Geological Quarterly, 2014, **58** (4): 685–694
DOI: http://dx.doi.org/10.7306/gq.1175

The influence of litho- and pedogenic processes on Luvisols formation of selected area of Vistula Glaciation

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Jaworska, H., Dąbkowska-Naskręt, H., Kobierski, M., 2014. The influence of litho- and pedogenic processes on Luvisols formation of selected area of Vistula Glaciation. Geological Quarterly, **58** (4): 685–694, doi: 10.7306/gq.1175

The objective of the study was to determine the effect of litho- and pedogenic processes on soils of the selected area of Vistula Glaciation, based on profile distribution of unweathered components such as titanium, zirconium and silica in relation to their morphology, mineralogy, micromorphology and physicochemical properties. The predominant type of soil in the study area are Luvisols. Analysis of texture allowed to classify the investigated soils to sandy silts with loamy material as their subsoil. In the bulk soil silica dominates and its content was in the range 71.4 to 88.6%. The content of TiO_2 within the profiles is fairy similar, without clear patterns in the profile distribution. The total content of zirconium in the samples was in range of 95.13 to 212.15 mg kg^{-1}. In the profile distribution of zirconium higher content of Zr was observed in the upper horizons compared to the top layer in all of the analysed profiles, indicating different origin of soil material. Statistical analysis showed positive correlation between the total content of zirconium and the content of fraction 0.05–0.002 mm (correlation coefficient value: 0.692384; significance level – $p < 0.05$) and negative correlation between zirconium and clay content (correlation coefficient: –0.668157; $p < 0.05$). The lithologic discontinuity within profiles of the investigated soils has been additionally has proved by X-ray analysis of the clay fraction. The micromorphological analysis confirmed the complex genesis of the studied soils. The results of the study clearly showed an overall inhomogeneity and stratification of the soils. Studied Luvisols did not form as weathering product of homogeneous bedrock. Changes in granulometric and chemical composition within soil profiles are the consequence of translocation of clay fraction during lessivage as well as lithologic discontinuity of the solum.

Key words: Luvisols, lithological discontinuity, lessivage, glacial sediments.

INTRODUCTION

On the early post-glacial area, covered by Vistula Glaciation sediments, significant areas of soil covers with variation in morphology within soil profile occur. These soils were formed from the parent materials deposited during the Poznań Phase and Kujawy-Dobrzyń Subphase of the Vistula Glaciation (Fig. 1). Date ranges for the Poznań Phase and Kujawy-Dobrzyń Subphase are 18.4 ka BP (Wysota et al., 2008). The predominant type of soil in the study area are Luvisols (Skłodowski and Bielska, 2009; *Mapa Gleb Polski 1:300,000*, 1961). The main soil forming process is lessivage – that is vertical translocation of fine particles from a superficial horizon called the eluvial horizon, or E horizon, to another horizon, called the illuvial or B horizon. Luvisols exhibit the following genetic horizon sequence: Ap-Et-Bt-C. Texture of the soil material and the morphology of soil pedons suggest lithological non uniformity within soil profiles in the region. Possibly the main pedogenic process-translocation of clay fraction during the soil formation impacted and altered changes caused by lithological discontinuity. Such a scenario of processes has to be checked by studying soil material composition.

There is a number of parameters that have been used to detect the presence of lithological discontinuity in soils: heavy minerals content (Chapman and Horn, 1968), morphology of sand particles (Schaetzl and Mokoma, 1998), clay mineralogy (Kuzila, 1995) formulas involving particle size fractions (Creemens and Mokma, 1986) and the change in the content of resistant minerals (Kuzila, 1995). The distribution of unweathered components within soil profile such as titanium, zirconium and silica can also prove parent material uniformity (Chapman and Horn, 1968; Semmel, 2004). Transformations of soil cover, as a result of pedogenic and geogenic processes, may be also defined in soils based on chemical composition of soil, or by mineralogical composition. This analysis should be applied to parent material of the investigated soils and its weathering products (Komisarek, 2000).

The study was undertaken to determine the effect of litho- and pedogenic processes on soil cover of the selected area of Vistula Glaciation (Weichselian), based on profile distribution of unweathered components such as titanium and zirconium, in relation to the morphology, micromorphology, mineralogy of clay fraction and chemical composition of bulk soils. The particularly important was to determine the depth of boundary between materials of different origin in the pedon and to asses if

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Received: April 30, 2013; accepted: March 24, 2014; first published online: June 18, 2014

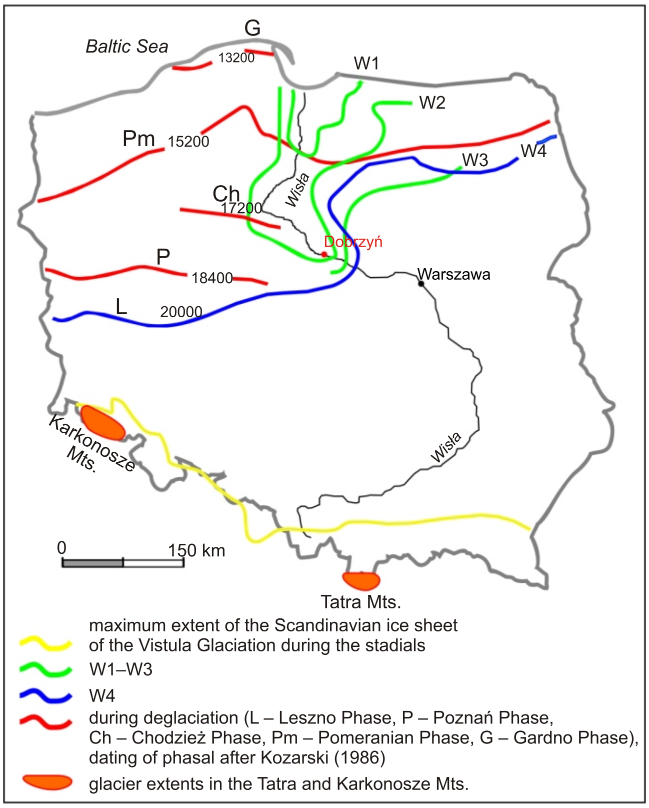

Fig. 1. Maximum extent of Pleistocene glaciations and ice sheet extents during stadials and phases of the Vistula Glaciation in Poland (according to Lindner and Marks, 1996)

the textural and compositional differences between the two parts of solum are due strictly to pedogenic processes or represent actual lithologic and pedogenic differences within profiles. The results of the study will help to understand landscape evolution and near surface hydrology in this region.

MATERIALS AND METHODS

For the study seven profiles of Luvisols, formed from silty material underlain by till and located on the area of Pojezierze Południowopomorskie region (Poland), were chosen (Kondracki, 2002). Selected profiles were located on the flat area of ground moraine plane formed during the Poznań Phase of the Vistula Glaciation, (Galon, 1972; Lindner, 1984; Marks, 2002). Studied Luvisols are under argicultural use. The morphology of soil profiles was characterized according to Polish Soil Classification (2011). The colour of soil horizons was described using Munsell Color Soil Charts (1994). Soil samples were taken from each genetic horizon of profiles (Fig. 2). In the dried and sieved material of earth fraction with diameter < 2.0 mm the following properties were determined: texture with the Casagrande aerometric method, modified by Prószyński (Polish Norm PN-ISO 11277, 2005) the content of fine clay fraction (< 0.0002 mm) was determined by centrifugation. Interpretation of the texture was performed according to Polish Soil Classification (2011: anex no. 3) and USDA (Soil Survey Staff, 2010) classification. Soil pH was measured in H_2O and 1MKCl solution using a 1:2.5 w:v soil/solution ratio on *PHM 84 Radiometer*. Organic C was determined by dichromate oxidation (Jackson, 1973) and total carbonate with the Scheibler apparatus. The total content of zirconium in the

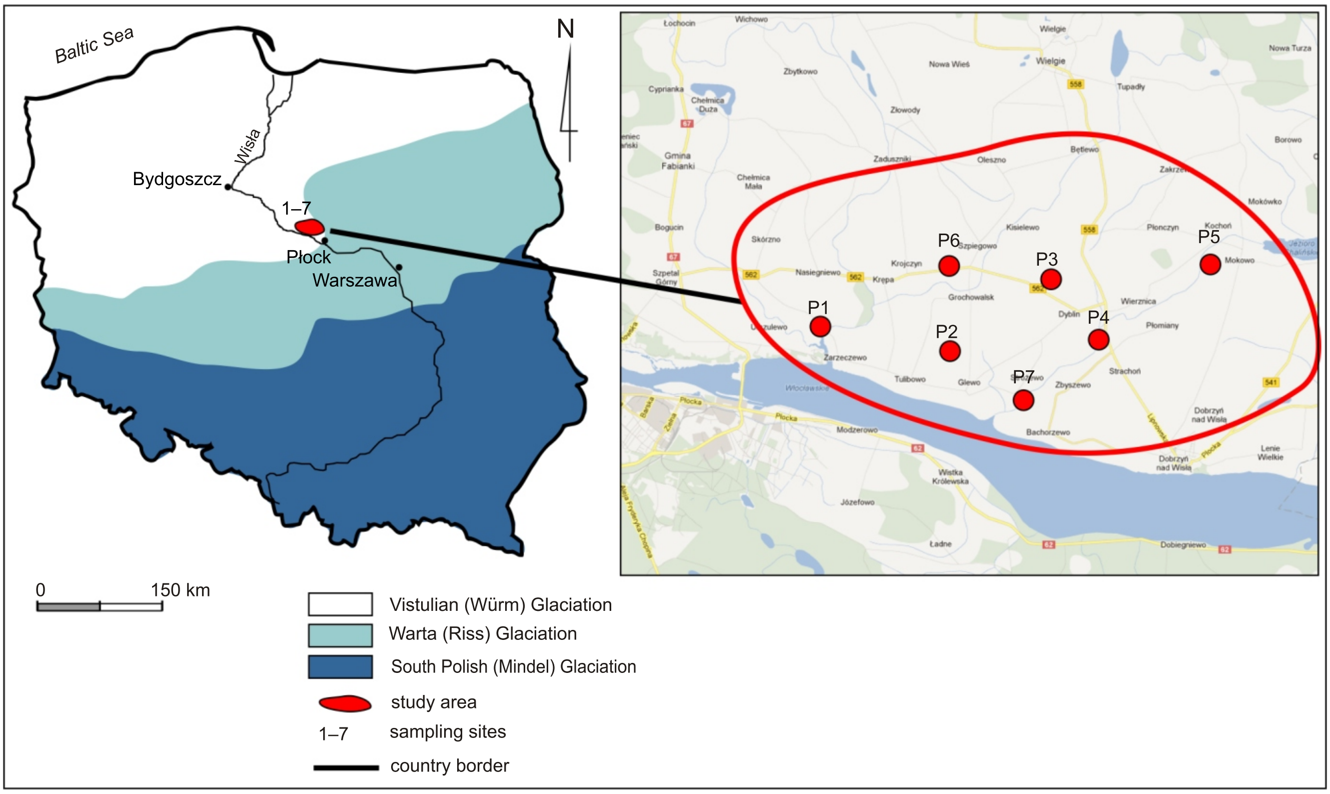

Fig. 2. Location of study area and sampling sites

P1 – Zarzeczewo, P2 – Glewo, P3 – Dyblin, P4 – Strachoń, P5 – Mokowo, P6 – Grochowalsk, P7 – Bachorzewo soil samples was determined by the fusion of soil with potassium pyrosulphate and its concentration in the solutions was determined with the spectrofluorimeter *Hitachi F-2000* according to Wan et al. (2000). The contents of Ti were determined after digestion in Teflon beakers with a mixture of concentrated HF and $HClO_4$ acids (Crock and Severson, 1980), by colorimetric method with tiron (Jackson, 1973). The results obtained were verified based on the Till-3 reference material (Geochemical Soil and Till Reference Materials certified by Breitländer Company). Changes in the oxides content within soil profile were evaluated on the basis of formulas given by Breemen and Buurman (1998), and Muhs et al. (2001).

For X-ray diffraction analysis (XRD) clay fraction (<0.2 μm) was separated according to Jackson (1973) procedure. Clay suspensions were treated with 30% H_2O_2 at 70–80°C to oxidize organic material. Free iron oxides were removed by the Na-citrate-bicarbonate dithionite method. The samples were dispersed with Na-amberlite. Clay samples were saturated with Mg and K and prepared on glass slides for X-ray diffraction analysis. The air-dried Mg-saturated samples were analysed at 25°C followed by ethylene glycol solvation. The air-dried K-saturated samples were analysed at 25°C and then heated at 550°C. XRD analyses were performed using a *X`Pert Powder* diffractometer operating at 40 KV and 30 mA with CuK radiation. Orientated clay slides were scanned in the range 2–30° 2 at the rate of 0.05° 2 min $^{-1}$. Semi-quantitative estimates of the proportions of the clay minerals were derived from peak area measurements (Brindley, 1980). Undisturbed soil samples were collected for micromorphological analyses. The thin sections were prepared following the standard procedure (FitzPatrick, 1984). To describe the thin sections, the Stoops (2003) terminology was used.

Statistical evaluation of results was performed using *Statistica 10* software by setting Pearson's linear correlation coefficients.

RESULTS AND DISCUSSION

Morphological features of the soils are presented in Figure 3. They presented the following genetic horizon pattern: Ap-Et-Bt-C. The feature which differentiated the soils is the variation in the thickness of diagnostic horizons: Et and Bt, across the profiles, which suggests a varied intensity of the illuvial process affecting the soils investigated.

Analysed soils are characterized by relatively low humus content, with organic carbon in the range of 8.29 to 12.98 g kg^{-1}. Investigated profiles are classified as soils with low content of $CaCO_3$ occurring only in parent material and ranging from trace amounts to 4.4% (Appendix 1*). In terms of pH, soils are in range 5.5–8.0 (Appendix 1). Lower values of pH were observed in surface horizons. Hydrolytic acidity varied in a profile (Appendix 1) and usually decreases along with depth with the highest values in humus horizons (excluding P2 profile).

Analysis of texture (Appendix 2) allows to classify the investigated soils to sandy silts with loamy material as their subsoil. Generally, surface horizons contain 20–55% of silt fraction with 0.05–0.002 mm, which corresponds to sandy silt texture. Bt horizons and parent material contain 16–52% of fraction with 0.05–0.002 mm and 4–29% of clay fraction, which classified them to loamy soils. The clay content of the Bt horizons lies within the typical range of Luvisols of this area (Dąbkowska-Naskręt and Jaworska, 1997) and is similar as in Bt horizons of Luvisols formed from glacial sediments in NE Germany (Kühn, 2003).

In all pedons soil texture tend to coarsen in upper part and are significantly finer below 40–56 cm. It is also noticeable in depletion of eluvial horizons with clay fraction compared to Bt horizon, which is a diagnostic feature for these horizons (Anderson, 1987). Observed texture non-uniformity in the profiles of the investigated soils may have a primal character related to periglacial processes or it can be a secondary origin related to pedogenesis.

Strong texture contrast within the profiles could point to a lithological discontinuity. Particularly, change in sand content, observed below 40–56 cm in studied profiles may be related to deposition of material of different origin, because pedogenic processes, in general, do not move sand particles (Birkeland, 1999). However, that feature cannot be used as an evidence of material deposition. To confirm foreign origin of the upper layer, other indexes should be applied.

Eluviation of clay fraction due to lessivage resulted in different texture within pedons. Quenard et al. (2011) reported that lessivage consists of vertical transfer of fine particles ranging in size from less than 2 to 10 μm.

The data on the clay contents in diagnostic horizons of the studied Luvisols (i.e., E and B horizon) indicate that the particles transfer was of different intensity (Appendix 2). Lessivage is a process that can be broken down into the three elementary processes: particle mobilization, particle transport and particle deposition. The mobilization and deposition are complex combination of dispersion (and mobilization) and flocculation (causing deposition) processes of clay colloids. According to Quenard et al. (2011), migration of soil particles is possible when the values of soil pH in the E horizon range from 4.5 to 6.5 and are higher than 6.5 in the B horizon. Consequently, pH between 4.5 and 6.5 favour dispersion of soil colloids (including clay particles) and their eluviation down the profile. Conversely, illuviation (deposition of clay minerals) occurs when the pH is higher than 6.5, in the conditions which flocculation can occur (Duchaufour, 1956; Soil Survey Staff, 2010). The evolution of pH over time due to either liming in cultivated soils or acidification by vegetation in forested areas impacts these processes. Thus, the intensity of lessivage is different and related to pedoenvironment conditions.

Moreover, particle mobilization is related to the nature of the exchangeable cations in soil. The dominance of monovalent cations accelerates dispersion and eluviation of clay particles and polyvalent cations favours flocculation. But the observed differences are caused not only by this soil forming process. The study carried out in northeastern Germany on genesis of Luvisols showed that the till plains are covered by periglacially formed silty layer (40–60 cm in thickness). The silty cover bed is discussed to be of mostly Holocene pedogenic origin (Helbig, 1999). It is also accepted, that periglacial soil-mixtive processes (e.g., repeated freeze – thaw cycles, cryoturbation), where a slight aeolian input cannot be excluded, led to the formation of the upper 40–60 cm of the ground, the so-called silty-cover bed. The origin of the upper strata of studied soils developed from boulder loam of the last Vistula (Weichselian) Glaciation, on the

* Supplementary data associated with this article can be found, in the online version, at doi: 10.7306/gq.1175

Ap [0–30 cm]
Silt, Munsell color:
moist – 10YR 5/4, dry – 10YR 6/6.
Soil structure medium, moderate, granular.
Consistence: soft, boundary clear, smooth.
Et [30–56cm]
Silt, Munsell color:
moist – 7.5YR 5/3, dry – 10YR 8/4.
Soil structure fine, medium, angular blocky.
Consistence: moderately firm, clear, smooth.
2Bt1 [56–98 cm]
Sandy loam, Munsell color:
moist – 10YR 3/4, dry – 10YR 5/2.
Soil structure medium, angular blocky.
Consistence: firm, boundary clear, smooth.
2Bt2 [98–110 cm]
Sandy loam, Munsell color:
moist – 10YR 6/6, dry – 10YR 6/4.
Soil structure medium, angular blocky, strong.
Consistence: firm, boundary clear, smooth.
2Ck [110–150 cm]
Sandy loam, Munsell color:
moist – 10YR 6/6, dry – 10YR 7/3.
Soil structure medium, angular blocky, strong.
Consistence: firm, boundary clear, smooth.

Ap [0–25 cm]
Silt, Munsell color:
moist – 10YR 4/3, dry – 10YR 6/2.
Structure fine, granular, strong.
Consistence soft, boundary clear, smooth.
Et [25–43 cm]
Silt, Munsell color:
moist – 10YR 6/3, dry – 10YR 8/2.
Structure fine and medium, angular blocky and subangular blocky, strong.
Consistence soft, boundary clear, smooth.
2Bt [43–110 cm]
Sandy loam, Munsell color:
moist – 10YR 4/6, dry – 10YR 8/4.
Structure medium, angular blocky, strong.
Consistence firm, boundary clear, smooth.
2Ck1 [110–130 cm]
Sandy loam, Munsell color:
moist – 10YR 4/6, dry – 10YR 6/4.
Structure medium, angular blocky, strong.
Consistence firm, boundary clear, smooth
2Ck2 [130–150 cm]
Sandy loam, Munsell color:
moist – 10YR 5/6, dry – 10YR 6/6.
Structure medium, angular blocky, strong.
Consistence firm, boundary clear, smooth.

Ap [0–25 cm]
Silt, Munsell color:
moist – 10YR 2/3, dry – 10YR 4/4.
Structure fine, granular, strong.
Consistence soft, boundary clear, smooth.
Etg [25–40 cm]
Silt, Munsell color:
moist – 7.5YR 4/4, dry – 10YR 4/5.
Structure fine and medium, angular and subangular, strong.
Consistence soft, boundary, wavy.
2Btg [40–95 cm]
Sandy loam, Munsell color:
moist – 10YR 4/4, dry – 10YR 6/6.
Structure medium, angular, strong.
Consistence firm, boundary wavy.
2Ckg1 [95–125 cm]
Sandy loam, Munsell color:
moist – 10YR 4/6, dry – 10YR 6/4.
Structure medium, angular, strong.
Consistence firm, boundary clear, smooth.
2Ck1 [125–150 cm]
Sandy loam, Munsell color:
moist – 10YR 4/6, dry – 10YR 6/4.
Structure medium, angular, strong.
Consistence firm, boundary clear, smooth.

Ap [0–30 cm]
Silt, Munsell color:
moist – 10YR 4/3, dry – 10YR 5/2.
Structure fine, granular, strong.
Consistence soft, boundary clear, smooth.
Et [30–50 cm]
Silt, Munsell color:
moist – 10YR 5/6, dry – 10YR 5/7.
Structure fine and medium, angular blocky, strong.
Consistence soft, boundary clear, wavy.
2Bt [50–80 cm]
Sandy loam, Munsell color:
moist – 10YR 4/6, dry – 10YR 6/6.
Structure medium, angular blocky,strong.
Consistence firm, boundary wavy.
2Ck1 [80–120 cm]
Sandy loam, Munsell color:
moist – 10YR 5/6, dry – 10YR 5/6.
Structure medium, angular blocky, strong.
Consistence firm, boundary clear, smooth.
2Ck2 [130–150 cm]
Sandy loam, Munsell color:
moist – 10YR 5/8, dry – 10YR 6/6.
Structure medium, angular blocky, strong.
Consistence firm, boundary clear, smooth.

Fig. 3. Morphology of the

Ap [0–22 cm]
Silt, Munsell color:
moist – 10YR 5/2, dry – 10YR 8/4.
Structure fine, granular, moderate.
Consistence soft, boundary clear, smooth.
Et [22–35 cm]
Silt, Munsell color:
moist – 10YR 4/6, dry – 10YR 6/6.
Structure fine and medium, angular, strong.
Consistence soft, boundary clear, smooth.
2Bt [35–110 cm]
Sandy loam, Munsell color:
moist – 10YR 6/4, dry – 10YR 7/2.
Structure medium, angular blocky,strong.
Consistence firm, boundary clear, smooth.
2BC [110–130 cm]
Sandy loam, Munsell color:
moist – 10YR 3/4, dry – 10YR 3/4.
Structure medium, angular blocky,strong.
Consistence firm, boundary clear, smooth.
2Ck [130–150 cm]
Sandy loam, Munsell color:
moist – 10YR 4/6, dry – 10YR 6/4.
Structure medium, angular blocky,strong.
Consistence firm, boundary clear, smooth.

Ap [0–20 cm]
Silt, Munsell color:
moist – 10YR 8/3, dry – 10YR 8/4.
Structure fine, granular, moderate.
Consistdence soft, boundary clear, smooth.
Et [20–42 m]
Silt, Munsell color:
moist – 10YR 6/3, dry – 10YR 7/3.
Structure medium, angular, strong.
Consistence soft, boundary clear, smooth.
2EB [42–90 cm]
Sandy loam, Munsell color:
moist – 10YR 7/2, dry – 10YR 7/3.
Structure medium, angular blocky, strong.
Consistence firm, boundary wavy.
2Bt [90–130 cm]
Sandy loam, Munsell color:
moist – 10YR 4/6, dry – 10YR 6/4.
Structure medium, angular blocky, strong.
Consistence firm, boundary clear, smooth.
2C2 [130–150 cm]
Sandy loam, Munsell color:
moist – 10YR 4/6, dry – 10YR 6/4.
Structure coarse, angular blocky, strong.
Consistence firm, boundary clear, smooth.

Ap [0–23 cm]
Silt, Munsell color:
moist – 2.5Y 4/2, dry – 2.5Y 6/2.
Structure fine, granular, moderate.
Consistence soft, boundary clear, smooth.
Et [23–43 cm]
Silt, Munsell color:
moist – 2.5Y 5/3, dry – 2.5Y 7/2.
Structure medium, angular and subangular, strong.
Consistence soft, boundary wavy.
2EBg [43–61 cm]
Sandy loam, Munsell color:
moist – 2.5Y 5/6, dry – 2.5Y7/4.
Structure medium, angular blocky, strong.
Consistence firm, boundary clear, wavy, stones.
2Btg [61–111 cm]
Sandy loam, Munsell color:
moist – 2.5Y 4/4, dry – 2.5Y6/6.
Structure coarse, angular blocky, strong.
Consistence firm, boundary wavy, stones.
2Cg [111–150 cm]
Sandy loam, Munsell color:
moist – 2.5Y 5/6, dry – 2.5Y7/4.
Structure coarse, angular blocky, strong.
Consistence firm, boundary clear, smooth.

investigated profiles

flat plain, in similar pedoclimatic conditions, could be the same as Luvisols being studied in NE Germany (Kopp and Kowalkowski, 1990; Kühn, 2001).

Lithologic discontinuity described as distinct change in texture and differences in soil morphology can be also identified on the base of chemical composition of the soil (Komisarek, 2000). For the estimation of changes in chemical composition within profile, only contents of hardly weathered components are regarded in studied soils (Table 1).

Chemical analysis of the bulk soils indicates that SiO_2 dominates and its content was in range 71.4 to 88.6% (Table 1). Usually content of SiO_2 decreases along with the depth in a soil profile. The highest amounts of silica were detected in surface and eluvial horizons. Moreover, in these horizons sand and coarse silt, rich in silica predominant. Lower content of this ingredient was observed in Bt horizon of the investigated soils, which is a result of different texture (Marion et al., 1976) and accumulation of clay fraction in Bt horizons (Komisarek and Szałata, 2011).

Additionally, a good evidence that two different materials are present in the profiles are changes in the contents of silicon, aluminum, iron, titanium and zirconium oxides in each of the horizon related to parent material content (Table 2). It was observed a significant difference in the calculated values between two strata: upper – and lower at 40–56 cm below the surface.

Commonly, Ti, Zr or rare earth groups of elements are used as index of soil genetic uniformity. In studied soils the content of TiO_2 (Table 1) within the profiles is fairy uniform, without clear patterns in the profile distribution. Slightly enrichment of illuvial horizons with TiO_2 was observed in three of the investigated profiles (P1, P2, P4), which is also reported by other authors (Czarnowska, 1989; Dąbkowska-Naskręt and Jaworska, 2001). Ti tends to be enriched in the finer fractions (<20 μm) easily transported down the profile during lessivage. Such a scenario is confirmed by the lack of statistical correlation between Ti content and coarse grains amounts (sand and silt fractions) in studied soils. Furthermore, there was no statistically significant correlation between the content of Ti and clay fraction. The results showed that Ti content as the indicator of soil material uniformity or lithological discontinuity within studied profiles cannot be used, due to its mobility.

Table 1

Content of SiO_2, Al_2O_3, Fe_2O_3, TiO_2 and ZrO_2 in the soil material (fraction < 2mm)

No.	Horizon	Depth [cm]	SiO_2 [%]	Al_2O_3 [%]	Fe_2O_3 [%]	TiO_2 [%]	ZrO_2 [%]	Ti/Zr
P1	Ap	0–30	82.2	5.11	1.13	0.27	0.015	2.89
	Et	30–56	83.3	4.81	1.02	0.36	0.028	2.04
	2Bt1	56–98	74.6	7.66	2.29	0.43	0.018	3.79
	2Bt2	98–110	75.4	8.51	2.09	0.46	0.013	5.66
	2Ck	110–150	87.2	6.23	1.92	0.36	0.013	4.55
P2	Ap	0–25	86.6	3.98	0.81	0.34	0.019	2.70
	Et	25–43	78.6	6.46	2.38	0.34	0.020	3.21
	2Bt	43–110	76.5	5.92	2.09	0.42	0.013	4.61
	2Ck1	110–130	79.6	4.96	1.32	0.37	0.014	3.40
	2Ck2	130–150	74.5	4.74	1.89	0.30	0.016	3.02
P3	Ap	0–25	88.6	4.13	1.15	0.30	0.018	4.23
	Et	25–40	84.0	4.72	1.15	0.51	0.022	3.65
	2Btg	40–95	76.6	7.37	2.29	0.47	0.016	3.79
	2Ckg1	95–125	78.2	6.84	2.05	0.51	0.013	3.98
	2Ck2	125–150	71.4	7.63	2.20	0.37	0.012	5.07
P4	Ap	0–30	80.4	5.28	1.11	0.34	0.025	2.48
	Et	30–50	83.8	5.86	1.49	0.40	0.023	3.12
	2Bt	50–80	79.5	7.44	2.28	0.41	0.015	4.37
	2Ck1	80–120	76.8	7.42	2.03	0.40	0.017	3.45
	2Ck2	120–150	73.6	6.92	1.59	0.45	0.014	3.74
P5	Ap	0–22	84.0	7.33	1.19	0.41	0.022	2.80
	Et	22–35	78.2	5.94	1.16	0.34	0.023	2.81
	2Bt	35–110	76.4	7.98	2.34	0.33	0.013	5.27
	2BC	110–130	78.8	7.14	2.12	0.35	0.014	4.03
	2Ck	130–150	76.5	8.70	2.26	0.39	0.014	4.47
P6	Ap	0–20	86.3	5.15	1.30	0.41	0.021	2.30
	Et	20–42	86.4	5.48	1.14	0.43	0.021	2.89
	2EB	42–90	74.9	6.95	1.90	0.35	0.020	2.63
	2Bt	90–130	70.8	7.11	1.19	0.39	0.012	4.05
	2C	130–150	71.0	6.46	1.30	0.32	0.014	3.52
P7	Ap	0–23	86.6	4.98	1.75	0.40	0.022	2.13
	Et	23–43	86.4	5.10	1.98	0.39	0.027	2.01
	2EBg	43–61	80.7	6.36	3.08	0.33	0.023	2.92
	2Btg	61–111	79.6	6.45	2.72	0.32	0.015	3.20
	2Cg	111–150	79.1	4.79	2.65	0.31	0.016	2.66

Table 2

Estimated changes of oxides content in relation to the deepest horizon in pedon (100%)

No.	Horizon	Depth [cm]	SiO_2 [%]	Al_2O_3 [%]	Fe_2O_3 [%]	TiO_2 [%]	ZrO_2 [%]
P1	Ap	0–30	94.2	82.0	58.9	75.0	115.0
	Et	30–56	95.5	77.2	53.1	100.0	215.0
	2Bt1	56–98	85.5	122.9	119.3	119.4	138.0
	2Bt2	98–110	86.5	136.6	108.9	127.8	100.0
	2Ck	110–150					
P2	Ap	0–25	116.0	82.1	42.9	113.3	118.0
	Et	25–43	105.0	136.3	125.9	113.3	125.0
	2Bt	43–110	102.7	124.9	110.6	140.0	81.0
	2Ck1	110–130	106.8	104.6	69.8	123.3	87.0
	2Ck2	130–150					
P3	Ap	0–25	124.1	54.1	52.3	81.1	150.0
	Etg	25–40	117.4	61.9	52.3	137.8	183.0
	2Btg	40–95	107.3	96.6	104.1	127.0	133.0
	2Ckg1	95–125	109.5	89.4	93.2	137.8	108.0
	2Ck2	125–150					
P4	Ap	0–30	109.2	76.3	69.8	75.6	178.0
	Et	30–50	113.8	84.7	93.7	88.9	164.0
	2Bt	50–80	108.0	107.5	143.4	91.1	107.0
	2Ck1	80–120	104.3	107.2	127.7	80.0	121.0
	2Ck2	120–150					
P5	Ap	0–22	109.8	84.3	52.7	105.1	157.0
	Et	22–35	102.2	68.3	51.3	87.2	164.0
	2Bt	35–110	99.8	91.7	103.5	84.6	93.0
	2BC	110–130	103.0	82.1	93.8	89.7	100.0
	2Ck	130–150					
P6	Ap	0–20	121.5	79.7	100.0	128.1	150.0
	Et	20–42	121.6	84.8	87.7	134.4	150.0
	2EB	42–90	105.5	107.6	146.2	109.4	143.0
	2Bt	90–130	99.7	110.1	91.5	121.9	86.0
	2C	130–150					
P7	Ap	0–23	109.5	103.9	66.0	129.0	137.0
	Et	23–43	109.2	106.5	74.7	125.8	169.0
	2EBg	43–61	102.0	132.8	116.2	106.5	144.0
	2Btg	61–111	100.6	134.7	102.6	103.2	63.0
	2Cg	111–150					

Table 3

The total content of zirconium in soils

No.	Horizon	Depth [cm]	Zr [$mg \cdot kg^{-1}$]	Zr/Zr p*
P1	Ap	0–30	111.23	1.17
	Et	30–56	212.15	2.23
	2Bt1	56–98	136.34	1.43
	2Bt2	98–110	98.44	1.03
	2Ck	110–150	95.13	
P2	Ap	0–25	149.59	0.65
	Et	25–43	155.94	0.68
	2Bt	43–110	97.15	0.42
	2Ck1	110–130	107.08	
	2Ck2	130–150	121.99	
P3	Ap	0–25	135.79	0.69
	Et	25–40	166.19	0.85
	2Bt	40–95	117.99	0.60
	2Ckg1	95–125	102.12	
	2Ck2	125–150	94.39	
P4	Ap	0–30	193.15	0.83
	Et	30–50	170.75	0.73
	2Bt	50–80	110.12	0.47
	2Ck1	80–120	127.60	
	2Ck2	120–150	105.29	
P5	Ap	0–22	167.49	1.62
	Et	22–35	175.35	1.69
	2Bt	35–110	96.18	0.93
	2BC	110–130	102.81	0.99
	2Ck	130–150	103.59	
P6	Ap	0–20	158.65	1.49
	Et	20–42	161.46	1.52
	2EB	42–90	150.79	1.42
	2Bt	90–130	93.52	0.88
	2C	130–150	106.26	
P7	Ap	0–23	168.45	1.32
	Et	23–43	201.07	1.61
	2EBg	43–61	173.83	1.39
	2Btg	61–111	112.93	0.90
	2Cg	111–150	124.89	

* – ratio of Zr concentration in genetic horizon to Zr concentration in the parent material

For the satisfactory confirmation of the hypothesis about the lithological discontinuities another criterion has been applied i.e. Zr distribution. Zirconium occurs principally in more resistant to weathering mineral – zircon ($ZrSiO_4$). The amount of Zr has been assumed to be uniform throughout all horizons of a soil profile in soils formed from the materials of the same origin (Stiles et al., 2003).

The total content of Zr in the investigated soils was in the range of 95.13 to 212.15 $mg \cdot kg^{-1}$ (Table 3) and is characteristic for Polish soils formed from boulder material (Jaworska and Dąbkowska-Naskręt, 2006). It was observed that underlaying material contains lower amounts of Zr (Table 3). The boundary between Zr contents within each soil profile occurs at the same depth as the abrupt change in sand grains contents i.e. 40–56 cm. Thus, the vertical distribution of Zr confirms different origin of soil material. Chapman and Horn (1968) stated that minerals which contain zirconium mostly occur in silt fraction (0.05–0.002 mm) and the same trends were observed in studied Luvisols. Statistical analysis showed positive correlation between Zr content and silt fraction (correlation coefficient: 0.692384; $p < 0.05$). Moreover, Zr content was negatively correlated with clay fraction (correlation coefficient: –0.668157; $p < 0.05$).

Distribution of Zr is also related to the loss of less resistant material during weathering; as a result Zr concentrations in the upper horizons relatively increase (Stiles et al., 2003). To exclude the impact of such a process on different contents of Zr in upper and lower parts of studied pedons, it was necessary to apply more stable index. Other authors (Chapman and Horn, 1968; Brimhall et al., 1991) used the Ti/Zr relationship to asses soil material uniformity. The ratio Ti/Zr should remain stable (constant) throughout profile depth, confirming soil material uniformity. In the present study a difference in the values of this index calculated for upper horizons compared to the lower horizons supports the hypothesis on different origin of material from the upper and lower layer (Table 1).

The lithologic discontinuity within profiles of the investigated soils has been additionally confirmed by X-ray analysis of the

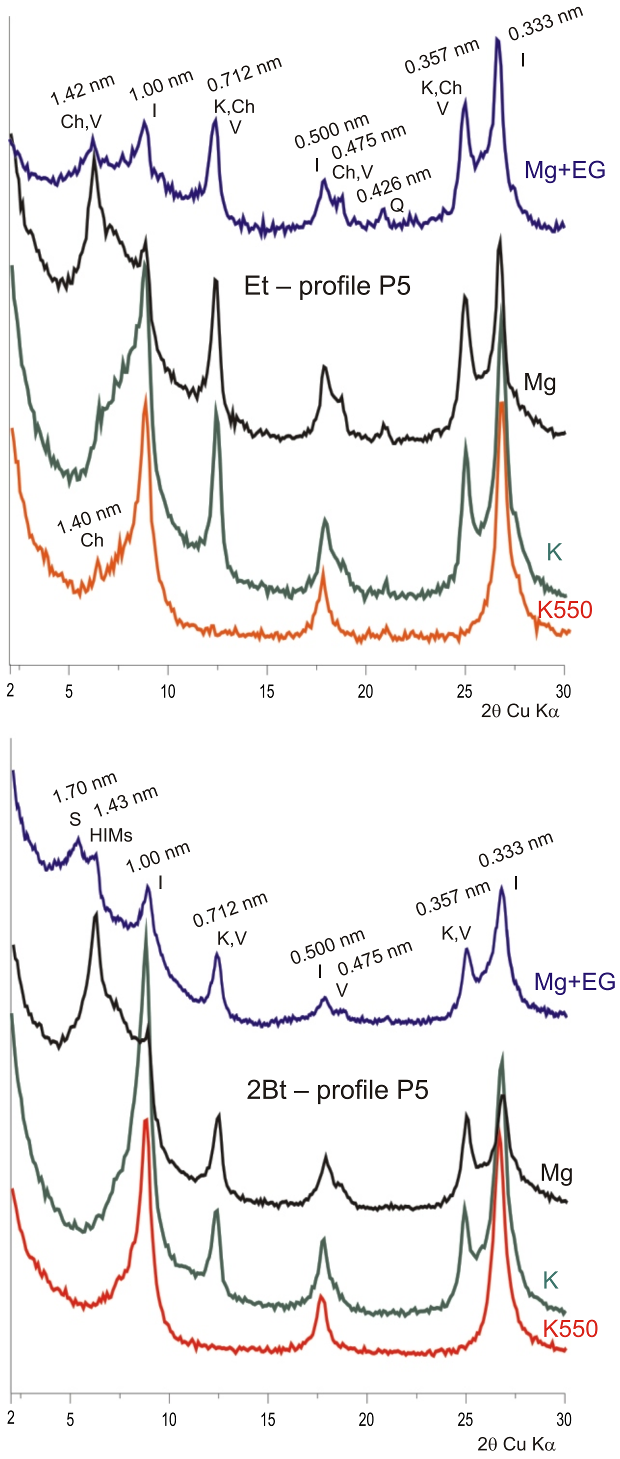

Fig. 4. X-ray diffractograms of clay fraction (< 2.0 μm) from Et and 2Bt horizons of profile P5

K – potassium saturated; K550 – potassium saturated and heated at 550°C; Mg – magnesium saturated; Mg+EG – magnesium saturated and ethylene glycol-solvated; Ch – chlorite, H/Ms – hydroxy interlayer minerals, I – illite, K – kaolinite, S – smectite, V – vermiculite

clay fraction since chlorite was found only in the Ap and Et horizons, which cover the silty layer of soil profiles (Fig. 4). The XRD pattern of Mg-saturated samples after ethylene glycol solvation, showed d-spacing 1.7 nm, which indicates the presence of smectite. Otherwise, after K-saturated samples were heated at 550°C, the 1.4 nm XRD peak shifted to low d-spacing and the intensity of the 1.0 nm peak increased, which indicates the presence of vermiculite. Moreover, hydroxy-interlayer minerals (HIMs) were detected in the Bt horizon (Fig. 4). When clay samples were heated to 550°C, the 1.4 nm peak collapsed and shifted towards 1.0 nm promoting the loss of hydroxy-interlayer materials (Barnhisel and Bertsch, 1989). Finally, chlorite and quartz can be identified after 550°C treatment due to the presence of small peak around 1.4 nm and another one at 0.426 nm.

Illite and illite-smectite or illite-vermiculite accounted for about 50% of all the clay minerals in the clay fraction. The other minerals present in all studied samples include smectite, vermiculite and other mixed-layer minerals.

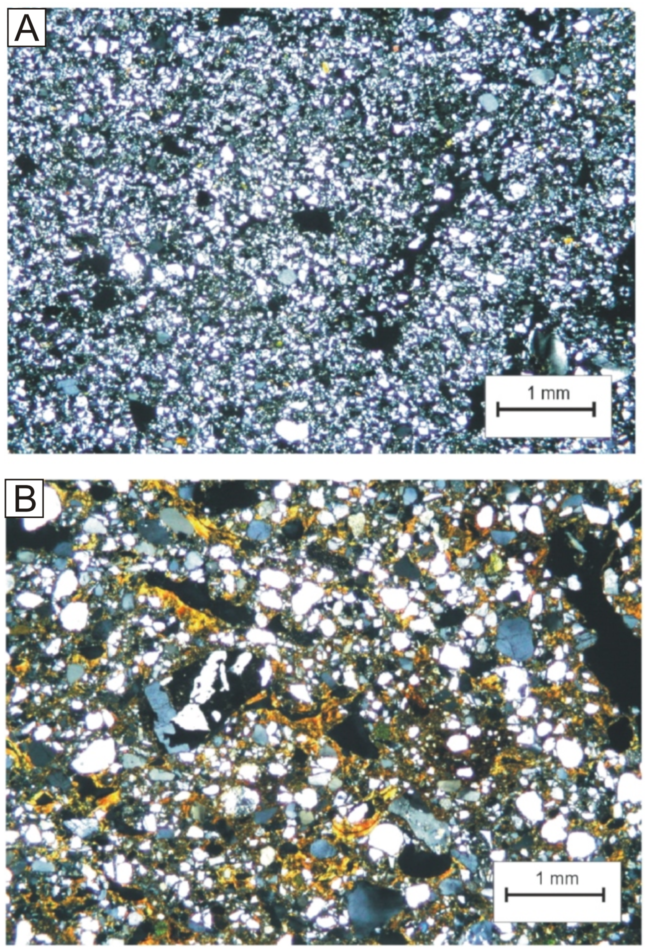

Fig. 5A – soil material from Et horizon of the profile P1; B – soil material from 2Bt horizon of the profile P1

Cross polarizing light (XPL)

The micromorphological analysis confirmed the complex genesis of the studied soils. The upper part of the profiles with silty texture contains well- or medium-rounded grains of quartz and a few grains of weathered potassium feldspars (Fig. 5A). Under that layer which forms the Ap and Et horizons one can find deposits of glacial till with medium- or poorly-rounded grains of quartz, a few grains of feldspars and plagioclases without clear evidence of weathering (Fig. 5B).

Aditionally, higher amount of coarse grains of quartz under the discontinuity have occurred.

Micromorphological image of Bt sample shows the presence of clay coatings and infillings – very characteristic for clay iluviation (Fig. 5A). Clay coatings and clay infillings are optically well-oriented. The presence of numerous forms of oriented colloidal clay is typical for the Bt diagnostic horizon (IUSS Working Group WRB, 2006). The micromass of Bt horizon is composed of clay domains enriched with iron oxides. Clay domains are oriented parallel to the walls of the channels forming porostriated b-fabric. The occurrence of such orientation of soil micromass indicates that the translocation of clay minerals and iron oxides (during lessivage) to the lower part of the soil profile has occurred.

The results of the laboratory analyses evaluated for trends relating to parent material differences observed in seven pedons support the presence and position of lithologic discontinuity identified by field observation. Distribution patterns of several soil components, clay mineralogy and micromorphology, collectively, indicate that the boundary between two layers of different origin occurs at the depth of 40–56 cm in studied Luvisols.

CONCLUSIONS

The results of the study clearly showed an overall inhomogeneity and stratification of the soils. Studied Luvisols developed on the area of Vistula Glaciation did not form as weathering product of homogeneous bedrock.

An abrupt change in texture and vertical differentiation of mineral material are the results of different origin of the upper part of the solum as well as the lessivage. Lithological discontinuity was confirmed by several criteria: Zr content, Ti/Zr ratio within soil profiles, chemical composition of soil material and the mineralogical composition of clay fraction. Photomicrographs of thin sections gave the evidence of clay translocation.

The above study indicated fairy complex origin of the studied soils.

Acknowledgment. The study was financed by the Ministry of Science and Higher Education No 0700/P06/2003/25. The authors appreciate the constructive comments and suggestions from the anonymous reviewers of the manuscript.

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