystallize after leaching into the subsurface horizons, forming secondary calcium carbonates. This, combined with well-developed organic carbon-rich horizons, is the reason for classifying the soils with the features described above as **Chernozems** (Profile 5; Eckmeier et al., 2007).

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Soils of the abandoned gold and silver mining area on volcanic-hydrothermal rocks (Hungary)

Tibor József Novák, János Szepesi

The study area is located in the northern part of the Tokaj Mountains, a Miocene volcanic mountainous area, where post-volcanic hydrothermal processes resulted in ore accumulation in quartzite veins. Gold and silver ore mining during the Middle- and Early Modern Ages considerably transformed the geomorphology of the surface and thus had a major impact on the soils too.

The slightly different character of the parent material and various types and intensity of human impact resulted in the increased diversity of soils, as natural soil profiles have also been preserved.

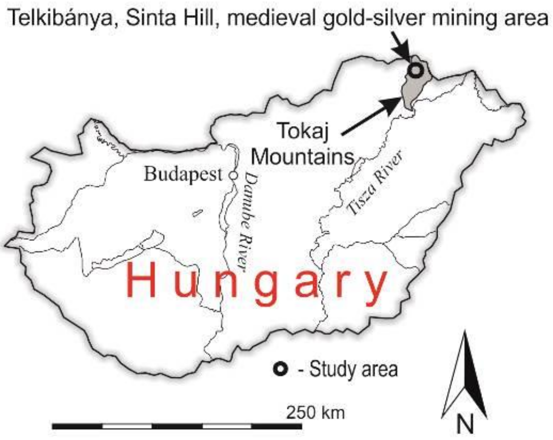


Fig. 1 Localization

Lithology and topography

The Sinta and Kecske Hát Hills form a 1.5 km long, 0.5 km wide, N-S oriented volcanic ridge at the southern margin of the hydrothermally altered andesitic area. The ridge is built of Miocene rhyodacite and partly covered by shallow marine marl and clay (Ilkey-Perlaky 1978; Molnár et al., 2009). The circulation of hydrothermal fluids caused intensive silicification, argillic alteration in NW–SE striking veins cutting through the host rocks (Zelenka and Horváth 2009). The 0.5–1 km long, 0.1–1m wide structures usually reaches 200 m in depth and contains gold and silver bearing ores (mainly sulphides). Large cavities in rhyodacite were filled with quartz crystals (up to 5 cm) forming the so-called geode. Long-term (10 million years) selective erosion (Zelenka et al., 2012) has prepared a harder, silicified ridge emerging 100 m above the surrounding valleys.

The mineral exploration in the gold-silver Telkibánya area started in the 12th century (Zelenka and Horváth, 2009). The open pit mining followed the ore bearing quartzite veins on the ground surface, while 100 m long adits quarried at underground levels (Zelenka and Horváth 2009). The yellowish, argillic vein material is well distinguished from the unaltered greyish dacite. Dense periglacial debris (0.5–1 m in thickness) of rhyodacite accumulated on the surface between the veins. Two NW-SE striking trails of open pits located on Sinta Hill were surveyed in 2016. The original morphology of pit holes was characterized by steep hanging walls. Waste of vein material and the host rock accumulated on the surface, which later fell down and partially filled the abandoned mine holes (Fig. 1b). The current average depth varied between 0.5 and 4 m. Some of the pits were reopened as a result of the resumption of mineral collection activity in the 1980s. Additionally, new shallow pits were excavated, tracing the occasional quartz filling the geodes of rhyodacite. The current landscape of the Sinta-Kecskehát Hills represents a special combination of primary volcanic and hydrothermal processes, coinciding with a special network of older and recent anthropogenic landforms.

Profile 1 – Skeletic Dystric **Cambisol** (Pantosiltic, Ochric)
Localization: Niche, medium slope - inclination 11°, deciduous forest vegetation, slope 453 m a.s.l.
N 48° 29' 48,42" **E** 21° 23' 16,76"

Morphology:

Ah – 0–3 cm, humus horizon, silt loam, very dark grayish brown (10YR 3/2), slightly moist, medium moderate granular-subangular blocky structure, very fine and common roots, clear and smooth boundary;

Bw – 3–20 cm, *cambic* horizon, silt loam, brown (10YR 4/6), moist, medium weak-moderate subangular blocky structure, fine common roots, gradual and smooth boundary;

BC – 20–45 cm, silt loam, dark yellowish brown (10YR 4/7), fresh, medium very weak subangular blocky structure, medium very few roots, gradual and wavy boundary;

C1 – 45–70 cm, silt loam, light yellowish brown (10YR 5/6), dry, rock structure, very few roots, illuvial lamellae, gradual and smooth boundary;

C2 – 70–105 cm, silt loam, light yellowish brown (10YR 6/4), dry, rock structure, gradual and smooth boundary;

C3 – 105–(150) cm, silt loam, light yellowish brown (10YR 6/4) dry, rock structure.

Table 1. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
Ah	0–3	1.8	1.6	3.9	8.5	12	12.6	28.6	22.4	5.9	4.5	SiL
Bw	3–20	0.5	1.4	3.1	5.6	12.6	4.7	18.1	25.9	13.9	14.7	SiL
BC	20–45	1.7	2.2	2.5	4	11.5	7.7	19.7	24.2	11.9	16.3	SiL
C1	45–70	1.5	1.7	2.2	3.3	8.8	9.4	20.6	23.1	11.7	19.2	SiL
C2	70–105	0.6	0.9	1.2	2.1	7.4	8.2	22.8	25.7	12.7	19.0	SiL
C3	105–(150)	0.4	1.1	1.9	4.4	9.1	11.9	23.0	21.7	9.3	17.6	SiL

Table 2. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		CaCO$_3$ [g·kg^{-1}]
					H$_2$O	KCl	
Ah	0–3	29.4	-	-	5.4	4.7	3.9
Bw	3–20	12.2	-	-	4.2	3.8	4.5
BC	20–45	4.0	-	-	4.7	3.8	5.8
C1	45–70	1.6	-	-	4.9	3.8	5.0
C2	70–105	2.3	-	-	5.0	3.9	3.2
C3	105–(150)	4.4	-	-	4.9	3.7	7.2

Profile 2 – Episkeletic **Umbrisol** (Pantosiltic, Siltinovic)
Localization: Niche, medium slope - inclination 13°, grass vegetation, slope 417 m a.s.l.
N 48°29'45.93 **E** 21°23'16.98"

Morphology:

Ah – 0–10 cm, *umbric horizon*, silt loam, very dark brown, dark grayish brown (10YR 2/2, 10YR 4/2), slightly moist, medium weak subangular blocky structure, skeletal parts (30%), very fine and common roots, clear and smooth boundary;

AC – 10–40 cm, *umbric horizon*, silt loam, very dark brown (10YR 2/2), slightly moist, medium weak subangular blocky structure, skeletal parts (50%), few fine roots, gradual and smooth boundary;

CR – 40–(80) cm, silt loam, dark brown (10YR 3/3), dry, few large roots, skeletal parts (70%), rock structure.

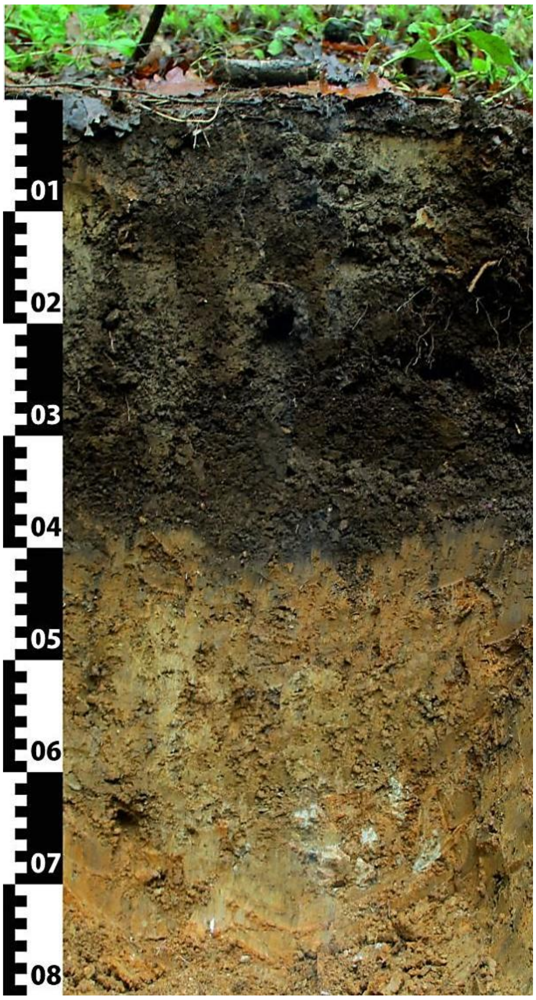
Table 3. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
Ah	0–10	0.7	0.5	1.5	4.5	9.8	8.3	26.1	28.4	8.9	12.0	SiL
AC	10–40	0.1	0.5	1.3	4	9.8	7.2	22.3	27.4	12.2	15.3	SiL
CR	40–(80)	7.1	3.6	2.4	2.1	8.8	8	19	22.7	11.8	21.6	SiL

Table 4. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [$g \cdot kg^{-1}$]	Nt [$g \cdot kg^{-1}$]	C/N	pH		$CaCO_3$ [$g \cdot kg^{-1}$]
					H_2O	KCl	
Ah	0–10	32.4	-	-	4.9	3.7	5.3
AC	10–40	10.0	-	-	5.4	3.9	5.0
CR	40–(80)	0.0	-	-	6.3	4.6	6.1

Profile 3 – Amphistagnic Amphiluvic **Umbrisol** (Episiltic, Amphiclayic, Endoloamic, Siltinovic, Transportic)
Localization: Niche, medium slope - inclination 13°, deciduous forest vegetation, slope 406 m a.s.l.
N 48°29'37.58" **E** 21°23'21.46"



Morphology:

Ahu – 0–20 cm, *umbric* horizon, silt loam, very dark grayish brown (10YR 3/2), slightly moist, medium moderate subangular blocky structure, very fine and common roots, redeposited soil material, gradual and smooth boundary;

Ahb – 20–40 cm, *umbric* horizon, silt loam, very dark grayish brown (10YR 3/2), slightly moist, fine moderate subangular blocky and granular structure, fine very few roots, clear and smooth boundary;

Btg – 40–60 cm, *argic* horizon, silty clay, dark yellowish brown (10YR 4/4), slightly moist, medium strong subangular - angular blocky structure, *stagnic* pattern (10YR 4/3; 7.5Y 4/6), cutans, fine and medium very few roots, gradual and smooth boundary;

BCg – 60–(75) cm, silty clay loam, yellowish brown (10YR 5/8), slightly moist, medium weak subangular blocky structure, *stagnic* pattern (10YR 4/3; 7.5Y 4/6), few small skeletal parts, rock fragments.

Table 5. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
Ahu	0–20	0.9	0.1	0.5	2.4	8.4	5.2	21.3	29.8	10.3	22.0	SiL
Ahb	20–40	0.1	0.4	0.5	2.3	9.8	5.8	23.9	29.5	10.4	17.4	SiL
Btg	40–60	0.1	0.1	0.4	2.3	10	3.2	12.2	19.7	9.3	42.8	SiC
BCg	60–75	0.3	0.3	0.3	2.4	9.5	6.1	13.5	18.6	9.3	39.8	SiCL

Table 6. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [$g \cdot kg^{-1}$]	Nt [$g \cdot kg^{-1}$]	C/N	pH		$CaCO_3$ [$g \cdot kg^{-1}$]
					H_2O	KCl	
Ahu	0–20	24.1	-	-	5.0	3.8	5.9
Ahb	20–40	26.1	-	-	4.9	3.8	5.3
Btg	40–60	4.4	-	-	5.4	3.6	4.9
BCg	60–75	4.7	-	-	5.8	4.0	4.1

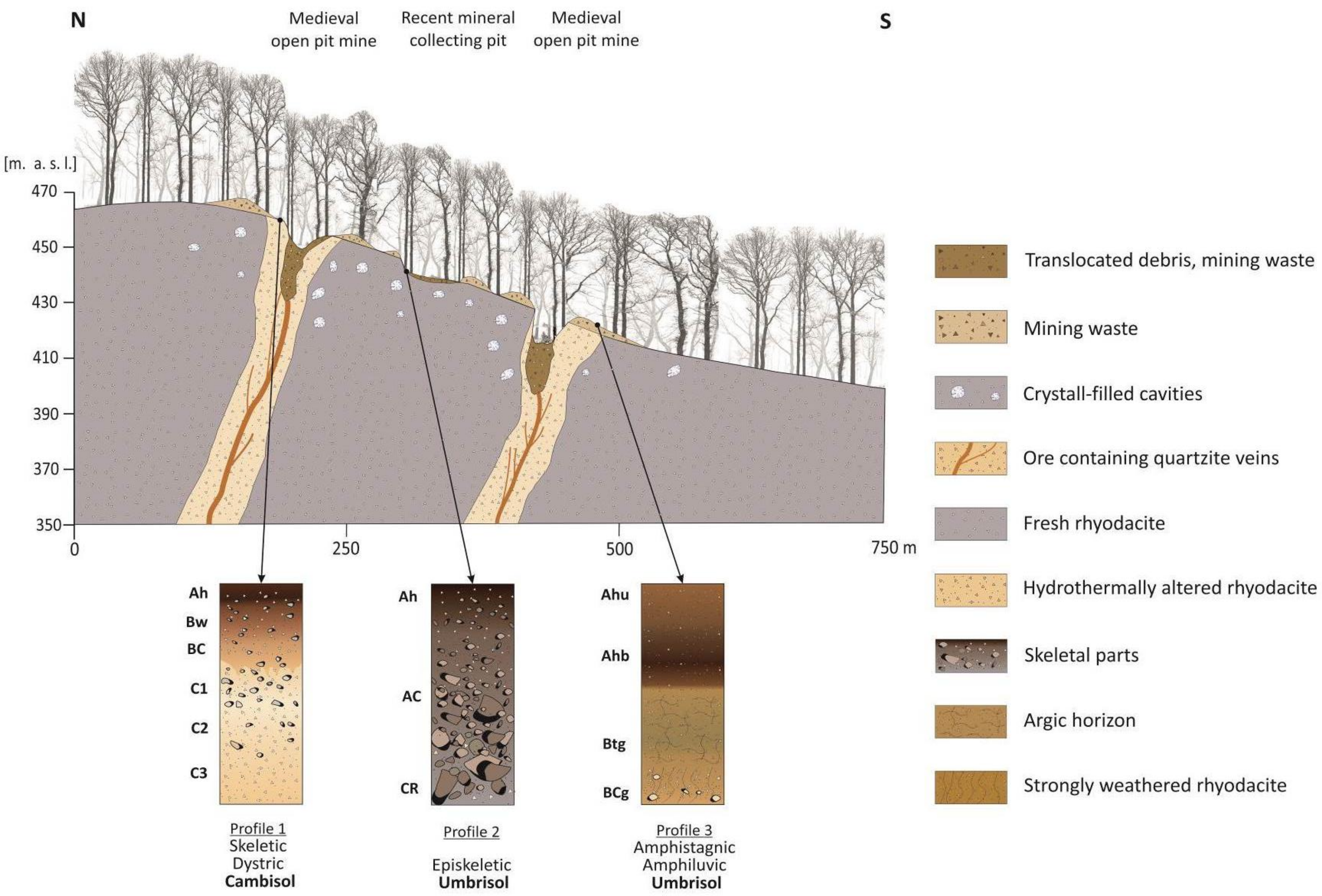


Fig. 2. Sequence of soils of the abandoned gold and silver mining area on volcanic-hydrothermal rocks

Land use

The ridges and southern slopes of Sinta-tető are covered by a typical mixed oak forest, *Quercetum petraeae-cerris*, dominated by sessile oak (*Quercus petraea*). The area is part of the Zempén Landscape Protection Area and is currently managed by forest administration. In the Middle Ages and the early New Age, the region was heavily transformed by the mining activity; spoil heaps and mining waste deposits indicate the intensity of this land use. At the end of the 19th century at the latest, all mining activities were discontinued here and the spontaneous post-mining vegetation development has started. The forests covering this area are the result of at least 150–200 years of secondary succession and nowadays it is difficult to distinguish them from natural ones.

Climate

The study area belongs to the Northern Hungarian Mid-Mountains. According to Kottek et al. (2006) the region is located in the humid zone with warm summer. The average annual temperature is 8°C. The average temperature of the coldest month (January) is -4.5 °C, while the warmest month is July (19.5 °C. The average annual precipitation is about 700 mm. The February is the driest (26 mm), while the highest precipitation is recorded in June (80 mm).

Soil genesis and systematic position

Profile 1 was classified as **Cambisol** (IUSS Working Group WRB, 2015), characterized by the presence of the *cambic* horizon starting at the surface and reaching a depth of 20 cm. Skeletal parts such as rock debris and rock fragments were present in >40%, therefore the ***Skeletic*** principal qualifier was applied, while low pH (3.8 in KCl solution) indicates its low base saturation, hence the ***Dystric*** qualifier was also added. The texture of fine earth is found to be silty loam in all horizons, which is indicated by the ***Pantosiltic*** supplementary qualifier. The shallow humus-rich layer and its relative low OC content is expressed by the ***Ochric*** supplementary qualifier.

Profile 2 was classified as **Umbrisol** (IUSS Working Group WRB, 2015), because the Ah and AC horizons have a dark colour (10YR 2/2 moist), a well-developed structure and a sufficiently high organic carbon content, but the base saturation is presumably low due to low pH (3.7). These first two horizons together exceed the minimum thickness criteria for the *umbric* horizon. The skeletal parts between the soil surface and the depth of 100 cm account for >40% of the soil volume. Therefore, the ***Skeletic*** principal qualifier was added to indicate it with the ***Epi***- specifier, since this characteristic appears already in the topsoil, between the soil surface and the depth of 50 cm. The base rock is different from the first location, but the chemical characteristics of its weathering products are similarly acidic, resulting in low pH and presumbly low base saturation. The texture of the soil in fine earth is entirely silty loam, therefore the ***Pantosiltic*** supplementary qualifier was added.

Profile 3 was similarly to Profile 2 defined as **Umbrisol**, having a 40 cm thick, well-structured, organic rich, dark coloured but strongly acidic surface horizon, which meets the criteria of the *umbric* horizon. Directly below the umbric horizon, the *argic* diagnostic horizon could be identified, which also has a *stagnic colour pattern* with rusty brown and greyish distinct patches. Both characteristics appear at a depth from 40 to 60 cm, therefore the ***Amphiluvic*** and ***Amphistagnic*** qualifiers were added. The texture is siltic in the *umbric* horizon, which was described with the ***Episiltic*** supplementary qualifier, clayic in the *argic* horizon, hence the ***Amphiclayic*** qualifier, and loamic below the *argic* horizon, which is expressed by the ***Endolamic*** qualifier. The surface horizon is still recognizable as redeposited soil material, in which parts of various colours and structures are not completely mixed. For this new surface layer, the supplementary qualifier ***Novic*** was added and its texture class is indicated by the ***Silty***- specifier. This together with the buried surface horizon still meets the criteria of the *umbric* horizon, but its anthropogenic modified thickness and position should be indicated by the ***Transportic*** supplementary qualifier.

Soil sequence

Mining areas are usually characterized by **Technosols** due to the presence of mining waste, which is classified as artefacts when the material brought to the surface by mining was previously not affected by surface processes and significantly differs from its environment. In our case, mining was present in the preindustrial time and only shallow layers of mining waste could be found on the surface. Furthermore, in the period since the cessation of mining, the debris was subjected to weathering processes and the mining waste is excavated from the direct vicinity of the surface. Therefore, the old mining waste in the studied profiles could not be defined as *artefacts*, but as *transportic*, and *novic* material above the original soil horizons.

Profile 1 is located on the edge of an abandoned medieval open mine pit and it represents soil developed on weathered, hydrothermally altered rhyodacite, which is not covered by later, anthropogenically translocated mining waste or debris. The surface further away from the pit is slightly elevated by the redeposited material excavated during the mining, but nearly the original soil surface was visible in profile 1. Therefore, in the case of profile 1, anthropogenic influences are not recognizable. Profile 2 is located at a shallow pit, excavated by hobby-mineralogists in fresh, dark grey rhyodacite rock, containing crystal-filled cavities. The redeposited rock debris and soil material covering the original soil surface is <20 cm and not continuous, therefore only the Novic supplementary qualifier applies, with the addition of the texture class of fine earth of this reworked material: ***Siltinovic***. At profile 3, the surface is covered by 20 cm thick redeposited soil material, which together with the original soil topsoil horizon meets the minimum thickness criterium for Umbric, which means that it contains part of the *umbric* horizon, but it is at the same time ***Transportic*** and ***Siltinovic***.

The soil sequence shows typical soils developed on weathered acidic volcanic rocks, containing a relatively large proportion of skeletal parts. Anthropogenic influences are still recognizable, but in the described soils the taxonomy reflects them only at the level of supplementary qualifiers.

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Loess-influenced soils on mountain slopes (Mt Ślęża, south-western Poland)

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Mt Ślęża is located in south-western Poland (Fig.1). It is the north-eastern extended body of the Fore-Sudetic Block (the northernmost tectonic part of the Sudeten Mountains), which is subdivided into two geological units: 1) the Ślęża ophiolite and 2) the Strzegom-Sobótka Massif. The first unit features mostly ultrabasic rocks such like: metagabbros, serpentinized peridotites, ultramafic cumulates, diabases and metabasalts (Kryza and Pin, 2010; Kierczak et al., 2016), while the second unit consists of Variscan granitoids. Also, younger Pleistocene materials occur on Mt Ślęża, such as glacial deposits related to the Odra glaciation (Żurawek, 1999) and aeolian silt deposition during the LGM (Jary, 2010). It is believed that the Great Odra Valley, which stretched in front of the Scandinavian ice sheet, is the source area of loess (Badura et al. 2013).

Fig. 1. Location

Lithology and topography

The altitude of Mt Ślęża reaches 718 m a.s.l. The soil catena was situated on the western slope of Mt Ślęża, where aeolian silt was deposited on granite/gabbro bedrock or on glaciofluvial sediments. The upper parts of the slopes are characterised by thinner covers of aeolian silt; their thickness increases in mid- and footslopes (Waroszewski, 2017).

Land use

The land use types are: forest (profile 1 and 4), grassland (profiles 2 and 3) and old orchards (profile 5). The deciduous forest is composed of beech (*Fagus sylvatica*) and oak (*Quercus sp.*) in the upper tree layer, birch (*Betula pendula*) and oak in the lower tree layer, while hazel (*Corylus avellana*) occurs in the shrub layer. Grasslands are formed by such species as e.g. false oat grass (*Arrhenatherum elatius*), orchard grass (*Dactylis glomerata*), nettle (*Urtica dioica*) and a few cherry trees (*Prunus avium).*

Climate

The mean annual air temperature in this area is 7°C. The coldest month is January (–2°C) and the warmest one – July (15°C). The mean annual precipitation ranges from 650 mm in the foothills to 800 mm in the summit area of Mt Ślęża. Snow cover persists for almost 70 days, between November and March (Bac and Rojek, 2012).

Profile 1 – Dystric Skeletic **Cambisol** (Loamic, Ochric, Raptic)
Localization: shoulder (inclination 18˚), deciduous forest, 529 m a.s.l.,
N 50°52’03,1” **E** 16°41'36.6"

Morphology:

Olf	– 7–0 cm, moderately decomposed organic material, slightly moist, clear and wavy boundary;
Ah	– 0–7 cm, humus horizon, brown (10YR 2/1), fine to medium moderate angular and subangular blocky structure, slightly moist, clear and wavy boundary;
Bw1	– 7–23 cm, *cambic* horizon, loam, brown (10YR 5/8), many fine angular fragments (gabbro), fine to medium moderate subangular blocky structure, slightly moist, few clay coatings, gradual boundary;
Bw2	– 23–44 cm, *cambic* horizon, loam, brown (7.5YR 5/6), abundant medium angular gabbro clasts, medium moderate subangular blocky structure, slightly moist, few clay coatings, gradual boundary;
2BC	– 44–71 cm, sandy loam, yellowish brown (10YR 4/6), abundant medium angular stones (granite), medium weak subangular blocky structure, slightly moist, gradual boundary;
2C	– 71–110 cm, parent material, sandy loam, yellowish brown (10YR 5/6), abundant medium angular stones (granite), fine weak subangular blocky structure, slightly moist.

Table 1. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm									Textural class
		>2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.002	< 0.002	
Ah	0–7	-	-	-	-	-	-	-	-	-	-
Bw1	7–23	25	4	9	8	9	12	20	28	10	L
Bw2	23–44	48	4	12	10	11	12	18	19	14	L
2BC	44–71	71	8	11	12	15	18	19	8	9	SL
2C	71–(105)	77	8	14	13	17	17	13	12	6	SL

Table 2. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [$g \cdot kg^{-1}$]	pH H_2O
Olf	7–0	-	4.8
Ah	0–7	68.9	3.9
Bw1	7–23	7.3	4.5
Bw2	23–44	4.3	4.3
2BC	44–71	1.0	4.4
2C	71–(105)	1.5	4.5

Table 3. Sorption properties

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	EA	ECEC	BS [%]
		[$cmol(+) \cdot kg^{-1}$]							
Ah	0–7	1.12	0.46	0.19	0.12	1.9	2.28	7	27
Bw1	7–23	0.80	0.35	0.04	0.11	1.3	5.00	5	28
Bw2	23–44	0.88	0.36	0.04	0.11	1.4	3.40	5	29
2BC	44–71	1.04	0.42	0.04	0.13	1.6	3.32	4	45
2C	71–(105)	0.96	0.35	0.04	0.14	1.5	1.96	4	35

Profile 2 – Stagnic **Luvisol** (Cutanic, Ochric, Raptic, Siltic)
Localization: midslope (inclination 4°), grassland, 265 m a.s.l.,
N 50°52'12.7" **E** 16°40'34.4"

Morphology:

AE – 0–20 cm, humus horizon (with features of eluviation), silt loam, yellowish brown (10YR 4/3), medium to coarse moderate angular and subangular blocky structure, moist, clear and wavy boundary;

Eg – 21–40 cm, eluvial horizon, silt loam, light yellowish brown (10 YR 5/3), medium moderate angular and subangular blocky structure, moist, gradual boundary;

Btg – 40–70 cm, *argic* horizon, silty loam, yellowish brown (10YR 5/6), medium moderate angular blocky structure, moist, common fine reductimorphic mottles, common clay coatings, clear and wavy boundary;

2Btg – 70–100 cm, *argic* horizon, sandy loam, reddish brown (7.5YR 5/8), many fine gravel and many rounded medium stones (glacial material), fine to medium weak platy and angular blocky structure, moist, common fine reductimorphic mottles, common clay coatings, clear and wavy boundary;

3Btg – 100–(139) cm, *argic* horizon, light reddish brown (10YR 6/8), loam, few fine gravel (glacial material), platy and angular blocky structure, moderate, fine to medium, moist, common, fine reductimorphic mottles, common clay coatings.

Table 4. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm									Textural class
		>2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.002	< 0.002	
AE	0–21	-	2	3	3	3	8	35	38	8	SiL
Eg	21–40	-	0	0	1	1	16	24	40	18	SiL
Btg	40–70	-	0	1	1	1	12	33	27	25	SiL
2Btg	70–100	37	5	10	19	24	12	6	6	18	SL
3Btg	100–(139)	4	1	1	2	9	14	26	21	26	L

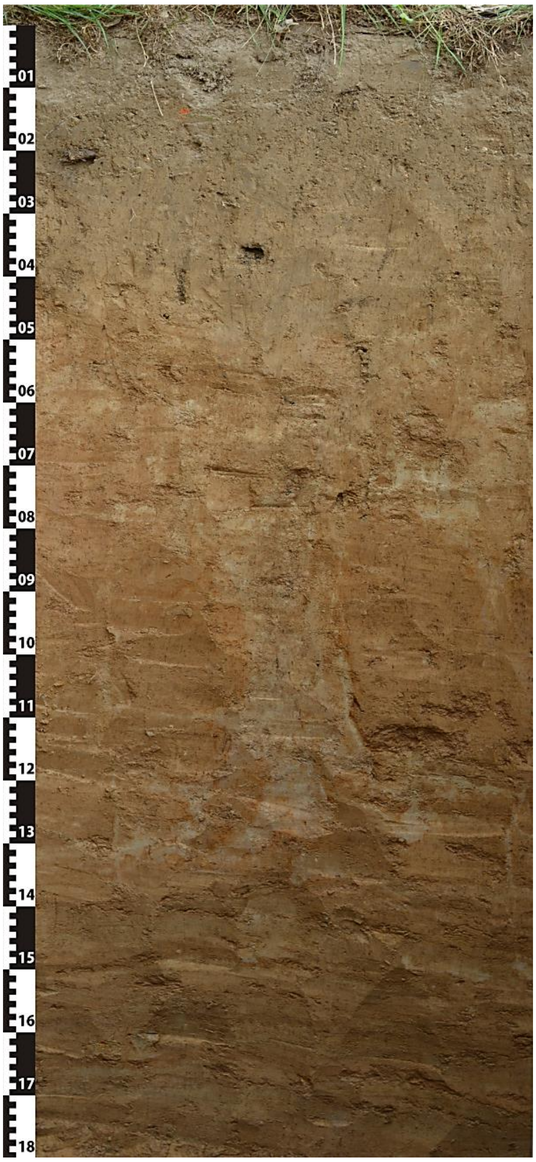
Table 5. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [$g \cdot kg^{-1}$]	pH H_2O
AE	0–21	9.3	5.2
Eg	21–40	1.9	5.8
Btg	40–70	1.1	5.0
2Btg	70–100	0.5	4.7
3Btg	100–(139)	0.7	5.0

Table 6. Sorption properties

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	EA	ECEC	BS [%]
		[$cmol(+) \cdot kg^{-1}$]							
AE	0–21	3.20	0.53	0.08	0.15	4.0	1.12	5	78
Eg	21–40	6.80	1.04	0.12	0.27	8.2	0.64	9	93
Btg	40–70	4.96	1.30	0.17	0.23	6.7	3.44	10	66
2Btg	70–100	3.60	1.87	0.12	0.19	5.8	2.00	8	75
3Btg	100– (139)	5.04	4.24	0.20	0.19	9.7	4.60	14	68

Profile 3 – Eutric Stagnic **Retisol** (Cutanic, Ochric, Siltic)
Localization: midslope (inclination 10˚), grassland, 248 m a.s.l.,
N 50˚52'26.4'' **E** 16˚40'33,2''



Morphology:

A – 0–20 cm, humus horizon, silty loam, yellowish brown (10YR 5/3), granular and subangular structure, clear and wavy boundary;

AEg – 20–40 cm, silty loam, light yellowish brown (10YR 5/4), angular structure, common fine reductimorphic mottles, common clay coatings, clear and wavy boundary;

Eg/Btg – 40-70 cm, *argic* horizon, silty loam, yellowish brown (10YR 5/6), angular structure, common fine reductimorphic mottles, common clay coatings, gradual boundary;

Btg/Eg – 70–100 cm, *argic* horizon, silty loam, reddish brown (7.5YR 5/5), platy and angular structure, few fine reductimorphic mottles, common clay coatings, gradual boundary;

BCg – 100–130 cm, silty loam, yellowish brown (10YR 5/6), angular structure, few fine reductimorphic mottles, common clay coatings, gradual boundary;

C1g – 130–150 cm, bedrock horizon, silty loam, yellowish brown (10YR 6/6), angular structure, few fine reductimorphic mottles, common clay coatings, gradual boundary;

C2g – 150–190 cm, bedrock horizon, silty loam, yellowish brown (10YR 5/6), angular structure, few fine reductimorphic mottles, common clay coatings, gradual boundary;

C3g – 190–(210) cm, bedrock horizon, silty loam, light yellowish brown (10YR 6/4), angular structure, few fine reductimorphic mottles, common clay coatings.

Table 7. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm									Textural class
		>2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.002	< 0.002	
A	0–20	-	2	7	7	7	10	33	30	4	SiL
AEg	20–40	-	1	3	3	4	11	31	37	10	SiL
Eg/Btg	40–70	-	0	0	0	1	9	26	38	26	SiL
Btg/Eg	70–100	-	0	0	0	1	10	25	39	25	SiL
BCg	100–130	-	0	0	1	3	12	39	30	15	SiL
C1g	130–150	-	1	1	1	2	19	27	33	16	SiL
C2g	150–190	-	1	1	1	3	17	31	29	17	SiL
C3g	190–(210)	-	0	1	3	8	8	47	27	6	SiL

Table 8. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	pH H_2O
A	0–20	13.6	5.4
AEg	20–40	4.5	5.8
Eg/Btg	40–70	0.9	5.2
Btg/Eg	70–100	0.7	5.0
BCg	100–130	0.7	5.1
C1g	130–150	0.6	5.1
C2g	150–190	0.5	5.2
C3g	190–(210)	0.5	5.2

Table 9. Sorption properties

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	EA	ECEC	BS [%]
		[cmol(+)·kg^{-1}]							
A	0–20	4.16	0.72	0.08	0.18	5.13	0.80	6	86
AEg	20–40	5.12	0.60	0.05	0.19	6.0	0.32	6	95
Eg/Btg	40–70	7.44	2.67	0.17	0.40	10.7	2.24	13	83
Btg/Eg	70–100	6.56	2.56	0.17	0.23	9.5	3.48	13	73
BCg	100–130	5.76	2.32	0.14	0.23	8.4	2.52	11	77
C1g	130–150	5.20	2.13	0.12	0.37	7.8	2.52	10	76
C2g	150–190	4.88	2.30	0.09	0.19	7.5	2.16	10	76
C3g	190–(210)	4.40	1.92	0.08	0.19	6.6	1.64	8	80

Profile 4 – Endoskeletic **Alisol** (Cutanic, Ochric, Raptic, Siltic)
Localization: summit/shoulder (inclination 2°), deciduous forest, forest, 260 m a.s.l.
N 50°52'35.0" **E** 16°40'09.1"

Morphology:

Ah – 0–3 cm, humus horizon, silty loam, nearly black (7.5YR 2.5/1), very few skeleton grains, granular structure, moist, gradual boundary;

ABw – 3–8 cm, *cambic* horizon, silty loam, brown (7.5YR 4/5), very few fine skeleton grains, fine to medium moderate granular structure, moist, gradual boundary;

Bw1 – 8–30 cm, *cambic* horizon, silty loam, yellowish brown (10YR 5/6), very few fine skeleton grains, granular and subangular structure, moist, gradual boundary;

2Bt – 30–50 cm, *argic* horizon, silty loam, brownish yellow (10YR 5/5), few fine skeleton grains, subangular structure, moist, few reductimorphic mottles, few/common silt-clay coatings, gradual boundary;

2BC – 50–70 cm, silty loam, light yellowish brown (10YR 6/4), few fine skeleton grains, platy and angular structure, moist, common reductimorphic mottles, common silt-clay coatings, clear or irregular boundary;

3BC – 70–110 cm, sandy loam, strong brown (7.5YR 5/8), abundant skeleton grains (granite), structure inherited from saprolite, moist;

3CR – 110–(130) cm, bedrock horizon, cryogenic granite saprolite, dominant slightly weathered, angular rock fragments (granite), moist.

Table 10. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm									Textural class
		>2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.002	< 0.002	
Ah	0–3	2	3	3	8	9	10	39	22	6	SiL
ABw	3–8	8	1	2	4	4	10	40	33	6	SiL
Bw1	8–30	8	1	2	3	5	8	34	35	12	SiL
2Bt	30–50	47	2	2	3	4	7	35	34	13	SiL
2BC	50–70	60	4	3	5	5	9	32	30	12	SiL
3BC	70–110	72	21	17	16	12	9	7	10	8	SL
3CR	110–(130)	85	32	15	10	9	6	8	15	5	SL

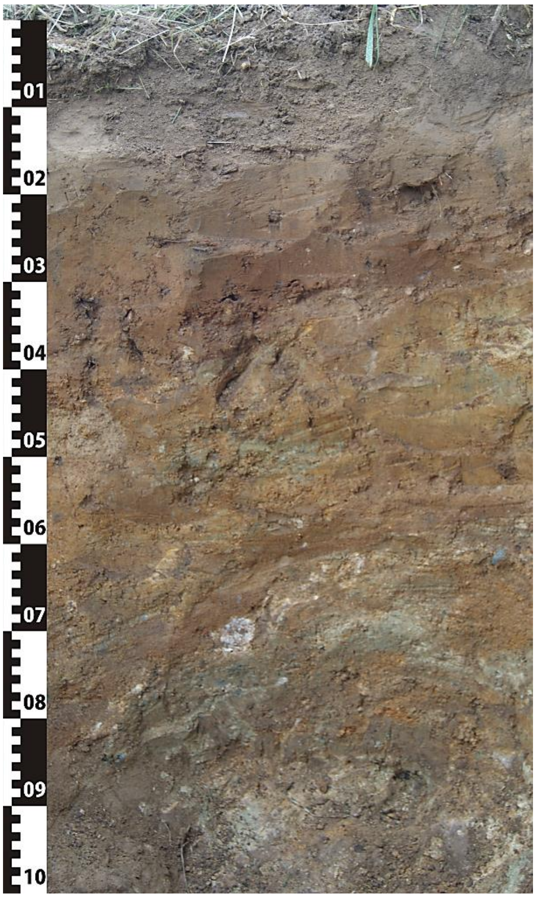
Table 11. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [$g \cdot kg^{-1}$]	pH H_2O
Ah	0–3	157.0	4.0
ABw	3–8	45.1	4.4
Bw1	8–30	11.9	4.5
2Bt	30–50	6.7	4.6
2BC	50–70	3.4	4.5
3BC	70–110	3.1	4.3
3CR	110–(130)	2.4	4.1

Table 12. Sorption properties

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	TEB	EA	ECEC	BS [%]
		[$cmol(+) \cdot kg^{-1}$]							
Ah	0–3	2.22	0.85	0.39	0.22	3.7	4.65	8	44
ABw	3–8	1.76	0.56	0.23	0.18	2.7	4.58	7	37
Bw1	8–30	1.44	0.47	0.11	0.09	2.1	3.74	6	36
2Bt	30–50	1.28	0.46	0.10	0.09	1.9	3.73	6	34
2BC	50–70	0.96	0.25	0.13	0.08	1.4	3.10	5	31
3BC	70–110	1.12	0.50	0.12	0.08	1.8	4.64	6	28
3CR	110–(130)	0.96	0.48	0.13	0.09	1.7	4.81	7	26

Profile 5 – Endoskeletic **Luvisol** (Episiltic, Endoloamic, Ochric, Raptic)
Localization: summit/shoulder (inclination 3°), old orchard, 230 m a.s.l.
N 50°52'24.6" **E** 16°40'09.1"



Morphology:

AE – 0–20 cm, humus horizon, silt loam, light yellowish brown (10YR 5/4), few rounded fine gravels, fine moderate subangular blocky structure, slightly moist, clear and wavy boundary;

EB – 20–36 cm, silt loam, light reddish brown (10YR 5/8), many rounded fine gravels, fine moderate angular and subangular blocky structure, slightly moist, gradual boundary;

2Btg1 – 36–64 cm, *argic* horizon, loam, light reddish brown (10YR 6/8), abundant rounded medium to coarse gravels, medium strong platy and angular blocky structure, slightly moist, few fine reductimorphic mottles, few clay coatings, gradual boundary;

2Btg2 – 64–81 cm, *argic* horizon, sandy loam, brown (7.5YR 5/6), abundant rounded medium to coarse gravel (glacial material), fine to medium weak granular structure, slightly moist, few fine reductimorphic mottles, few clay coatings, gradual boundary;

2BC – 81–(105) cm, sandy clay loam, reddish brown and light reddish (5YR 4/6 and 5Y 8/3), abundant rounded and subrounded medium to coarse gravels (glacial material), fine to medium weak granular structure, slightly moist.

Table 13. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm									Textural class
		>2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.002	< 0.002	
AE	0–20	4	1	2	4	4	13	30	38	8	SiL
EB	20–36	22	1	3	6	8	11	27	25	19	SiL
2Btg1	36–64	72	3	8	8	13	8	10	24	26	L
2Btg2	64–81	72	5	14	20	19	5	7	12	18	SL
3BC	81–(105)	65	7	14	11	12	7	5	19	25	SCL

Table 14. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	pH H_2O
AE	0–20	10.2	5.3
EB	20–36	4.0	5.3
2Btg1	36–64	1.8	5.3
2Btg2	64–81	0.8	5.2
3BC	81–(105)	1.0	5.2

Table 15. Sorption properties

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	EA	ECEC	BS [%]
		[cmol(+)·kg^{-1}]							
AE	0–20	4.72	1.09	0.17	0.19	6.2	0.96	7	87
EB	20–36	7.52	1.66	0.15	0.26	9.6	1.12	11	90
2Btg1	36–64	16.0	5.29	0.12	0.39	21.8	2.12	24	91
2Btg2	64–81	8.40	4.09	0.11	0.29	12.9	1.40	14	90
3BC	81–(105)	12.8	5.77	0.09	0.42	19.1	0.84	20	96

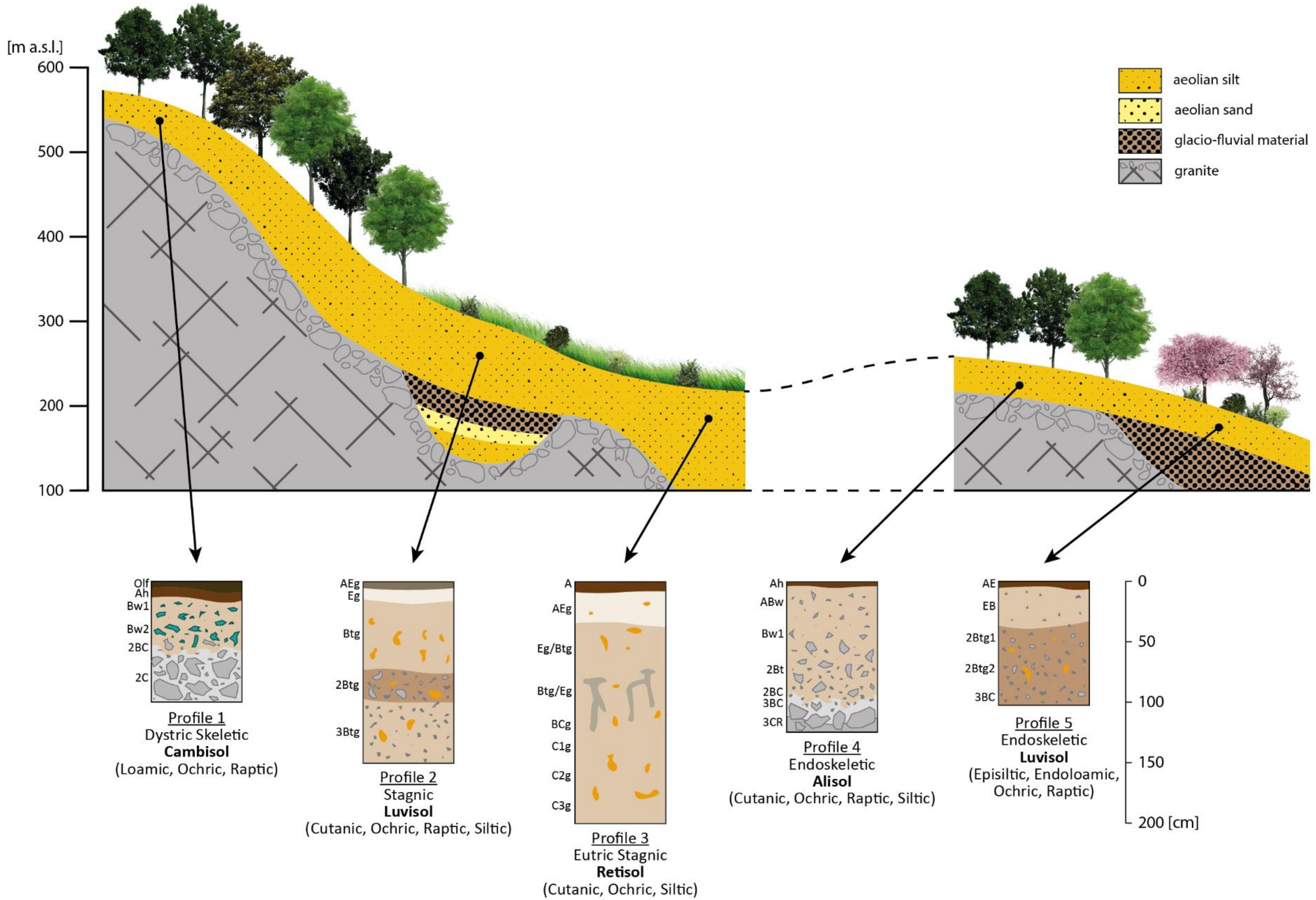


Fig. 2. Lithotoposequence of loess-influenced soils on mountain slopes of Mt Ślęża, SW Polamd

Soil genesis and systematic position

Soil formation, morphology and classification of the analysed slope catena is controlled by aeolian silt admixture. Soil profile 1 is located on granite regolith with some contribution of gabbro clasts on the slope exposed to erosion. The upper part of the soil profile has a texture of loam with a higher content of silt fraction (up to 48%) and very fine sand fraction (Table 1). The topsoil also has a high content of coarse fragments of gabbro, which reaches 25–50% of the soil volume. However, the bottom part of the soil developed from granite regolith, which is characterised by sandy loam texture and significantly lower proportion of silt and clay fractions compared to the overlying layers. These facts indicate that the upper part of the soil, enriched with aeolian silt, was mixed with gabbro and partially granite regolith (mixed zone). Based on the colour and structural transformations typical for *cambic* horizons, which are evident both in the mixed zone and in the upper part of granite regolith, the soil was classified as **Cambisol** with an indication of loam texture (IUSS, 2014). The ***Dystric*** principal qualifier was used to indicate the low base saturation, and ***Skeletic*** to identify abundant gabbro clasts. Furthermore, the ***Raptic*** supplementary qualifier was used to indicate the lithological discontinuity.

Soil profile 2 is located in the midslope and consists of two silt-enriched layers (0–70 cm and 110–139 cm) separated by glacial sediments, which contain ca. 40% of rounded and subrounded gravels, mostly the Scandinavian red granites. Clay cutans are well developed on soil structures between a depth of 40 and 139 cm, featuring a very thick *argic* diagnostic horizon (having 3 subhorizons), which allowed to classify the soil as **Luvisol** (IUSS, 2015). Furthermore, the common fine reductimorphic mottles were observed between the depth of 40 and 139 cm, typical of ***Stagnic*** properties. The ***Siltic*** qualifier was used to indicate the silt-dominated texture, as well as ***Raptic*** – to identify the lithological discontinuity between aeolian and glacial materials. In addition, the ***Cutanic*** qualifier was used to indicate the nature of the *argic* horizon.

Soil profile 3 is situated in the slightly concave midslope. Three different layers of loess derivates can be distinguished. Despite different morphological features, all layers consist of nearly uniform material, with a clear dominance of the silt fraction (60–70%). The topsoil material is believed to be a colluvial material, whereas clay illuviation at a depth of 40–100 cm testified to the presence of a well-developed argic Bt horizon. Due to the interfingering of the bleached coarser-textured soil material and a net-like pattern within the argic horizon, the soil was classified as **Retisol.** The ***Eutric*** principal qualifier was used to indicate the high base saturation. Moreover, qualifiers ***Siltic*** and ***Cutanic*** indicate the silt-loam texture and the presence of cutans in the argic horizon, respectively.

Soil profile 4 is located in the shoulder slope section on the granite regolith. This soil illustrates the case when the silt loam mantle overlies the clearly different regolith, but the contact is transitional rather than abrupt, and the sharp lithological discontinuity is absent. This profile is also characterised by apparently higher clay content and the presence of common clay cutans in the transitional (mixed) zone, thus identified as the Bt (argic) horizon. Clay cutans are absent in the topsoil silty layer, where the transformation of colour and structure, typical for a cambic horizon (Bw), was identified. Due to the accumulation of clay particles in the subsoil (and visible clay cutans), the soil was classified as **Alisol** (IUSS, 2015). The ***Endoskeletic*** principal qualifier was used to identify abundant skeleton grains. Additionally, ***Cutanic, Siltic*** and ***Raptic*** qualifiers were used to indicate the presence of cutans in argic horizons, dominant silt-loamy texture, and the lithological discontinuity, respectively.

Soil profile 5 is situated in the shoulder and is a good illustration of the case when silt loam directly overlies the glaciofluvial sediments, without any transitional layer. The surface silty mantle comprises humus-enriched and eluvial horizons, whereas clay cutans are absent. In the underlying layer, below the lithological discontinuity (***Raptic***), clay cutans are very abundant both on structural soil aggregates and on rock fragments, which results in the classification of the soil into **Luvisols**. The content of coarse fragments exceeds 40% from a depth of 36 cm till the 2BC horizon (***Endoskeletic***). To identify the silty material in the topsoil layers and the loamy texture in the subsoil layers, the ***Episiltic*** and ***Endoloamic*** qualifiers were applied.

In all profiles of the catena, the ***Ochric*** qualifier was also used to indicate the content of soil organic carbon higher than 0.2% in the 20 cm thick topsoil layers.

Soil sequence

The soil catena presents the loess-influenced soils on the mountain slope. The silt loam mantles of varying thickness were present in all profiles, partly mixed with the underlying materials. In the upper parts of the slope, **Cambisols** have developed from the silt-enriched mixed layer over the granite bedrock (profile 1). Multi-stratified slope cover-beds with thick silt loam layers in the midslope section are parent material for **Luvisols** (2). The shallow silt loam mantles with mixed transition to underlying granite regolith are the parent material for **Alisols** in the midslope section (3). In the lower parts of the slope, the thick silt loam beds are present with **Retisols** (4), distinguished by interfingering of bleached coarser-textured soil material into the argic (Bt) horizon. The lowest slope section is occupied by **Luvisols,** developed from the shallow silt loam layer sharply separated from the underlying glaciofluvial materials (5).

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Area with hydrolithotoposequence of different deposits in the Haanja Upland (Estonia)

Endla Reintam, Marcin Świtoniak, Alar Astover, Raimo Kõlli, Merrit Shanskiy

The study area is located in the hilly area of South Estonia. It is the most "mountainous" area of Estonia and the Baltic States (Estonica, 2018). It consists of Devonian denuded sandstones and is mainly covered with moraine and ice lake sediments from different, predominantly the last Weichselian glaciation of the Lower Pleistocene (Raukas et al., 1995; Raukas and Kajak, 1997). The area is characterized by varied soils, which is caused by rapid alteration of sediments of different texture and origin, such as gravel, sand, varved clays, loams of different types and peat. According to Arold (2005), the study area is located in the Haanja Upland (Fig. 1). The Haanja Upland has a particularly characteristic border in the northwest and north, where it rises sharply from the outwash plain of the Hargla Depression and the eastern elongation, the Võru Vale, towards the south and southeast (Estonica, 2018). Various types of forests (predominantly spruce forest) cover about half of the territory (Haanja Nature Park, 2012).

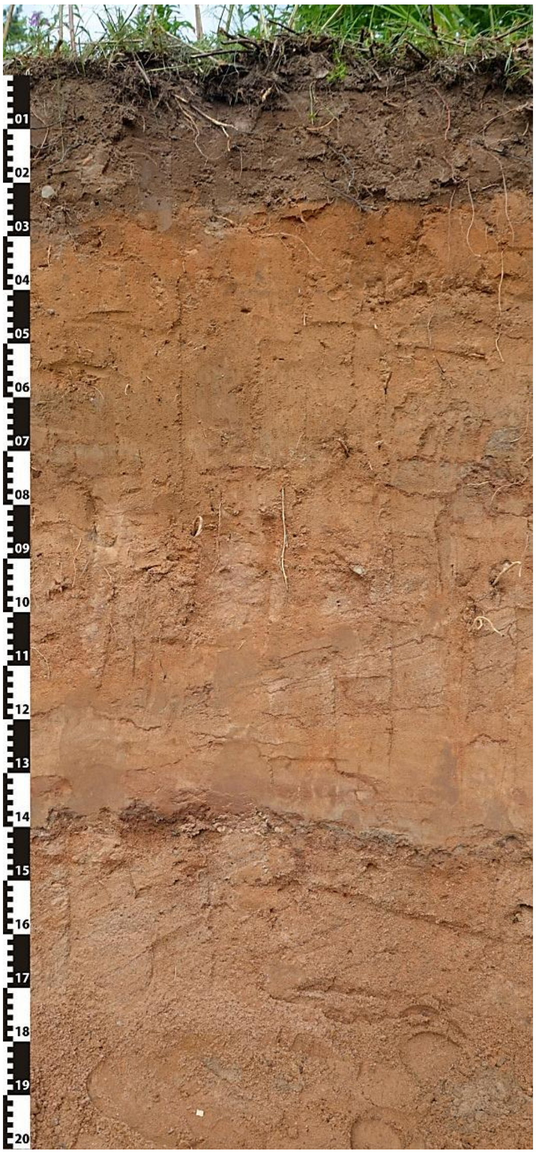
Fig. 1. Location

Lithology and topography

In Estonia, the Haanja Upland covers an area of 816 km^2 and the distance of 30 km from north to south at the Latvian border and about 40 km from west to east at the Russian border. The total area of the upland is about 2,500 km^2 as part of the Haanja Upland continues as the Aluksne Upland in Latvia (Arold, 2005; Haanja valla …, 2018). The contemporary Haanja Upland has probably been formed during the last million years. Part of its height is related to the crystal basement (gneiss and granite), covered by Vendi and Balti sedimentation cycles, Mid-Cambrian, Ordovicean and Silurian carbonated rocks and Devonian sands and sandstones. These sediments are covered by Quaternary deposits, such as glacial tills and fluvio- and limnoglacial sediments from four different ice ages. The most important sediments from ice melting periods are fluvioglacial sands and gravels as well as limnoglacial clays and sands. The glacial till cover ranges from a few meters to 20–40 m. The depth of Quaternary deposits exceeds 150 m in some parts of the upland (Haanja valla …, 2018). Most of the hillocks' bases are large moraines, which are covered with knolls of ice lake sediments. At the end of the glacial age, lakes were filled with sand and clay from their icy slopes. When the surrounding ice melted, hills (kames) remained. Many gravel-sand hillocks are covered with 1–2 m reddish brown glacial till with varying carbonate content (Raukas, Teedumäe, 1997; Arold, 2005; Haanja Nature Park, 2012).

Profile 1 – Epidystric Endoeutric Rubic Brunic **Arenosol** (Aric, Ochric, Endostagnic)

Localization: Hummock, middle slope – inclination 5–10°, south, deciduous scrub, 228 m a.s.l.
N 57°41'06.8" **E** 27°07'06.9"



Morphology:

Ah – 0–5 cm, fine sand, dark brown (10YR 3/3) many fine roots, granular moderate medium size structure, gradual smooth boundary;

Ap – 5–25 cm, fine sand, dark yellowish brown (10YR 3/4), few fine subrounded fresh coarse fragments, granular moderate medium size structure, few fine roots, abrupt and smooth boundary;

Bw – 25–60 cm, fine sand, strong brown (7.5YR 5/8), very few fine subrounded fresh coarse fragments, subangular weak fine structure, very few fine roots, gradual boundary;

BCg – 60–120 cm, fine sand and sandy loam mixture, strong brown (7.5YR 5/6), oximorphic features, few mottles, very few fine subrounded fresh coarse fragments, subangular weak fine structure, very few fine roots, gradual boundary;

Cg – 120–150 cm, fine sand, strong brown (7.5YR 5/6), very few fine subrounded fresh coarse fragments, oximorphic features, single grain structure, few fine roots, abrupt and smooth boundary;

2C – 150–(200) cm, medium sand, strong brown (7.5YR 5/6), single grain structure, very few fine roots.

Table 1. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
Ah	0–5	n.o.	4	15	33	39	6	3	0	0	0	FS
Ap	5–25	n.o.	3	9	28	46	7	7	0	0	0	FS
Bw	25–60	n.o.	3	11	31	43	6	6	0	0	0	FS
BCg	60–120	n.o.	2	11	39	43	3	2	0	0	0	FS
Cg	120–150	n.o.	0	1	15	70	10	4	0	0	0	FS
2C	150–(200)	n.o.	7	33	42	16	1	1	0	0	0	MS

Table 2. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
Ah	0–5	52.1	2.87	18	6.1	5.7	n.o
Ap	5–25	5.9	0.23	26	5.3	4.3	n.o
Bw	25–60	-	-	-	5.6	4.6	n.o
BCg	60–120	-	-	-	6.0	4.7	n.o
Cg	120–150	-	-	-	6.2	4.9	n.o
2C	150–(200)	-	-	-	7.0	6.9	n.o

Profile 2 – Stagnic Endogleyic **Luvisol** (Endoarenic, Aric, Colluvic, Cutanic, Humic, Epiloamic, Endoraptic)
Localization: medium gradient hill, lower slope – inclination 5–10°, terraced, grazed permanent grassland, 218 m a.s.l., **N** 57°41'01.3" **E** 27°07'10.9"

Morphology:

Ap – 0–25 cm, loam, dark yellowish brown (10YR 4/4), few fine subrounded fresh coarse fragments, medium size moderate granular structure, common fine roots, few concreate fragments, consisting *colluvic* material, clear and smooth boundary;

A – 25–40 cm, loam, very dark greyish brown (10YR 3/2), few fine subrounded fresh coarse fragments, medium size moderate granular structure, common fine roots, few medium charcoal pieces; clear and wavy boundary;

Btg – 40–55 cm, *argic* horizon, sandy loam, dark yellowish brown (10YR 4/4), many brown (7.5YR 5/6) mottles, *stagnic* properties, common fine subrounded fresh coarse fragments, fine size moderate angular blocky structure, common pedfaces clay coatings, few fine roots, clear and wavy boundary;

2Cl – 55–70 cm, fine sand, yellowish brown (10YR 5/4), common brown (7.5YR 5/6) mottles, very few fine subrounded fresh coarse fragments single grain structure, very few fine roots, common soft iron concretions, gradual boundary;

2Cl2 – 70–(90) cm, fine sand, light yellowish brown (10YR 6/4), common brown (7.5YR 5/6) mottles, very few fine subrounded fresh coarse fragments, single grain structure, reducing conditions, water table.

Table 3. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
Ap	0–25	n.o	0	4	13	14	9	14	21	12	13	L
A	25–40	n.o	2	6	14	19	8	9	15	11	16	L
Btg	40–55	n.o	4	8	21	29	10	5	4	2	17	SL
2Cl	55–70	n.o	2	11	26	45	7	9	0	0	0	FS
2Cl2	70–(90)	n.o	6	11	25	45	8	5	0	0	0	FS

Table 4. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
Ap	0–25	29.2	1.27	23	5.8	4.6	n.o
A	25–40	16.5	0.76	22	5.8	4.6	n.o
Btg	40–55	–	–	n.o	5.6	4.5	n.o
2Cl	55–70	–	–	n.o	6.0	4.7	n.o
2Cl2	70–(90)	–	–	n.o	6.3	5.0	n.o

Profile 3 – Eutric Rheic Epifibric Episapric Endohemic **Histosol**

Localization: Marsh in depression between hummocks, mixed forest dominated by spruce, groundwater feed bog peat, 214 m a.s.l., **N** 57˚41'00.8'' **E** 27˚07'13.3''

Morphology:

Ha – 0–20 cm, *histic* horizon, very strongly decomposed *sapric* organic material, gradual boundary;

Hi – 20–50 cm, *histic* horizon, slightly decomposed *fibric* organic material; gradual boundary;

He – 50–100 cm, *histic* horizon, strongly decomposed *hemic* organic material, gradual boundary;

Ha – 100–(130) cm, *histic* horizon, highly decomposed *sapric* organic material.

Table 5. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		CaCO$_3$ [g·kg^{-1}]
					H_2O	KCl	
Ha	0–20	372	25.4	15	7.0	6.7	0.3
Hi	20–50	375	22.0	17	7.0	6.6	0.3
He	50–100	367	18.6	20	7.3	6.7	0.4
Ha	100–(130)	–	–	–	–	–	–

The most elevated parts lie in the central and northern part of the upland, in the territory of Estonia, but the elevation of 250 m and more above sea level can be found over quite a large area (Estonica, 2018). Hills of varying size, shape and origin separated by hollows and valleys can be found here (Haanja Nature Park, 2012). The altitude difference in the Haanja Upland is 220 m and the average height above sea level is 200 m. Suur Munamägi, with the height of 317.4 m above sea level, is the highest elevation in the Baltic countries. The relative height of 84 m makes the hill of Vällamägi (303.9 m above sea level) 22 m higher than Suur Munamägi. The lowest place of 98.6 m above sea level is located at Lake Kahrila in the Rõuge Primeval Valley (Haanja Nature Park, 2012; Estonica, 2018). The central part of the study area is dominated by vast and high (25–60 m) flat-bottomed hillocks and drumlins with up to 40° inclination. The upland is cut by deep valleys — Kütiorg and the Piusa primeval valley, starting in the centre of the upland and descending towards the north. The depth of Kütiorg, the grandest primeval valley in Estonia, is up to 70 m and the length – approximately 5 km. The valleys are characterized by steep slopes and relatively narrow bottoms. The slopes of valleys are intersected by numerous gullies (Arold, 2005). The Haanja Upland has the largest number (175) of lakes in Estonia, formed as a result of melting dead ice blocks. Many of these lakes have become mires. Calcareous deposits are formed on the slopes of the buried valleys, due to the springs that release karst water rich in lime (Estonica, 2018).

Land use

Due to the changing texture and relief, 160–170 (maximum 400) different soil polipedons (contours on maps) per 1 km^2 can be found. This results in mosaic land use and vegetation pattern. More than half of the Haanja Upland is covered with forests and a heterogeneous network of small villages. As the area is hilly, every patch of land suitable for cultivation has been turned into fields and later overgrown with forest again. The main forest types are spruce (43–46%) and mixed forests (31%) along with secondary birch and aspen forests and shrublands. Pine forest grows on small hummocks with sandy texture. Marshes, mostly covered with sedges and/or birch, cover approximately 2.4% of the area. Due to the human activity, 22% of the arable soils are eroded and 9% covered by colluvium (Arold, 2005; Estonica, 2018).

Climate

The climate of study area is Boreal – snow, fully humid with warm summers (Kottek et al. 2006). The mean air temperature of the region is +4.0°C being lowest in Estonia. Also the coldest month February is with −7.7°C the coldest in Estonia. The average temperature in July is 16.3°C. The amount of precipitations with 750–800 mm is by 100–150 mm bigger than in the surroundings. Due to the high variability of the landscape, the temperature differences up and down hill can vary by 10°C in early spring and late autumn. Night frost can last more than 30 days longer and start 15 days earlier in the valleys than on the hills. Vegetative period generally lasts for 170–185 days. Snow cover lasts in average 125 days – from December till April. It means almost 2 months longer than in average in Estonia (Haanja valla …, 2018; Haanja Nature Park, 2012; Arold, 2005).

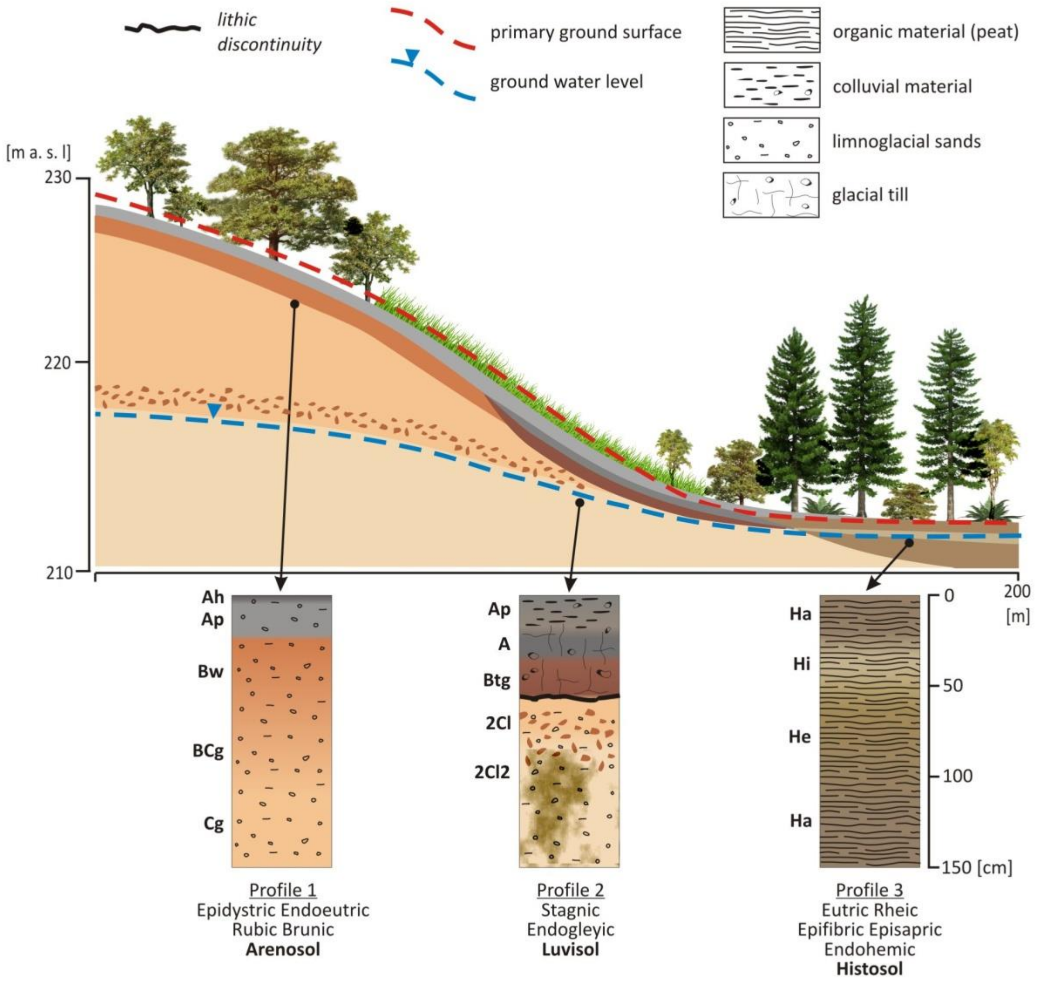


Fig. 2. Hydrolithotoposequence of the soils on different deposits in the Haanja Upland

Soil genesis and systematic position

The investigated soil profiles represent the typical variation of soils of the Haanja Upland with different deposits at different heights and covered by various vegetation.

Profile 1 is typical for the middle, drier part of sandy hummocks. Soil is formed on fine limnoglacial sands (Table 1) without a layer of organic matter. The 25 cm deep humus (A) horizon is well developed and clearly divided into two parts. The upper 5 cm contain more organic carbon (Ah) and the lower 20 cm contain less organic carbon (Ap). The abrupt boundary of the humus horizon (Ah+Ap) with the following accumulation horizon (Bw) indicates the use of the area as a field in the past. The ploughed layer provides the soil with the supplementary qualifier ***Aric***. The humus horizon is not dark and deep enough to meet the requirements of *Mollic* or *Umbric*. However, with an organic carbon content higher than 0.2% (Table 2) and a total depth of more than 10 cm, it meets the requirements of the qualifier ***Ochric***. The accumulation horizons (Bw, BCg) are well developed. The profile is Ah–Ap–Bw–BCg–Cg–2C. There are no diagnostic horizons or materials presented. Its textural class is sand (Table 1), hence it meets the requirements of **Arenosol**. As the pH of water in the most upper part of the A horizon is less than 5.5 (Table 2), the soil principal qualifier ***Epidystric*** can be used. The lower part of the solum has higher pH values, which allows the use of ***Endoeutric***.

The accumulation horizon (Bw) with a strong brown (7.5YR 5/8) colour and the thickness of 35 cm meets the criteria of the principal qualifiers ***Brunic*** and ***Rubic***. Due to the sandy texture, it cannot be indicated as a *cambic* horizon. Oximorphic features at a depth of 60–200 cm meet the criteria of the supplementary qualifier ***Endostagnic***. The abrupt textural change is deeper than 100 cm and cannot be considered as the *Endoraptic* qualifier in this profile.

There are usually no *Brunic Arenosols* classified in the Estonian local classification system. Soils with sandy texture and with low pH having a dark brown illuvial or accumulation horizon are classified as weakly podzolic soils (Astover et al., 2012) or if the humus horizon is dark enough, the soils can be classified as *Umbrisols*. However, intensive podsolization may occur only under the influence of strong fulvic acids and good infiltration on sandy texture (Lundström et. al, 2000). In addition, the area has long been used for agricultural purposes. As the profile is not at the very top of the slope, the soil is classified as gleyic colluvic soil on the Estonian soil map (Estonian Soil Map). Soils of the higher part of the slope are classified as strongly eroded soils (230 m a.s.l.), while soils at the top of the hill (235 m a.s.l.) as weakly eroded ***Endocalcaric*** **Luvisols**. According to the WRB, soils of the upper hill, if eroded, can be classified as ***Dystric*** or ***Eutric*** **Regosols** (IUSS Working Group WRB, 2015). Adding the supplementary qualifier ***Colluvic*** to Profile 1 may be justified as the total depth of the humus horizon varies from 25 cm to 30 cm. However, as the ploughed layer (Ap) is already covered with a 5 cm thick layer containing larger amounts of organic carbon (Table 2), this indicates a long period of permanent vegetation cover for decades.

Profile 2 differs from Profile 1 in the elevation but also in texture. Profile 2 is located in the lower part of the slope. The texture ranges from loam to sandy loam in the upper 55 cm part of the profile. Fine sand occurs again in deeper parts, as in Profile 1. The humus horizon (A) is clearly visible, which can be divided into two parts (Ap+A), and the illuvial horizon (Bt), giving us the profile Ap–A–Btg–2Cl–2Cl2. There is no *mollic* or *umbric* horizon present, as the colour of the humus horizon is too light (10YR 4/4). The illuvial horizon meets the requirements of the *argic* horizon. The clay content is 17% (Table 3) and clay coatings were visible. Due to the *argic* horizon at a depth of 40–55 cm, the soil can be classified as **Luvisol**. The soil principal qualifier ***Stagnic*** can be applied based on the oximorphic colour pattern in the Bt horizon and the qualifier ***Endogleyic*** – based on the colour change and the presence of water in the profile in deeper sand. Due to the textural change in the profile at a depth of 55 cm, the supplementary qualifiers ***Endoarenic*** and ***Endoraptic*** can be applied. Nowadays, the study area is used as a permanent grassland for grazing. In the past, the area was used as a ploughed field. The deep (40 cm) humus horizon has a clear boundary between the upper and lower part. The presence of charcoal at the boundary indicates the initial upper part of the humus horizon. It is likely that the upper part of the humus horizon was formed as a result of the material accumulation due to erosion in the upper slope. The supplementary qualifiers ***Aric*** and ***Colluvic*** reflect the ploughing and soil erosion, respectively. The presence of clay coatings in the Bt horizon justifies the qualifier ***Cutanic***. More than 1% of organic carbon in the humus horizon (Table 4) justifies the qualifier ***Humic***.

Luvisol with a heavier texture on the sand in the lower part of the slope indicates the high variability of the deposits of the investigated area. This part of the slope is probably covered with a thin layer of glacial till, which lies on glacilimnic sands (Raukas, Teedumäe, 1997; Arold 2005; Haanja Nature Park, 2012). Due to the higher content of clay and silt (Table 3) and infiltration, the illuviation of clay particles and the formation of the *argic* horizon was possible. However, in similar soils it is questionable whether we have a *cambic* or *argic* horizon (Świtoniak et. al., 2016). Typically, similar soils without an eluvial horizon are classified in the Estonian classification system as *Cambisols*. In the current profile, the B horizon can be classified as *cambic* according to the requirements of colour and thickness. However, since the horizon contains more clay compared to the upper A horizon and there is clear evidence of clay coatings, it should be distinguished as an argic horizon (IUSS Working Group WRB, 2015). Another question arises due to the water in the profile. With such a high water level, the soils in the Estonian classification are classified as *Gleysols*. According to WRB, **Gleysols** are soils with *gleic* properties and reductiomorphic ≥95% or oximorphic colour >5% starting closer than 40 cm from the soil surface. The oximorphic mottles starts deeper than 40 cm in this profile and thus only the ***Endogleyic*** qualifier can be added to the profile according to the WRB.

Profile 3 is located at the bottom of the slope. The area is covered with a mixed forest. The whole profile (more than 130 cm deep) consists of organic material at various stages of decomposition meeting the criteria of the *histic* horizon and the soil should be classified as **Histosol**. The overall profile is Ha–Hi–He–Ha. The upper 20 cm contained a very strongly decomposed *sapric* organic material, followed by 30 cm of *fibric* and more than 80 cm of *hemic* organic material. As the pH of water is 7.0, the principal qualifier ***Eutric*** can be added to the soil. The qualifier ***Rheic*** can be used due to the constantly high groundwater level. The higher degree of decomposition of organic matter in the upper part results from seasonal fluctuations in groundwater levels. The fluctuation of the groundwater table can be more than 1 m during the season. The driest month is usually May, when also the growth of vegetation and thus the water consumption is the highest.

The paludification of wet hollows between the hillocks is widespread on the Haanja Upland. Since many small lakes have no outflow, after some time they become overgrown with vegetation. The depth of moderately or strongly decomposed peat is usually more than 100 cm. The thickest peat layer in Estonia – 17 m was measured on the eastern foot of Vällämägi (Haanja Nature Park, 2012). The peat is formed mainly from different sedges and covered with sedges and birches (Arold, 2005).

Soil sequence

The above-described transect shows transformations of soil cover on different deposits in the Haanja Upland. Properties of the two analysed profiles, Profile 1 and Profile 2 were influenced by rainwater and human activity. Profiles 2 and 3 were affected by groundwater. The differences between all profiles are the result of different deposits as a parent material and also hydrological conditions. Both Profile 1 and Profile 2 are strongly influenced by human activity through soil tillage in the past, resulting in a thicker humus horizon, so Profile 2 is more affected by colluvium. The transect does not reflect the whole diversity of the area, as more than 150 soil types can be found in one km^2. The sequence from ***Epidystric Endoeutric Rubic Brunic Arenosol*** (***Aric, Ochric, Endostagnic***) to ***Stagnic Endogleyic Luvisol (Endoarenic, Aric, Colluvic, Cutanic, Humic, Endoraptic)*** and to ***Eutric Rheic Epifibric Episapric Endohemic Histosol*** represents part of the typical soil formation with changing water saturation conditions on different deposits in the Haanja Upland.

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Soils of tunnel valleys (Brodnica Lake District, Poland)

Marcin Świtoniak

Soil pits are located on the slope and the bottom part of a tunnel valley (these valleys in the Polish literature are also referred to as subglacial channels), which was formed during the youngest, Pomeranian phase of the Weichselian glaciation (16–17 kyr BP; Fig.1; Roszko, 1968; Marks, 2012). It represents specific for this region, very important and characteristic part of the young glacial landscape. According to Kondracki (2001), the studied soil sequence is located at the border of two mesoregions – the Brodnica Lake District and the Drwęca Valley.

Fig. 1. Location

Lithology and topography

The tunnel valleys of the region are long landforms (NW–SE orientation) reaching several dozen kilometres in length, clearly intersected on the morainic plateau and outwash plains. Their slopes are up to 40 m high. The width rarely exceeds 500 m (Burak et al., 2008). During the deglaciation period (16–17 kyr), tunnel valleys were filled with dead ice and thus they were not filled with outwash sediments. Melting of buried ice during warm phases of the late glacial period, mostly in the Alleröd led to the "exhumation" of subglacial channels, which were then filled with water from numerous lakes (Niewiarowski, 1986). The slopes of tunnel valleys were built of coarse- and medium-grained outwash sands. In the southern part of the Lake District, outwash sediments are finer and better sorted (more homogenous). The bottom part of the tunnel valleys in the parts not covered by lake water is filled with organic (peat or gyttja) and mineral sediments (Wysota, 2003). The thickness of these sediments reaches many meters.

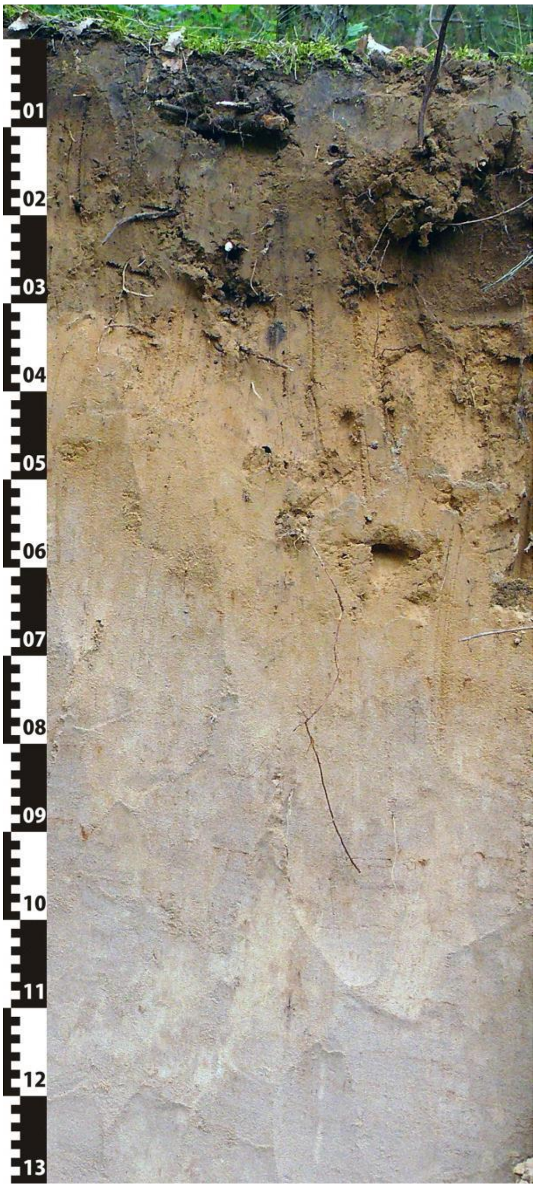
Land use

The slopes of the tunnel valley are overgrown with Scots pines (*Pinus sylvestris*). Species typical of hornbeam forest (*Carpinus betulus, Tilia cordata,* and *Quercus sp.*) dominate in the understory, the herb layer and the forest floor. The bottom of the channels is mostly occupied by lakes, in some places – alders and marshy meadows.

Climate

The region is located in the zone of moist and cool temperate climate (IPCC, 2006). According to Köppen–Geiger Climate Classification, the region is located in the fully humid zone with temperate and warm summer (Kottek et al., 2006). The average annual air temperature is about 7°C. The warmest month is July (17.6°C). The mean air temperature during January (coldest winter month) is about -4°C. The average annual precipitation is 552 mm. July is the wettest month with average precipitation around 90 mm (Wójcik and Marciniak, 1987a, b, 1993).

Profile 1 – Epidystric Endoeutric Brunic **Arenosol** (Aric, Nechic, Ochric)
Localization: Outwash plain, flat - inclination 1°, pine plantation with deciduous forest undergrowth,
85 m a.s.l., **N** 53°17'15.1" **E** 19°28'52.5"



Morphology:

Oi – 3–1 cm, slightly decomposed organic material;

Oe – 1–0 cm, moderately decomposed organic material;

A – 0–10 cm, humus horizon, fine sand, dark brown (10YR 5/3; 10YR 3/3), slightly moist, weak granular fine structure, fine and medium common roots, gradual and smooth boundary;

A(p) – 10–30 cm, plough humus horizon, fine sand, yellowish brown (10YR 6/3; 10YR 5/4), slightly moist, weak granular fine structure, fine and medium few roots, abrupt and smooth boundary;

Bw – 30–65 cm, *brunic* material, *in-situ* concentration of sesquioxides, fine sand, brownish yellow (10YR 7/6; 10YR 6/8), slightly moist, weak granular very fine/single grain structure, very few roots, diffuse and wavy boundary;

C – 65–(130) cm, parent material, fine sand, very pale brown (10YR 8/3; 10YR 7/3), slightly moist, single grain structure.

Table 1. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
A	0–10	2	2	12	53	25	2	1	2	2	1	FS
Ap	10–30	3	3	16	52	23	4	1	0	0	1	FS
Bw	30–65	1	4	18	51	19	5	1	0	1	1	FS
C	65– (130)	1	3	17	48	22	6	2	1	1	0	FS

Table 2. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
Oi	3–1	411	15.2	27	4.2	4.0	-
Oe	1–0	409	16.2	25	4.3	3.7	-
A	0–10	9.1	0.61	15	4.3	3.9	-
Ap	10–30	6.4	0.42	15	4.5	4.1	-
Bw	30–65	-	-	-	4.8	4.5	-
C	65– (130)	-	-	-	5.4	5.0	-

Profile 2 – Eutric Rubic Brunic **Arenosol** (Nechic, Ochric)
Localization: Tunnel valley, foot slope, inclination 10°, mixed forest with dominant pines in first floor,
75 m a.s.l. **N** 53°17'12.4" **E** 19°28'45.6"

Morphology:

Oi – 2–1 cm, slightly decomposed organic material;

Oe – 1–0 cm, moderately decomposed organic material;

A – 0–15 cm, humus horizon, fine sand, dark brown (10YR 6/3; 10YR 3/3), slightly moist, weak granular fine structure, fine and medium common roots, clear and smooth boundary;

Bw – 15–50 cm, *brunic* material, concentration of sesquioxides, fine sand, dark yellowish brown (10YR 6/4; 10YR 4/4), slightly moist, weak granular very fine/single grain structure, fine and medium common roots, diffuse and smooth boundary;

BC – 50–90 cm, transitional horizon, fine sand, brownish yellow (10YR 7/6; 10YR 6/8), slightly moist, weak granular very fine/single grain structure, very few roots, diffuse and wavy boundary;

C – 90–(150) cm, parent material, fine sand, very pale brown (10YR 8/3; 10YR 7/3), slightly moist, single grain structure.

Table 3. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
A	0–15	2	5	15	48	22	3	3	1	2	1	FS
Bw	15–50	3	4	18	50	21	4	1	0	0	2	FS
BC	50–90	4	4	16	47	20	7	1	2	2	1	FS
C	90– (150)	3	2	14	45	24	8	3	2	1	1	FS

Table 4. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
Oi	2–1	442	16.2	27	4.6	4.2	-
Oe	1–0	318	16.7	19	4.7	4.2	-
A	0–15	12.1	0.92	13	4.9	4.5	-
Bw	15–50	3.5	0.33	11	5.4	5.0	-
BC	50–90	-	-	-	5.7	5.2	-
C	90– (150)	-	-	-	6.2	5.7	-

Profile 3 – Eutric Mollic **Gleysol** (Arenic, Humic)
Localization: Bottom of the tunnel valley - flat 1°, riparian forest, 71 m a.s.l.
N 53°17'12.7" **E** 19°28'43.2"

Morphology:

Oi – 1–0 cm, slightly decomposed organic material;

Ah – 0–40 cm, *mollic* horizon, fine sand, dark brown (7.5YR 4/1; 7.5YR 3/2), moist, weak moderate granular structure, fine and very fine and common roots, abrupt and wavy boundary;

Cr – 40–(50) cm, fine sand, light gray (2.5Y 6/2; 2.5Y 7/2), very wet, single grain structure, fine and very few roots, strong reduction, few ferruginous soft concretions.

Table 6. Texture

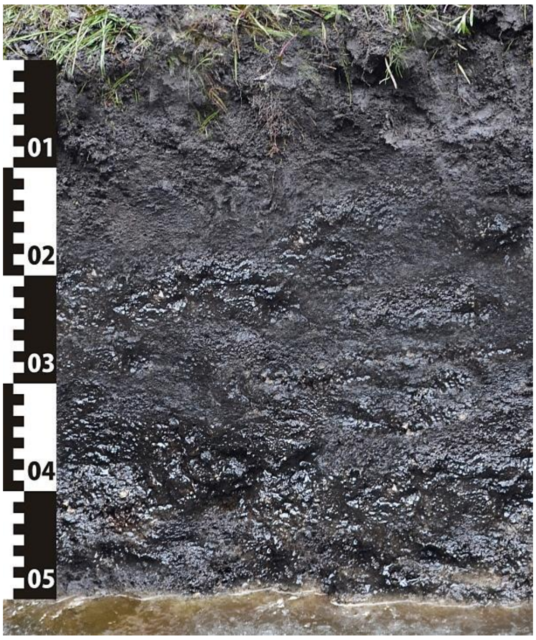
Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
Ah	0–40	5	5	17	39	24	5	5	2	2	1	FS
Cr	40–(50)	4	3	19	42	25	7	2	0	1	1	FS

Table 7. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
Oi	1–0	428	19.6	22	5.3	5.0	-
Ah	0–40	22.7	1.88	12	5.9	5.5	-
Cr	40-(50)	-	-	-	6.7	6.5	trace

Profile 4 – Eutric Rheic Sapric **Histosol**

Localization: Bottom part of tunnel valley, flood plain, flat terrain 0°, meadow, 70 m a.s.l.
N 53˚19’12.7’’ **E** 19˚26’48,7’’



Morphology:

Ha – 0–20 cm, highly decomposed *histic* horizon, very dark gray (5Y 4/1; GLEY1 3/N), moist, coarse granular moderate structure, fine common roots, gradual and smooth boundary;

Ha2 – 20–(50) cm, highly decomposed *histic* horizon, black (5Y 4/1; GLEY1 2.5/N), very wet, granular / layered structure, fine few roots, gradual and smooth boundary.

Table 7. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		CaCO$_3$ [g·kg^{-1}]
					H$_2$O	KCl	
A	0–10	35.5	2.76	13	6.1	5.8	-
2Cr	70–(90)	-	-	-	6.8	6.5	trace

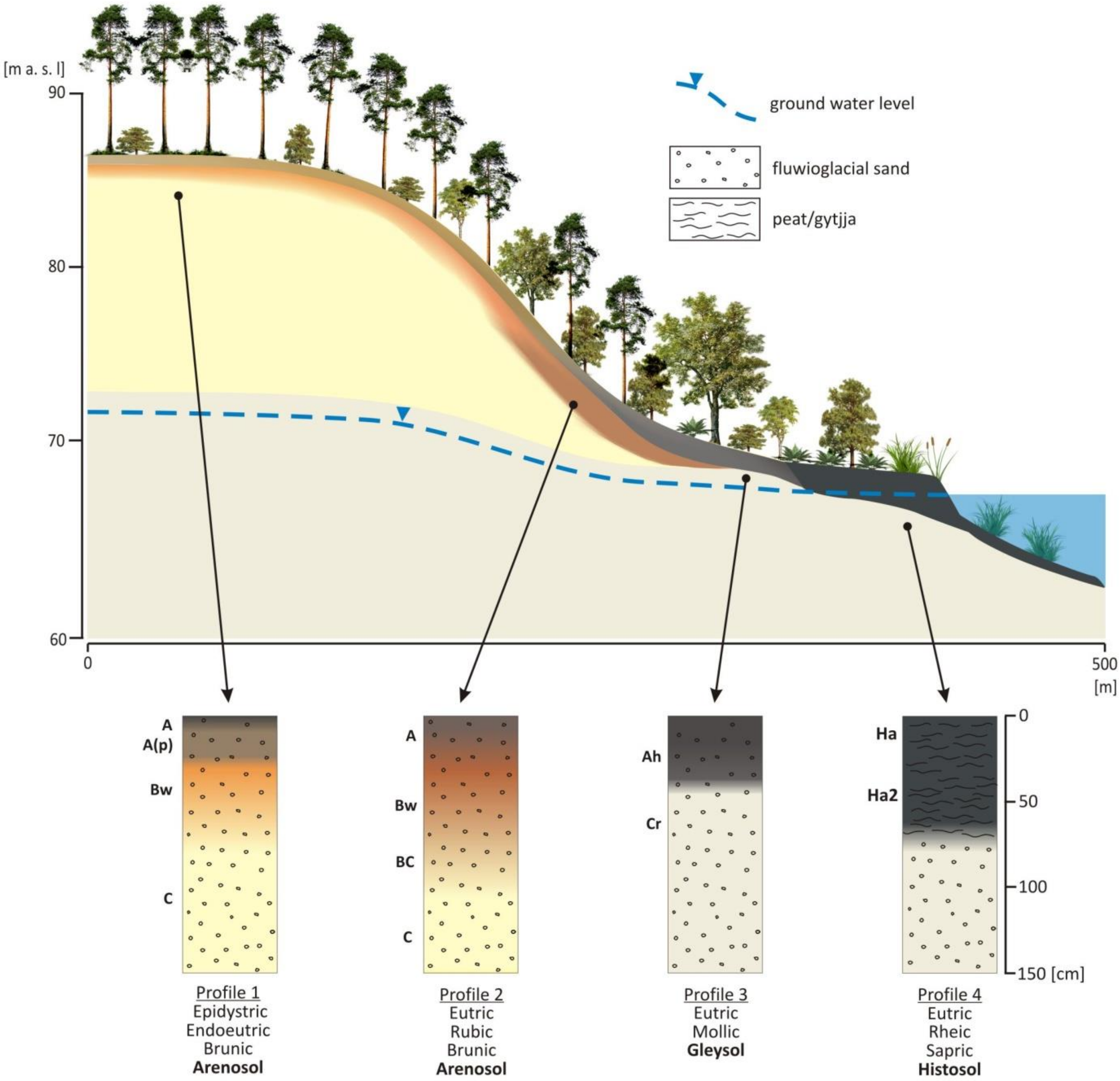


Fig. 2. Hydrotoposequence of the soils on slopes of tunnel valley, Brodnica Lake District

Soil genesis and systematic position

The investigated soil profiles represent the typical variability of soils developed on slopes and bottom parts of the tunnel valleys in the Brodnica Lake District. A common feature for most of the described soils is coarse texture inherited from fluvioglacial sands prevailing on slopes of these valleys.

Pedons 1 and 2 were classified as **Arenosols.** The entire profiles of these soils were built of material, in which the fraction of 0.5–0.25 mm dominates (Table 1 and 3). Both pedons had a A-B-C sequence of horizons, but none of them had a diagnostic character. Humus horizons were not dark enough to meet the criteria of *mollic* or *umbric*, except for the upper part of the A horizon in the first profile, which in turn was not thick enough. The only way to express the presence of these humus horizons in the classification of the soil was to apply the ***Ochric*** supplementary qualifier. The relatively weak development of A horizons (compared to fertile soils of this region – like Gleyic Chernozems, Phaeozem etc.) relates to strong permeability (low moisture) and lack of minerals rich in mineral nutrients – the composition of fluvioglacial sands is characterized by the predominance of quartz. Moreover, the composition of humus compounds in the described soils is dominated by light-coloured fulvic acids (Plichta, 1981). The uppermost part of A horizons (between approximately 0 and 10 cm – from the mineral surface of soil) had common uncoated quartz grains of sand in the dark humus matrix – therefore, the ***Nechic*** qualifier was used. These bleached grains are probably the result of the impact exerted by the initial podzolization process. Migration of Al, Fe and organic compounds was stimulated by acidification of the upper part of the soil as a consequence of planting pine monocultures (Jankowski, 2014). The homogeneous nature of the A horizon from 0 to 30 cm from the mineral surface in Profile 1 and its abrupt lower boundary are not typical for forest soils. These features are generally found in arable soils (***Aric***) and, in this case, may be inherited from the past agricultural use of the described soils (Bednarek and Michalska 1998; Sewerniak et al., 2014a) or they are remnants of pine planting (Sewerniak et al., 2014b). Despite the presence of the above-mentioned “tillage” features, the studied soils have not been ploughed for many years and the “p” designation was used in brackets.

Bw horizons with a significant *in situ* concentration of aluminium and iron sesquioxides are located directly below the humus horizons. This is clearly visible in the form of brown and orange colouring of the mineral material. The accumulation of iron and aluminium in these horizons is mainly the result of biochemical weathering of fluvioglacial sands (Bednarek, 1991). In both cases, the Bw material meets diagnostic criteria 2–4 of the *cambic* horizon, but fails criterion 1 due to sandy texture (IUSS Working Group WRB, 2015). Therefore, the presence of this pedogenic material could only be emphasized by the use of the ***Brunic*** principal qualifier. In Profile 2, the Bw horizon was also red enough (Munsell colour chroma ≥ 5 in moist state) for the ***Rubic*** qualifier. Although both soils are acidic, the pH values allow to assume that the effective base saturation is < 50% only in the upper part (0–65 cm) of the first pedon (***Epidystric***) and ≥ 50% in the remaining mineral part of the discussed soils (***Endoeutric*** in Profile 1 and ***Eutric*** in Profile 2).

The third profile is also characterized by sandy texture (***Arenic***) along with *gleyic* properties and strong reductimorphic features clearly visible just below the lower boundary (40 cm) of the humus horizon. The colour of the soil matrix in the parent material (hue 2.5Y and chroma 2 – moist) indicates the reducing conditions. The presence of all these features related to the strong influence of groundwater allows to classify the soil as **Gleysol** (IUSS Working Group WRB, 2015). The pH values imply high base saturation (higher than > 50%), which resulted in the use of the ***Eutric*** qualifier. The humus horizon has a significant thickness – 40 cm, dark colour and high content of organic carbon (more than 2%). The described features along with BS > 50% and well-developed soil structure, made it possible to determine the *mollic* horizon expressed by the ***Mollic*** qualifier. The soil organic carbon as a weighted average to a depth of 50 cm from the mineral soil surface was > 1%, which was emphasized by the ***Humic*** supplementary qualifier.

The last investigated pedon (Profile 4) was classified as **Histosol**. It was built of *organic* material having a thickness of > 50 cm (*histic* horizon) formed from the accumulation of highly decomposed ***(Sapric)*** remnants of wetland plants. The predominant saturation by groundwater was expressed by the ***Rheic*** qualifier.

Soil sequence

The described sequence of soils is determined by changes in water conditions resulting from different topographic positions of particular pedons. Spatial arrangement of soils resulting from such a set of soil-forming factors is called **hydrotoposequence**. The first two profiles (**Arenosols**) were located on the slope of the valley, beyond the influence of groundwater. In Profile 2, however, accumulation of iron compounds (***Rubic***) is much greater compared to Profile 1. The former soil has only *in situ* (***Brunic***) accumulation of sesquioxides resulting from biochemical weathering of fluvioglacial sands. The foot slope position of Profile 2 enables also the accumulation of allochthonous iron compounds, migrating with subsurface waters down the slope (Jankowski, 2013). The influence of this water is also visible in slightly higher pH values in Profile 2 (***Eutric***) compared to Profile 1 (***Epidystric, Endoeutric***).

Profile 3 was located in the bottom of the tunnel valley – in the toe slope position. This soil is strongly influenced by groundwater (***Gleysol***). It is reflected by reductimorphic features and high pH values (***Eutric***). Moreover, the high moisture obstructs the flow of oxygen from the atmosphere and reduces the rate of decomposition of organic remnants, which led to the development of a thick Ah *mollic* horizon (***Mollic, Humic***).

Profile 4 was located in the lowest topographic position – within the biogenic plain in the form of a narrow strip north-east of Lake Bachotek. A very shallow groundwater level led to frequent oxygen depletion in the soil, organic material accumulation and development of **Histosol**.

The presented catena shows slight anthropogenic changes of soils. Forest vegetation protects steep slopes against soil erosion. Planting of pines could lead to the development of the initial phase of the podzolization process (***Nechic***)

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Soils of erosional valleys on the Pleistocene terraces of the Drwęca Valley (North Poland)

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The River Drwęca with a total length of 207 km is the largest right-bank tributary of the lower Vistula. The Drwęca Valley covers an area of 320 km^2, a length of 100 km and a width of 1 to 6 km. The valley was developed as an ice-marginal streamway during the Pleistocene in the Pomeranian phase of the Weichselian glaciation (16–17 kyr BP; Fig.1; Niewiarowski, 1968, 1986; Roszko, 1968; Marks, 2012). According to Kondracki (2001), the Drwęca Valley is a mesoregion that dissects the morainic plateaus adjacent to the north-west (Brodnica and Chełmno Lake District) and south-east (Dobrzyń Lake District and Mound of Lubawa).

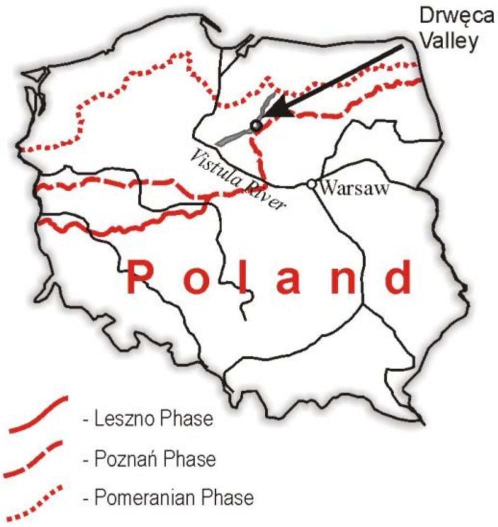

Fig. 1. Location

Lithology and topography

The valley consists of 11 terraces (Niewiarowski, 1968), which in the studied region lie at an elevation ranging from approx. 70 to 90 m a.s.l. They are mainly built of non-calcareous fluvial sands, rarely separated by layers of limnic silts and clays, calcareous in many cases. Limnic deposits usually occur at depths of a few meters and are a remnant of periodic shallow closed lakes formed after melting of dead ice blocks. The slopes between individual terraces are often steep and several meters high. The surface of the Drwęca terraces are relatively flat but are dissected by a large number of small valleys of different origin. The surveyed erosional forms developed as a result of the activity of small permanent or seasonal creeks flowing down the morainic plateaus (Niewiarowski, 1968).

The bottom part of the Drwęca Valley is a flood plain filled with alluvial deposits and biogenic plains – peat bogs. The thickness of these sediments reaches many meters.

Land use

The flat surfaces and slopes of the sandy terraces are overgrown with managed forests dominated by Scots pine (*Pinus sylvestris*) in the upper floor. Species typical of hornbeam forest (*Carpinus betulus, Tilia cordata,* and *Quercus sp*) dominate in the understory, the herb layer and the forest floor. Deciduous forests with a dense forest floor regenerate at the bottoms of erosional valleys.

Climate

The region is located in the zone of moist and cool temperate climate (IPCC, 2006). According to Köppen–Geiger Climate Classification, the region is located in the fully humid zone with temperate and warm summer (Kottek et al., 2006). The average annual air temperature is about 7°C. The warmest month is July (17.6°C). The mean air temperature during January (coldest winter month) is about -4°C. The average annual precipitation is 552 mm. July is the wettest month with average precipitation around 90 mm (Wójcik and Marciniak, 1987a, b, 1993).

Profile 1 – Dystric Brunic **Arenosol** (Aric, Nechic, Ochric)

Localization: Pleistocene terrace, upper slope, inclination 4°, pine plantation with deciduous forest undergrowth, 92 m a.s.l., **N** 53°16'50.4" **E** 19°30'35.3"

Morphology:

Oi – 3–2 cm, slightly decomposed organic material;

Oe – 2–0 cm, moderately decomposed organic material;

A – 0–5 cm, humus horizon, fine sand, dark grayish brown (10YR 6/2; 10YR 4/2), slightly moist, weak granular fine structure, few uncoated white sand grains, fine and medium common roots, clear and smooth boundary;

AB(p) – 5–20 cm, transitional horizon with plough features, fine sand, dark yellowish brown (10YR 5/4; 10YR 3/4), slightly moist, weak granular fine structure, fine and medium few roots, abrupt and smooth boundary;

Bw – 20–80 cm, *brunic* material, *in-situ* concentration of sesquioxides, fine sand, dark yellowish brown (10YR 6/6; 10YR 4/6), slightly moist, weak granular very fine/single grain structure, very few roots, diffuse boundary;

C – 80–(140) cm, parent material, fine sand, pale brown (10YR 7/3; 10YR 6/3), slightly moist, single grain structure, very few roots.

Table 1. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
A	0–5	2	1	1	19	64	8	4	1	0	2	FS
AB(p)	5–20	3	2	5	32	47	8	3	1	0	2	FS
Bw	20–80	5	2	3	40	50	3	2	0	0	0	FS
C	80–(140)	0	0	0	36	62	1	1	0	0	0	FS

Table 2. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
Oi	3–2	463	9.89	46	5.0	4.0	-
Oe	2–0	398	16.5	40	4.8	3.7	-
A	0–5	20.1	0.81	25	4.0	3.4	-
AB(p)	5–20	9.5	0.41	23	5.4	4.0	-
Bw	20–80	2.6	0.15	-	5.6	4.2	-
C	80–(140)	-	-	-	5.9	4.3	-

Profile 2 – Epidystric Endoeutric Brunic **Arenosol** (Colluvic, Ochric, Bathyprotocalcic)
Localization: Erosional valley, middle slope, inclination 30°, mixed forest with dominant pines in overstory, 88 m a.s.l., **N** 53°16'50.8" **E** 19°30'33.8"

Morphology:

Oi – 2–1 cm, slightly decomposed organic material;

Oe – 1–0 cm, moderately decomposed organic material;

A – 0–20 cm, humus horizon, fine sand, brown (10YR 6/3; 10YR 4/3), slightly moist, weak granular fine structure, fine and medium common roots, gradual and broken boundary;

A/Bw – 20–70 cm, mixed horizon – humus and *brunic* material, concentration of sesquioxides, fine sand, brown (10YR 7/3; 10YR 5/3), slightly moist, weak granular very fine/single grain structure, fine and medium common roots, diffuse and broken boundary;

BC – 70–120 cm, transitional horizon, fine sand, brown (10YR 6/3; 10YR 5/3), slightly moist, weak granular very fine/single grain structure, very few roots, diffuse boundary;

2BCk – 120–180 cm, transitional horizon with *protocalcic* properties, loam, very pale brown (10YR 8/3; 10YR 7/3), slightly moist, secondary and primary carbonates, weak granular very fine structure;

3C – 180–(230) cm, parent material, loamy fine sand, very pale brown (10YR 8/2; 10YR 8/3), slightly moist, weak granular very fine structure.

Table 3. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
A	0–20	3	1	2	12	69	12	3	0	1	0	FS
A/Bw	20–70	3	4	1	12	67	12	2	0	1	1	FS
BC	70–120	1	3	1	5	54	32	3	0	1	1	FS
2BCk	120–180	0	15	0	1	3	24	29	15	4	9	L
3C	180–(230)	0	2	0	0	16	60	15	3	1	3	LFS

Table 4. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
Oi	2–1	253	14.9	25	6.7	6.1	-
Oe	1–0	153	8.14	15	7.1	6.2	-
A	0–20	8.6	0.5	16	5.3	3.8	-
A/Bw	20–70	1.8	0.1	-	5.9	4.1	-
BC	70–120	1.9	0.2	-	8.6	7.7	16
2BCk	120–180	1.2	0.05	-	8.9	7.8	134
3C	180–(230)	-	-	-	9.2	8.1	65

Profile 3 – Dystric **Arenosol** (Ochric, Bathythaptoochric)

Localization: Erosional valley, lower slope, inclination 30°, mixed forest with dominant pines in overstory, 85 m a.s.l., **N** 53°16'54.0" **E** 19°29'55.6"

Morphology:

Oi – 2–1 cm, slightly decomposed organic material;

Oe – 1–0 cm, moderately decomposed organic material;

A – 0–10 cm, humus horizon, fine sand, very dark gray (10YR 5/2; 10YR 3/1), slightly moist, weak granular fine structure, fine and medium common roots, clear and smooth boundary;

C – 10–130 cm, parent material, fine sand, pale brown (10YR 7/2.5; 10YR 6/3), slightly moist, single grain structure, fine and medium very few roots, abrupt and smooth boundary;

2Ab – 130–140 cm, buried humus horizon, fine sand, very dark grayish brown (10YR 4.5/2; 10YR 3/2), slightly moist, weak granular very fine/single grain structure, very few roots, abrupt and smooth boundary;

2C – 140–210 cm, parent material, fine sand, pale brown (10YR 7/3; 10YR 6/3), slightly moist, single grain structure;

3Ck – 210–220 cm, parent material, silt loam, light olive brown (2.5Y 7/3; 2.5Y 5/3), slightly moist, primary and secondary carbonates, weak granular very fine structure;

4C – 220–240 cm, parent material, fine sand, brown (10YR 6/3; 10YR 5/3), slightly moist, single grain structure;

5Ckr – 240–(260) cm, parent material with *gleyic* properties, silt loam, dark grayish brown (2.5Y 6/2; 2.5Y 4/2), wet, massive structure.

Table 6. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
A	0–10	1	1	3	18	66	7	2	2	0	1	FS
C	10–130	0	0	0	3	89	8	0	0	0	0	FS
2Ab	130–140	0	1	2	17	68	8	2	1	1	0	FS
2C	140–210	1	9	1	7	54	21	5	1	2	0	FS
3Ck	210–220	0	19	0	1	2	6	14	36	14	8	SiL
4C	220–240	2	5	4	20	59	8	2	1	1	0	FS
5Ckr	240–(260)	0	20	0	0	0	4	14	36	13	13	SiL

Table 7. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
Oi	2–1	276	11.0	28	5.8	4.9	-
Oe	1–0	135	6.7	13	5.7	4.6	-
A	0–10	10.2	0.7	15	3.9	3.7	-
C	10–130	-	-	-	5.3	4.5	-
2Ab	130–140	4.3	0.3	15	7.2	6.0	trace
2C	140–210	-	-	-	8.6	7.6	12
3Ck	210–220	2.8	0.3	-	8.5	7.3	167
4C	220–240	-	-	-	8.9	8.0	4
5Ckr	240–(260)	8.4	0.3	-	8.2	7.3	205

Profile 4 – Haplic **Phaeozem** (Arenic, Colluvic, Pachic)

Localization: Erosional valley, bottom, inclination 2°, mixed forest with dominant pines in overstory, 81 m a.s.l., **N** 53˚16’52.8’’ **E** 19˚29’56.3’’

Morphology:

Oi – 4–2 cm, slightly decomposed organic material;

Oe – 2–0 cm, moderately decomposed organic material;

A1 – 0–20 cm, *mollic* horizon, fine sand, very dark gray (10YR 5/1.5; 10YR 3/1), slightly moist, moderate granular fine structure, fine and medium common roots, clear and smooth boundary;

A2 – 20–50 cm, *mollic* horizon, fine sand, very dark grayish brown (2.5Y 5/2; 2.5Y 3/2), slightly moist, weak granular fine structure, fine and medium few roots, visible stratification, abrupt and broken boundary;

A/C1 – 50–75 cm, mixed, disturbed stratification: humus horizon and parent material, fine sand, olive brown (2.5Y 6/3; 2.5Y 4/3), slightly moist, weak granular very fine/single grain structure, few iron concentrations and segregations, very few roots, abrupt and broken boundary;

A/C2 – 75–140 cm, mixed, disturbed stratification: humus horizon and parent material, fine sand, dark grayish brown (2.5Y 6.5/2; 2.5Y 4/2.5), slightly moist, weak granular very fine/single grain structure, few iron concentrations and segregations, very few roots, abrupt and broken boundary;

2Cl – 140–(170) cm, parent material with gleyic properties, fine sand, light olive brown (2.5Y 7/3; 2.5Y 5/3), slightly moist, weak granular very fine/single grain structure, few iron concretions and segregations.

Table 7. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
A1	0–20	0	10	3	7	52	15	8	3	1	1	FS
A2	20–50	1	6	2	10	57	17	4	3	1	0	FS
A/C1	50–75	15	11	7	14	41	13	7	4	2	1	FS
A/C2	75–140	1	5	3	13	58	15	4	2	0	0	FS
2Cl	140–(170)	6	2	4	20	66	5	1	1	1	0	FS

Table 8. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
Oi	4–2	400	13.6	40	6.0	5.2	-
Oe	2–0	183	7.48	18	6.8	5.9	-
A1	0–20	26.1	1.55	17	7.9	7.1	16.2
A2	20–50	8.2	0.53	16	8.3	7.4	8.8
A/C1	50–75	2.7	0.18	15	8.6	7.7	29.0
A/C2	75–140	4.1	0.28	15	8.8	7.6	9.1
2Cl	140–(170)	-	-	-	9.2	8.1	8.0

Profile 5 – Haplic **Phaeozem** (Arenic, Colluvic, Pachic)
Localization: Erosional valley, bottom, inclination 2°, broadleaf forest, 81 m a.s.l.,
N 53˚16'50.3'' **E** 19˚30'34.7''

Morphology:

Oi – 1–0 cm, slightly decomposed organic material;

A1 – 0–30 cm, *mollic* horizon, loamy fine sand, dark brown (10YR 5/2; 10YR 3/3), slightly moist, moderate granular fine structure, fine and medium common roots, gradual and smooth boundary;

A2 – 30–140 cm, *mollic* horizon, loamy fine sand, dark brown (10YR 5/3; 10YR 3/3), slightly moist, weak granular fine structure, fine and medium few roots, visible disturbed stratification, abrupt and wavy boundary;

2C1 – 140–145 cm, parent material, fine sand with gravel line, brown (10YR 6/3; 10YR 5/3), slightly moist, single grain structure, abrupt and smooth boundary;

2C2 – 145–(190) cm, parent material, fine sand, disturbed stratification, brown (10YR 6/3; 10YR 5/3), slightly moist, single grain structure, very few roots.

Table 9. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
A1	0–30	0	8	4	17	41	13	7	4	2	4	LFS
A2	30–140	1	8	4	16	44	8	9	4	3	4	LFS
2C1	140–145	47	15	25	28	15	17	0	0	0	0	FS
2C2	140–(190)	0	3	3	32	51	7	1	1	1	1	FS

Table 10. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
Oi	1–0	356	13.4	36	6.7	6.1	-
A1	0–30	11.8	0.97	12	7.8	6.3	trace
A2	30–140	6.5	0.48	14	8.4	7.0	trace
2C1	140–145	-	-	-	8.8	7.4	5.8
2C2	140–(190)	-	-	-	8.7	7.3	4.2

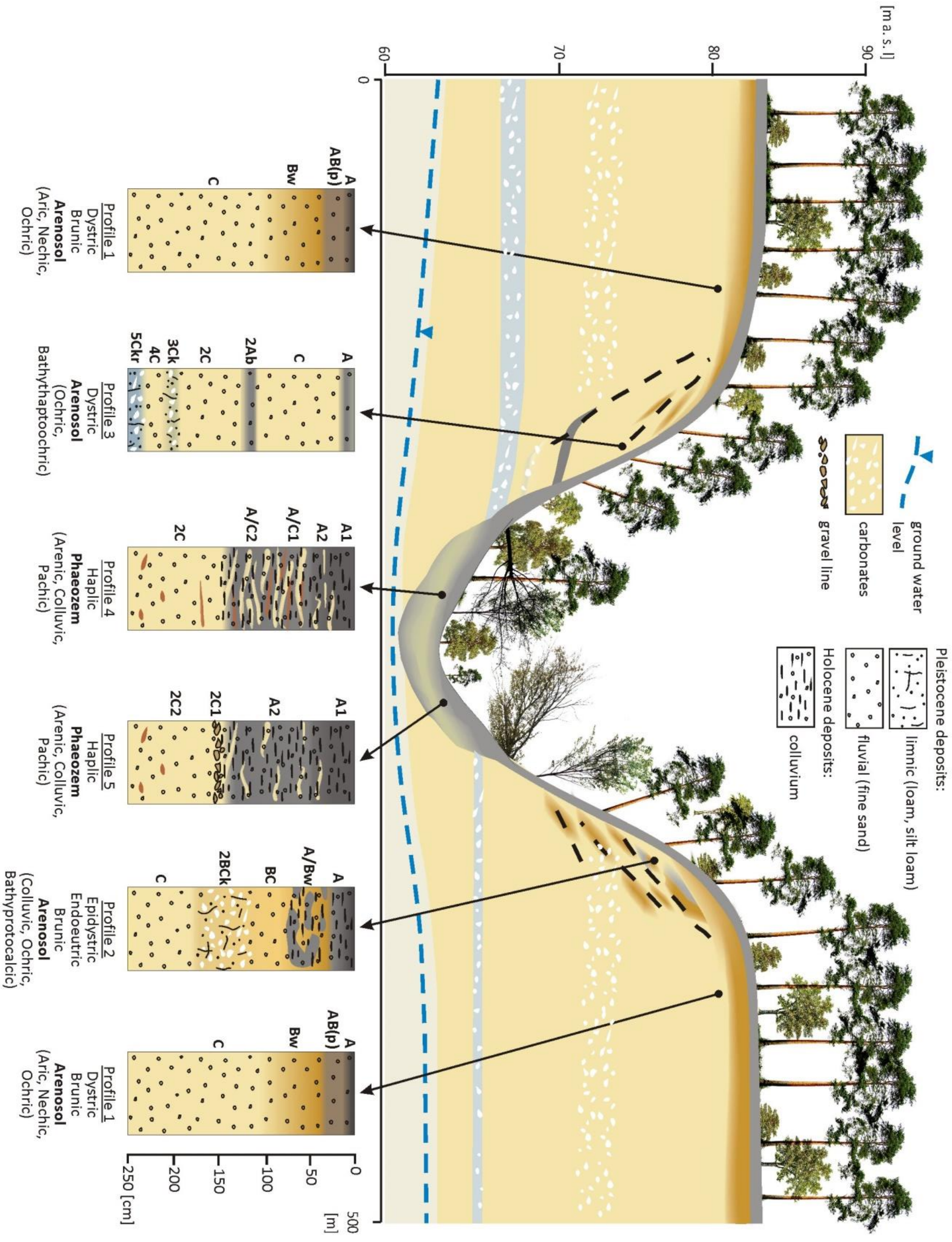

Fig. 2. Toposequence of the soils of erosional valleys on the Pleistocene terraces

Soil genesis and systematic position

All investigated soils inherited coarse (mainly sandy) texture from fluvial deposits prevailing on the surface of Pleistocene terraces. With the exception of texture, the studied pedons show the high variability of soil cover in the described area resulting from the development of the erosional valley.

Flat surfaces of Pleistocene terraces are dominated by well-developed **Arenosols** with the A-B-C sequence of horizons. The horizons do not meet the criteria of any diagnostic horizon, e.g. *mollic* or *umbric*. Although they contain a sufficient amount of humus, their colour is bright, which is probably due to the relatively high content of fulvic acids. It is a typical feature of A horizons developed in sandy and acidic deposits (Plichta, 1981, Licznar et al., 1993). Because humus epipedons contained more than 0.2% of soil organic carbon to a depth of 10 cm, the ***Ochric*** supplementary qualifier was used. The uppermost 5 cm of A horizons contained common uncoated quartz grains of sand in the dark humus matrix, which was expressed in the name of the soil by using the ***Nechic*** qualifier. These white uncoated grains are probably the result of the initial podzolization process. The downward movement of Al, Fe and organic compounds was stimulated by acidification of the upper part of soil as a consequence of planting pine monocultures (Jankowski, 2014). The homogeneous nature of the A horizon from 0 to 20 cm in described profile and its clear lower boundary are not typical for forest soils. These features are generally found in arable soils and they may be inherited from the past agricultural use of the pedon (Bednarek and Michalska, 1998; Sewerniak et al., 2014a) or are remnants of alterations resulting from tree planting (Sewerniak et al., 2014b). Despite the presence of the above-mentioned "tillage" features (***Aric***), the studied soils have not been ploughed for many years and the "p" designation was used in brackets. The endopedon Bw occurring below A is also not recognized in WRB (IUSS Working Group WRB, 2015) as a diagnostic horizon. The accumulation of iron and aluminium in these horizons is mainly the result of biochemical weathering of fluvioglacial sands (Bednarek, 1991). Due to its sandy texture, it does not meet the criteria of *cambic*. In the Polish Soil Classification (2011), the coarse textured Bw horizons with a significant *in situ* concentration of aluminium and iron sesquioxides are defined as diagnostic horizons (*sideric*) of rusty soils. In WRB, their presence is expressed by the use of the ***Brunic*** principal qualifier. Based on the low pH values, it can be assumed that the effective base saturation is < 50% in the whole first pedon, which was expressed by the ***Dystric*** qualifier.

The second profile (***Epidystric Endoeutric Brunic*** **Arenosol** (***Colluvic, Ochric, Bathyprotocalcic***)) was located in the middle slope of the studied erosional valley. Similarly to the first pedon, due to its light colour, the A horizon meets only the criteria of the ***Ochric*** qualifier. Its lower boundary is gradual and broken, which indicates common bioturbations or mixing of this material. Part of the humus material is also mixed with the lower Bw horizon to a depth of 70 cm, which meets the criteria of ***Brunic*** (*in situ* concentration of aluminium and iron sesquioxides) and ***Colluvic*** (downslope movement) at the same time. At a depth of 120–180 cm there is a layer with the dominant very fine sand and coarse silt (loam texture), rich in calcium carbonate – 13.4%. The carbonates are mainly dispersed in the soil matrix (primary carbonates) but also form nodules and soft concentrations (secondary carbonates). This moderately calcareous and fine textured material was probably deposited in a shallow, seasonal Pleistocene lake and meets the criteria of *protocalcic* properties. As it occurs at a depth greater than 100 cm, the ***Bathyprotocalcic*** subqualifier was used. The presence of carbonates also increased the base saturation in the lower part of the pedon (***Endoeutric***), while the upper, strongly acidic part meets the criteria of ***Epidystric***.

The third profile was also classified as **Arenosol,** but its solum is characterized by an extremely small thickness limited to the lower boundary of the A horizon at a depth of 10 cm. In this case, the colour and other features of the humus horizon meets the criteria of the *umbric* epipedon, but it is not deep enough. As in the previous soils, only the ***Ochric*** qualifier could be used. The sandy fluvial deposits, very slightly changed by pedogenesis, occur directly under the A horizon. These sediments clearly show well-preserved stratification characteristic for Pleistocene fluvial deposits. Their acid reaction and low base saturation allows the use of the ***Distric*** qualifier. The buried humus horizon was visible at a depth of 130–140 cm (***Bathythaptoochric***). Under this buried 2Ab horizon, there was a sandy parent material with two strongly calcareous silt loamy layers of probably limnic origin. The lower silty horizon (deeper than 240 cm) had distinct *gleyic* properties. Almost all material had dark greyish brown reductimorphic colour with very few oximorphic mottles near the surface of aggregates. These *gleyic* properties were formed as a result of stagnation of rain and/or subsurface water in silty material. The described horizon had no contact with the groundwater table.

Profiles 4 and 5 represent the most fertile soils of the investigated fragment of Pleistocene terraces and were developed in the bottom of the erosional valley. In both cases, the humus material formed horizons of large thickness – up to 140 cm and was stratified and mixed with pure mineral parent material. This mixed material had sandy texture (***Arenic***) and all the features of slope deposits (***Colluvic***). Due to the high content of humus, dark colour and high base saturation (high pH values), both epipedons (in Profile 4 and 5) meet the criteria of the *mollic* horizon to a depth of ≥ 50 cm (***Pachic***). Due to the absence of any other diagnostic horizons, these pedons were classified only as ***Haplic*** **Phaeozems.**

Soil sequence

The described sequence of soils is strongly connected with the development of the erosional valley and slope processes occurring there. The spatial arrangement of soils resulting from such a set of soil-forming factors is called **toposequence**. Due to the unilateral connection (downslope direction) of individual pedons, it can also be called "downward translocation catena" (Sommer and Schlichting, 1997).

The first profile (***Dystric Brunic*** **Arenosol**) was located on the upper slope of the investigated valley, but the occurrence of such soils within flat surfaces of Pleistocene terraces of the Drwęca Valley was also confirmed by many augerholes. These soils had fully developed sequences of soil horizons (Świtoniak and Bednarek, 2014) and were beyond any significant influence of slope processes. Anthropogenic changes in Profile 1 were related only to changes in the humus horizon – the initial stage of podzolization (bleaching of sand grains – ***Nechic***) triggered by pine planting and evidence of their ploughing in the past (***Aric***).

Profile 2 was located in the middle of a steep slope. This soil was significantly transformed by slope processes. The upper zone of soil from 0 to 70 cm was strongly mixed, while the material was moving down the slope. Despite the visible influence of erosion processes, a substantial part of the Bw (***Brunic)*** material was preserved and mixed with humus material. The surface of the erosional valley penetrates deep into the fluvial sediments at this place and as a result, calcareous limnic deposits occur in the bottom of the profile (***Endoeutric, Bathyprotocalcic***).

The third profile (***Dystric*** **Arenosol**) is an example of highly eroded soil with a very shallow solum limited to 10 cm of the humus horizon. The whole material from 0 to 130 cm has structural and textural features, which indicate its origin from a landslide (Karasiewicz et al., 2018) and was presumably entirely pushed down on the older shallow soil represented only by horizon 2Ab. This buried humus horizon may have colluvial character evidenced by its abrupt boundaries. This colluvial material (2Ab) was probably deposited in the bottom of the erosional valley before the translocation of a landslide (0–130 cm) material. However, it is not known whether the surface soil truncation took place – before or after the landslip. The fact that the upper part (0–130 cm) of the profile has been moved down from the shoulder of the slope is also confirmed by low pH values which are characteristic for surface sediments of the investigated terraces (e.g. horizon C in Profile 1 – Table 2).

Soils shown in Profiles 4 and 5 (**Phaeozems**) result from the accumulation of thick (140 cm) colluvic material trapped along the main axis of the bottom part of the erosional valley. It was deposited directly on the parent material – calcareous fluvial sands – exposed during a strong erosive phase of the valley evolution. Primarily, before the development of the described valley, this material was at a depth of about 20 m and therefore was not decalcified. The colluvial material originates from the vicinity of the studied erosional valley, which is indicated by its texture. They were sandy as fluvial Pleistocene deposits on terrace surfaces with a small admixture of finer fractions, as a result of the cutting of silt loam limnic layers (e.g. horizons 3Ck and 5Ckr in Profile 3 – Table 6) by slopes of the erosional valley. The effect of supplies and incorporation of some limnic materials into colluvium is also noticeable in the presence of calcium carbonate and high pH values. Alkaline reaction of the colluvium can also be partly caused by the influence of groundwater rich in dissolved alkaline minerals. These waters flow down from the nearby morainic plateau built of calcareous glacial tills. The colluvic material contains considerable amounts of humus to significant depths. These organic compounds were partially allochthonous – came from eroded soils located at higher elevations. Nevertheless, the contemporary dense vegetation indicates the stabilization of the area and the slowdown of erosion processes in recent years. Penetration by strong root systems led to an increase in the content of humus in the post-sedimentation phase and the development of diagnostic *mollic* horizons. In Profile 4, the upper part of the humus horizon meets, except for thickness, very demanding criteria of *chernic*. Formation of well-developed "colluvic" *mollic* horizons in areas surrounded by eroded acidic and sandy soils is one of the rare cases (Świtoniak, 2015). In the presented colluvial soils of erosional valleys, this is due to the supply of calcium carbonate from exposed limnic layers and the accumulation of autochthonous soil organic carbon in the sod-forming process.

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Soils of reclaimed dumpsites in a lignite mining area, North Czechia

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The area of interest comprises a reclaimed dumpsite of the Bílina lignite open-cast mine. The wider surrounding area is a large mining area where lignite has been extracted for more than 150 years. The intensity of mining increased tremendously in the 1950s and changed the landscape into a mosaic of untouched landscape, open-cast mines and reclaimed land covered by the excavated material overlying the lignite. Different approaches and methods were used during the time, leading to a variety of man-made soils (Penížek and Rohošková, 2002).

Fig. 1. Location

Lithology and topography

The area is formed by Cenozoic sediments represented mainly by clays that in the Pleitocene were locally covered by loess deposits of various thicknesses. The original terrain tends to be flat. The mining activity changed the character of the landscape by dumping huge volumes of the barren rocks overlying the lignite deposits onto so-called “outer dumpsites”. These reach heights of several tens of metres above the original surface and often present as anthropogenic shapes, such as terraces or gentle slopes, to the fulfil the landscape stability criteria appropriate to the mechanical characteristics of the dumped material to prevent future landslides. In general, the elevation of the wider area varies between 200 and 250 m a.s.l.

Land use

The dumpsite consists of various forms of land use, that is determined by type of reclamation and the time period when the reclamation was carried out. Sloping areas are usually covered by broadleaf forests that are artificially planted, but with the use of native species such as *Tilia*, *Acer* or *Quercus*. Flat areas are exploited as agricultural land. Both permanent grass cover and arable land is established, depending on the available material and its quality for reclamation. Small artificial lakes are established to improve the hydrological regime and to promote diversification of flora and fauna in the reclaimed areas.

Climate

The region belongs to warmest and driest region in Czechia. The amount of precipitation is rather low because of rain shadow of Ore Mountains bordering this area in its NW edge. The climate is characterized by a mean annual precipitation of 450-500 mm and mean annual temperature of 8.5 °C. July is a month with maximal precipitation.

Profile 1 – Spolic **Technosol** (Clayic, Eutric, Ochric)
Localization: Dumpsite, midslope - inclination 5°, forest, 450 m a.s.l.,
N 50°36'32.1" **E** 13°43'40.5"

Morphology:

Ah – 0–5 cm, humus horizon, clay, dark brown (10YR 3/4), slightly moist, medium moderate angular structure, few roots, cracks, clear boundary;

Bw – 5–20 cm, *cambic* horizon from barren material (clays), clay, dark yellowish brown (10YR 4/6), slightly moist, weak angular structure, cracks, fine and few roots, diffuse boundary;

C – 20–(60) cm, *artefacts* – barren rock (clays sediments) dark yellowish brown (10YR 4/6), slightly moist, massive structure, very few roots.

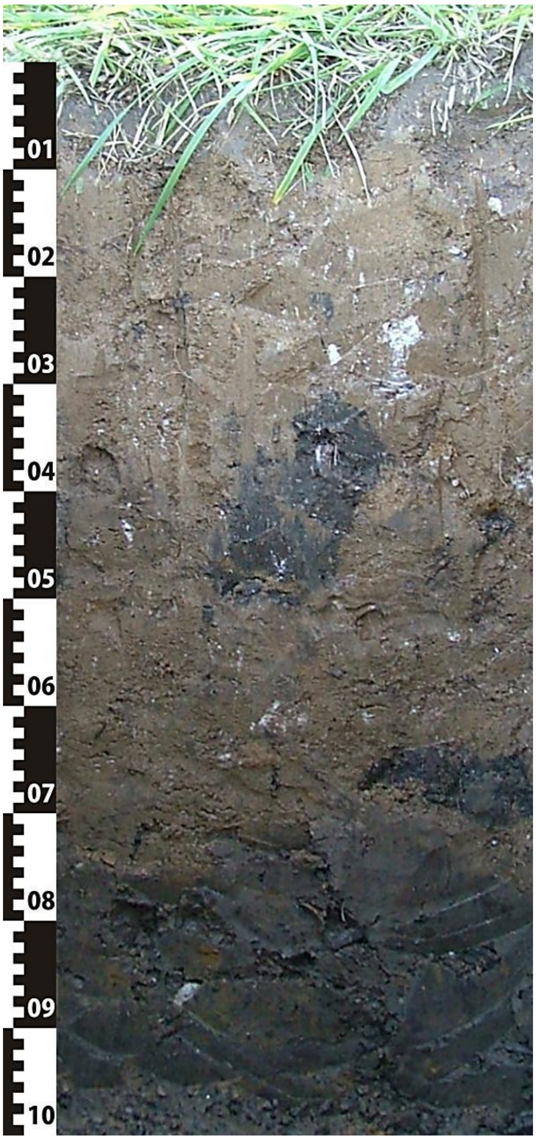
Table 1. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm				Textural class
		> 2.0	2.0-0.05	0.005-0.002	< 0.002	
Ah	0–5	-	3	15	82	C
Bw	5–20	-	1	12	87	C
C	20– (60)	-	1	15	84	C

Table 2. Chemical, physicochemical and sorption properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	pH		$CaCO_3$ [g·kg^{-1}]	CEC [cmol(+)·kg^{-1}]	BS [%]
			H_2O	KCl			
Ah	0–5	9.4	6.3	5.4	0	27.7	89
Bw	5–20	0.5	6.6	6.1	0	24.3	91
C	20– (60)	-	6.8	6.3	0	23.1	93

Profile 2 – Endospolic **Technosol** (Anoloamic, Endoclayic, Ochric, Raptic)
Localization: Dumpite, upper slope - inclination 3°, grassland, 485 m a.s.l.,
N 50°35'49.8" **E** 13°44'07.2"



Morphology:

Ah – 0–10 cm, humus horizon, silty loam, very dark grayish brown (10YR 3/2), slightly moist, medium moderate granular structure, fine and common roots, abrupt and undulating boundary;

Ck/2C – 10–70 cm, *calcic* horizon - parent material - loess, silty loam, pale brown (10YR 6/3), slightly moist, fine weak subangular structure, fine and few roots, common soft concretions of secondary carbonates; incorporated parts of lower laying C2 horizon, abrupt and wavy boundary;

2C – 70–(100) cm, *artefacts* – barren rock (clays sediments) dark yellowish brown (10YR 4/6), slightly moist, massive structure, no roots.

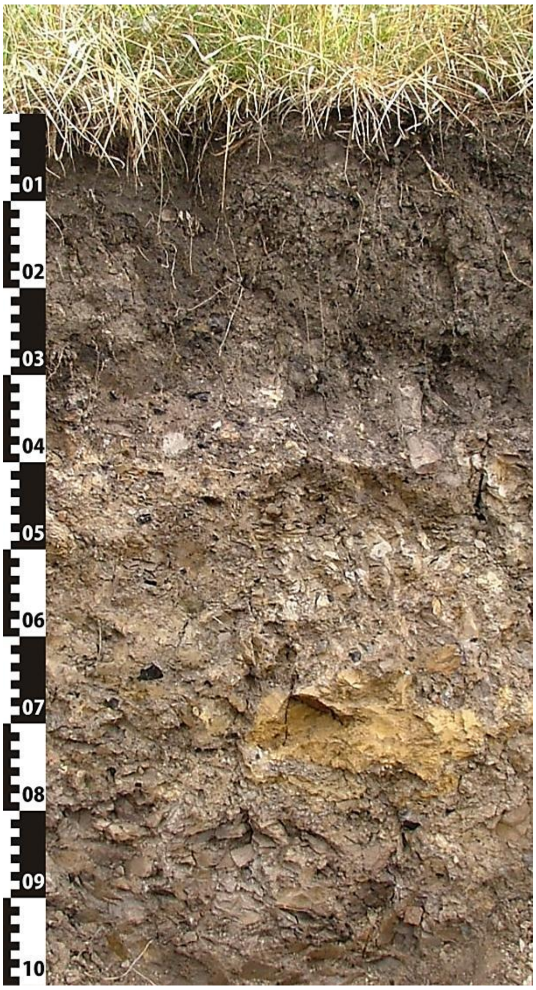
Table 4. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm				Textural class
		> 2.0	2.0-0.05	0.005-0.002	< 0.002	
Ah	0–10	-	8	71	21	SL
Ck	10–70	-	12	68	24	SL
2C	70–(100)	-	4	13	83	C

Table 5. Chemical, physicochemical properties and sorption properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	pH		$CaCO_3$ [g·kg^{-1}]	CEC [cmol(+)·kg^{-1}]	BS [%]
			H_2O	KCl			
Ah	0–10	27.4	6.7	6.2	5	25.7	81
Ck	10–70	1.5	7.2	6.8	18	18.3	100
2C	70–(100)	0.3	6.4	5.9	0	17.1	75

Profile 3 – Chernic **Phaeozem** (Aric, Amphiclayic, Epiloamic, Raptic, Transportic)
Localization: Dumpsite, slope - inclination 3°, arable field, 475 m a.s.l.,
N 50°36'07.4" **E** 13°43'36.5"



Morphology:

Ah – 0–35 cm, *chernic* humus horizon, silty loam, dark brown (10YR 2/2), slightly moist, granular structure, many roots, earthworm casts, clear boundary;

2C – 35–80 cm, *artefacts* – barren rock (clays sediments) with significant amendmens of lignite, clay, dark yellowish brown (10YR 4/6), slightly moist, massive structure, very few roots

2C2 80–(100) cm, *artefacts* – barren rock (clays sediments), clay, dark yellowish brown (10YR 4/6), slightly moist, massive structure, no roots.

Table 5. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm				Textural class
		> 2.0	2.0-0.05	0.005-0.002	< 0.002	
Ah	0–35	-	3	15	82	C
2C	35–80	-	1	12	87	C
2C2	80–(100)	-	1	15	84	C

Table 6. Chemical, physicochemical properties and sorption properties

Horizon	Depth [cm]	OC [$g \cdot kg^{-1}$]	pH		$CaCO_3$ [$g \cdot kg^{-1}$]	CEC [$cmol(+) \cdot kg^{-1}$]	BS [%]
			H_2O	KCl			
Ah	0–35	32.4	7.0	6.4	2	27.7	89
2C	35–80	10.5	5.6	5.1	0	20.3	65
2C2	80–(100)	1.3	6.6	5.3	0	18.1	80

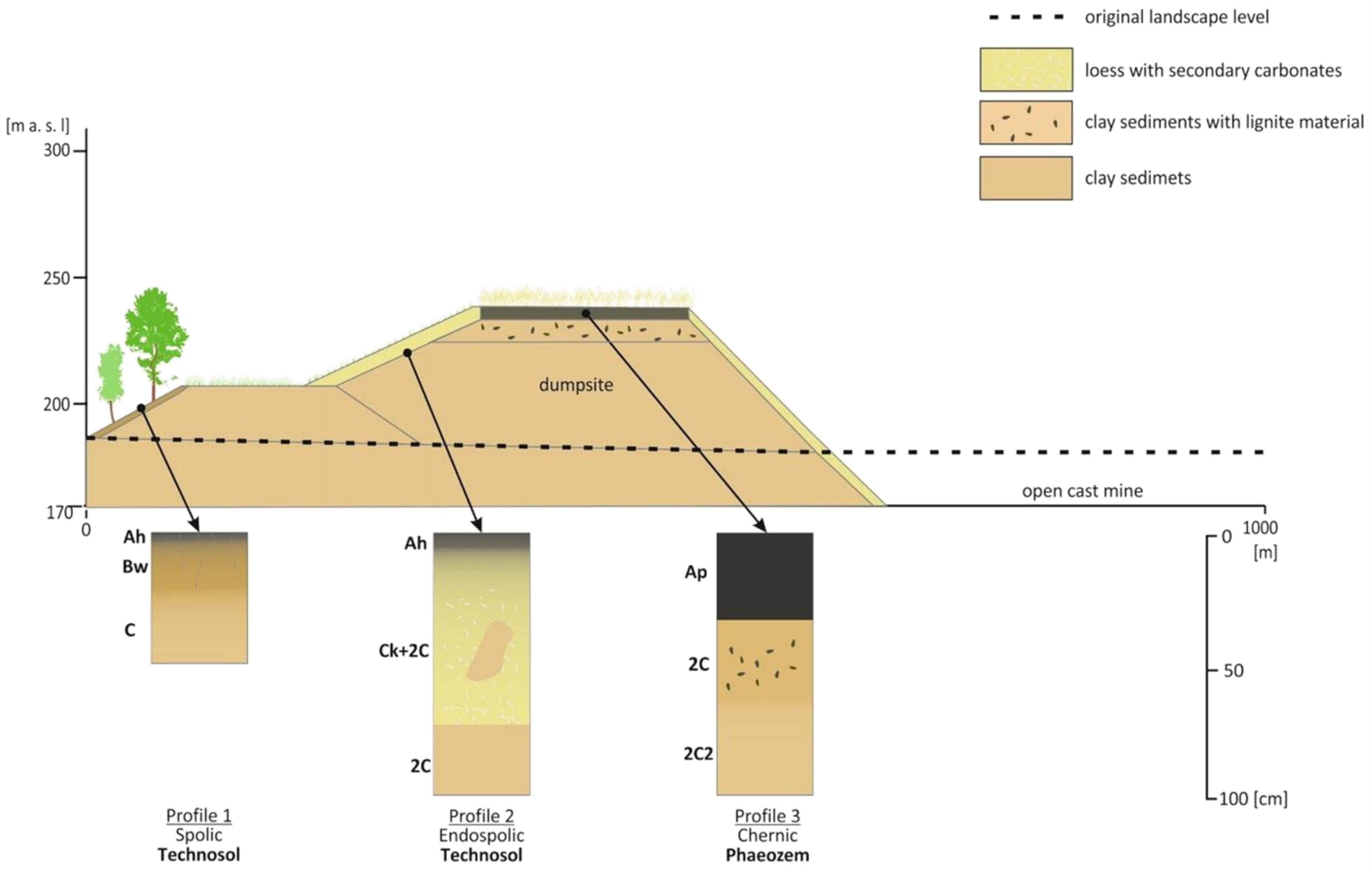


Fig. 2. Anthroposequence of soils of reclaimed dumpsites in a lignite mining area

Soil genesis and systematic position

The presented soil profiles represent the different approaches to land reclamation that were used during different periods. Diverse technical facilities, knowledge of the art of reclamation procedures and availability of material led to the development of diverse soil.

Profile 1 represents the oldest part of the dumpsite, which was reclaimed in the 1960s. The dumped material from which the soil profile is constructed is represented by tertiary clay sediments that were excavated from depths of several of tens of metres and therefore can be considered within the WRB classification as ***Artefacts*** and, because of their character, the principal qualifier ***Spolic*** is used. The material is semi-consolidated with a typical plate structure. Within several months, weathering and deconsolidation of the material leads to total dispersion of the material, which in turn leads to the very unfavourable physical condition of the material (Rohošková and Valla, 2004). The content of clay particles is more than 80% and the massive structure is problematic for root penetration and water infiltration. From a chemical point of view, the clay sediments are characterised by prevalence of illite-type clay minerals. The reclamation technique consisted of simple levelling of the mined clay sediments that overlay the lignite. Additionally, some organic-rich material such as sewage slag or waste from paper processing industry was often incorporated to improve the biological properties for the established vegetation. The vegetation is represented by a poplar (*Populus nigra*) plantation. Poplar trees were very popular for reclamation purposes as they are an easily grown pioneer tree species that is suitable for initial biological reclamation.

The soil profile now exhibits much evidence of soil development within the parent material. The originally very massive material show features of slight shrink and swell processes due to the very high clay level content (***Clayic*** supplementary qualifier). Cracks are important because they favour the growth of roots and better infiltration of water after the dry periods that occur quite often in this area due to the regional climate conditions. The material in the upper part of the soil profile shows new structure development of some weathering and can be therefore designated as a *cambic* horizon (***Cambic*** supplementary qualifier). Because of the presence of the Artefacts, the soil is classified as a **Technosol.**

Profile 2 represents another method of recultivation of the dumpsite. The clay sediments (again taken in considered as ***Artefacts***) are covered by more than 70 cm of loess (***Endoclayic*** supplementary qualifier) that has much better physical properties and makes the land more suitable either for forest plantation of agricultural use. The loess layer shows evidence of an admixture of clay sediments due to the displacement of the material by heavy machinery. The loess is overlain by only a thin layer of organo-mineral material from what was originally a *chernic* horizon, as described for Profile 3. The only diagnostic horizon in this soil is the ***Calcic*** horizon formed by the loess layer, which has a loamy soil texture (***Anoloamic*** supplementary qualifier). The soil can be classified as a **Technosol** because the average volume of the clay sediments over first 100 cm is more than 20%. The type of artefacts brings the ***Spolic*** principal qualifier into the name.

Profile 3 represents soil from a different type of reclamation. The soil profile consists of two contrasting materials. The upper part (35 cm) of the profile is formed by humus-rich topsoil. This material is the original natural topsoil from the original soil cover above the mine, and during the extension of the mining areas was screened and deposited for reclamation purposes. The material originates from loess material, has a loamy soil texture (***Epiloamic*** supplementary qualifier), is highly base saturated, and is rich in humus, and can therefore be classified as a ***Chernic*** horizon. The underlying material is, as in case of Profile 1, clay sediment (considered as ***Artefacts*** with the

Amphiclayic supplementary qualifier and ***Spolic*** principal qualifier) excavated from the mine. In this case, the material represents transition layers of the sediment closely overlying the lignite so there is a significant portion of lignite material. This material can be problematic when exposed at the very surface because of the presence of pyrite. Its weathering can cause extreme acidification of the material up to a level that is toxic for plants (Borůvka et al., 2012). On one hand the presence of a *chernic* horizon excludes the possibility of classifying the soil as a Technosol, but, on the other hand, nor can the soil not be classified as a Chernozem because of the missing calcic horizon. When considering the *chernic* horizon as a special case of a mollic horizon, the soil can be classified as a **Phaeozem**.

Soil sequence

The above-described sequence shows different approaches to the land reclamation of areas influenced by open-cast mining. The resulting soil cover and character of the soils is influenced by the state of the art of reclamation practices as well as materials available for recultivation, as well as the proposed land-use of the reclaimed areas. All described soils represent soil with fully artificially arranged (layered) profiles. The initial methods of reclamation consisted in levelling the mined material overlying the lignite, and the soil profile is very simple with few evidences of soil development. Due to the consideration of mined material as artefacts, such soil are classified as Spolic **Technosols** (Profile 1). The same classification is used for soils where the unfavourable material is covered by other materials with better physical properties, such as loess, as shown in Profile 2. A method where topsoil material from soils stripped from the location of a present-day mine leads to the presence of soil that has a seminatural character and can be classified in this case as a **Phaeozem** (Profile 3).

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