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Vistulian litho- and pedosedimentary cycles recorded in the Kolodiiv loess-palaeosol sequence (East Carpathian Foreland, Ukraine) determined by laser grain-size analysis

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In the Kolodiiv site, occurring in the valley of the Sivka River (tributary of the Dniester River, Ukraine), Vistulian loess forms a subaerial cover over the Pleistocene terrace II. This terrace consists also of Eemian deposits (palaeosol or organic sediments) underlain by an alluvial succession of Wartanian age. The Kolodiiv 2 profile was studied in detail in order to reconstruct the conditions of loess accumulation, and consequently the climatic-environmental changes, that took place in this region. Eight lithogenetic units were distinguished in the profile: five transformed by pedogenesis, and three loess beds. The main purpose of this study was to conduct a thorough examination of the units lithology, in particular the grain-size distribution, in order to investigate those loess-forming factors that are influenced by environmental changes (i.e. nature of source material, distance and dynamics of transport, type of deposition and redeposition, and hypergenetic processes). To achieve this, 174 samples were taken at 10 cm spacings along the profile, and the grain-size distributions of the deposits were determined using a laser method with 21 grain-size intervals examined in each sample and statistically analyses. Statistical analysis included: calculation of the main grain-size parameters (according to Folk and Ward's method), grain-size index (Ding *et al*., 1994) and also two statistical tests (Kolmogorov-Smirnov and Spearman rank correlation) applied in order to find differences or similarities between the grain-size distributions of the lithogenetic units distinguished. Stratigraphic variations in grain-size distribution reflect the division of the deposits into stratigraphic units previously arrived at. Mean values of grain-size index (I_{gs1}) indicate that loess units 2, 4 and 6, differ from the palaeosol units 3, 5 and 7. The grain-size distribution of loess deposits in the Kolodiiv 2 profile varies, with marked dominance of the silt fraction, which indicates that these deposits were transported by winds of similar velocities carrying material a short distance from source. As the aeolian conditions that formed loess deposits in the Kolodiiv 2 profile were generally stable, differences in the grain-size distribution of unit 2 representing the Upper Pleniglacial, suggest three cycles of loess deposition during that interval (with the middle cycle characterized by the most distinct, short-term oscillations in environmental dynamics). The variability in grain-size distribution in units 3–5, which together represent the Interplenivistulian (Middle Pleniglacial), reflects the climatic heterogeneity of this period. The palaeosol layers are diamictic. Higher values of grain-size indices show that all Upper Pleistocene palaeosol units of high (interglacial) and low (interstadial) rank are characterized by higher content of fine relative to coarse fraction the lowest mean values of grain-size index occur the soil unit 1, of Holocene age, suggests that this unit is probably a product of very recent, Neoholocene pedogenesis and does not represent the entire Holocene epoch. The statistical tests results show, great similarity between loess units 2 and 4 (from the middle and upper part of the Pleniglacial), and also between palaeosol units 7 and 8 forming the Horohiv sl palaeosol unit (an Eemian palaeosol and interstadial palaeosols from the Early Vistulian). Furthermore, the individual nature of loess unit 6, deposited during the Lower Pleniglacial, seems to be associated with the climatic characteristics of this interval.

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INTRODUCTION

This study presents the results of lithological investigations into the Quaternary deposits near the village of Kolodiiv in the central part of the East Carpathian Foreland (Fig. 1A). The loess-palaeosol sequence examined (Fig. 1B) is exposed in the scarp of the terrace occurring 20–25 m above the valley bottom of the Sivka River, near its confluence with the Dniester River. Thick loess deposits composing the terrace represent the entire Vistulian, and contain several palaeosols. The Eemian deposits (palaeosol or organic sediments) occurring in the bottom of this sequence are underlain by an alluvial succession (sands and

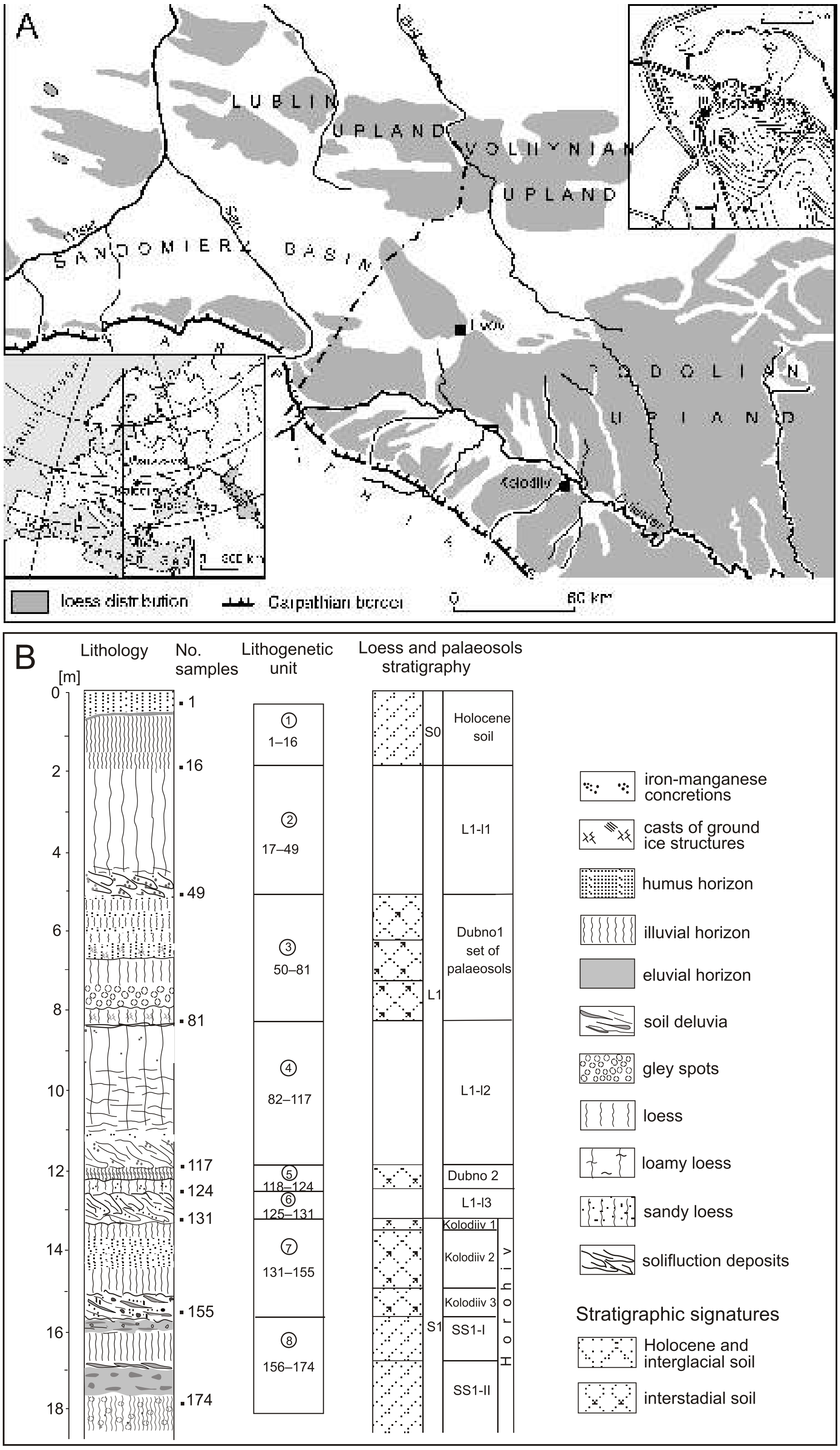

Fig. 1. A — location of the profile investigated at Kolodiiv (East Carpathian Foreland) and sketch map of loess regional distribution, B — lithogenetic units and stratigraphy of the Kolodiiv 2 profile

gravels) of Wartanian age. This Pleistocene cover overlies the 1.5–2 m high solid basement composed of Cretaceous rocks. According to the Ukrainian geomorphologic scheme of terraces in the Dniester River catchment in the East Carpathian Foreland, the terrace described is termed terrace II. In Kolodiiv it forms a narrow shelf, poorly distinguishable in places, which adjoins high slopes of the Vojnyliv Upland (320–330 m a.s.l.).

Nine profiles were examined along the almost 1 km long section of the terrace in 1997–2001. The deposits were characterized in all profiles on the basis of standard lithological investigations (Łanczont and Boguckyj, 2002), petrographical, palaeobiological, and archaeological studies, and also thermoluminescence dating. An attempt was made to reconstruct the climatic-environmental conditions under which the deposits were formed. Their stratigraphy was established by Łanczont and Boguckyj (2007).

Excavations in the Kolodiiv 2 profile were made in 1999, particularly to aid palaeomagnetic investigations, and supplementary explorations took place in 2001 when additional samples were taken for palaeomagnetic and thermoluminescence analyses. Almost all the loess and palaeosol stratigraphic units found in the Kolodiiv site occur also in the Kolodiiv 2 profile. Moreover, it contains thick layers of primary loess. However, the first studies did not encompass the lithology of this profile so in 2003 samples for granulometric, mineralogical, and geochemical analyses were collected at 10 cm intervals.

The grain-size distribution of the Kolodiiv 2 profile was studied in detail in order to determine the lithology of loess-palaeosol sequence as influenced by the environmental changes (nature of loess accumulation, dynamics of the depositional environment) and the post-depositional transformation/diagenesis of the deposits. The evidence of short-term climatic fluctuations during the last glacial, which were recorded in the loess cover of the Carpathian Foreland, can be a basis for correlation with global events recognized from marine sediments and in ice cores (e.g. Bond *et al.*, 1993), and terrestrial deposits (among others: Xiao *et al.*, 1995; Vandenberghe *et al.*, 1998, 2001; Bokhorst, 2003; Jary, 2004).

This problem was analysed through the detailed study of grain-size distributions, which were determined using a laser method, by statistical analysis of the results obtained, and also by lithological-structural and palaeopedological analyses.

DESCRIPTION OF THE KOLODIIV 2 PROFILE

The first description of the Kolodiiv 2 profile was published in 1999, and included strata with a total thickness of over 19 m (Łanczont and Boguckyj, 2002). During field work in 2003 it was not possible to expose the lower parts of the profile, buried under thick colluvial deposits.

Eight lithogenetic units were distinguished: five palaeosol units of different stratigraphic rank, and three loess units (Fig. 1B). Their thickness varies from 0.7 m (unit 5 and 6) to 3.6 m (unit 4). Some boundaries between individual units are of a denudational erosional nature.

The Holocene soil succession (unit 1) occurring in the top part of the profile is 1.8 m thick. This succession is composed of lessivé soil containing an Eet horizon and a bipartite Bt horizon, and a superimposed chernozem-like soil in the upper part of this succession which is antropogenically disturbed. Gleying from the top is evidenced by numerous iron-manganese concretions found in all horizons of this Holocene soil succession. It is underlain by unit 2, a gleyed buff loess, with slight ferruginous lamination and thin sandy lenses, formed by aeolian and washdown processes. Its lower part is more distinctly layered and deformed by solifluction. These features are revealed by ferruginous and gley streaks with a discontinuous, wavy pattern. The next unit 3 (5.1–8.3 m) contains loess with intercalated tundra gleys or gleyed weak brown soils. These fossil soils are named the Dubno 1 set of palaeosols. The lowest of these is cemented with iron compounds, and thick wavy ortstein streaks occur on the top, on the bottom and within it. Casts of small reticulate structures of segregated ground ice occur in all deposits of unit 3. The under lying unit 4 is over 3.5 m thick, and consists of gleyed sandy-silty and silty-loamy deposits, which are stratified, and their bottom part contains distinct structures formed by solifluction deformation. The unit 5 (11.9–12.6 m) is a single interstadial palaeosol named the Dubno 2. It is a weakly developed subarctic soil of brown type, with numerous Mn-Fe concretions. Unit 6 is thin (only 0.7 m) and composed of strongly gleyed, horizontally stratified silty-sandy deposits. Unit 7 (13.3–15.7 m) contains three interstadial palaeosols named the Kolodiiv set of palaeosols. The upper of these (Kolodiiv 1) is truncated, and the bottom one (Kolodiiv 3) is represented by reworked humic-rich material (chernozem-like soil) with agglomerations of charcoals. Only the middle palaeosol (Kolodiiv 2 developed on solifluction deposits covering the Kolodiiv 1 palaeosol) is completely preserved. This palaeosol is composed of thick a humus-gley horizon and an underlying Bbr horizon, which is enriched with iron compounds. Gley spots occur throughout the palaeosol profile. The lowest unit, 8 (15.7–18.5 m), consists of two Eemian forest soils named the Horohiv *ss*.; the upper palaeosol is superimposed on the lower one, and covered by the Kolodiiv 1 palaeosol. The humus horizon of the lower palaeosol is preserved only partially. Eluvial and illuvial horizons are well developed in both palaeosols. Their profiles are strongly gleyed, contain large and numerous Mn-Fe concretions, and casts of structures associated with the existence of a small pedofauna. The bottom of the lower palaeosol was not found.

The thickness of individual units is variable, and in places some of the palaeosols are in complete along the exposure, occurring in the terrace scarps.

LASER ANALYSIS

Particle sizes were measured using the "*Analysette 22*" *Laser-Particle-Sizer* (produced by the German firm Fritsch GmbH). A helium-neon laser is the light source. The laser beam (wave length 0.6328 µm) detects particle sizes (within the total range of 0.1 to 1250 µm) in a particle suspension which is pumped into the measuring cell. Diffraction patterns, obtained as a result of wave interference, are used for the determination of particle size distribution. The computer programme controls the course of measurement, calculates, displays and prints the results. The basis for the results' calculation are the Fraunhofer theory and the Mie theory (for particles finer than 1 m) (Instruction…, 1994).

Sample preparation is important. A portion of the material (1–2 g) is put in a vessel. After pouring distilled water with sodium pyrophosphate over the sample, it is thoroughly ground and left for 24 hours. Then, the suspension is carefully stirred, and put in portions into the dispersing unit. Just before the laser measurement, in order to desegregate the material, the suspension is mechanically stirred and dispersed with horizontal ultrasonics for 10 minutes.

Instrument indications are periodically verified using the standards delivered by the producer (Starch — potato flour and quartz powder — BCR 70). Measurements on these calibrating materials showed very good accuracy and repeatability of the results.

Comparative studies of grain-size distribution in the loess samples shower good consistency of the percentage contents of clay and silt fractions determined with an areometer and with the "*Analysette 22*". This consistency results from the shape of grains and particles, which in aeolian deposit are approximately spherical, and from the high content (about 80%) of quartz grains (Frankowski and Smagała, 2000).

GRAIN-SIZE DISTRIBUTION OF DEPOSITS

Samples (174 in total) for laser grain-size analysis were taken every 10 cm, starting from a depth of 30 cm (Fig. 1B). Using the "*Analysette 22*", percentage contents of 21 particle size intervals were determined in each sample. Statistical parameters, such as mean, median, minimum, and maximum values were calculated for each size interval (Fig. 2). Mean and

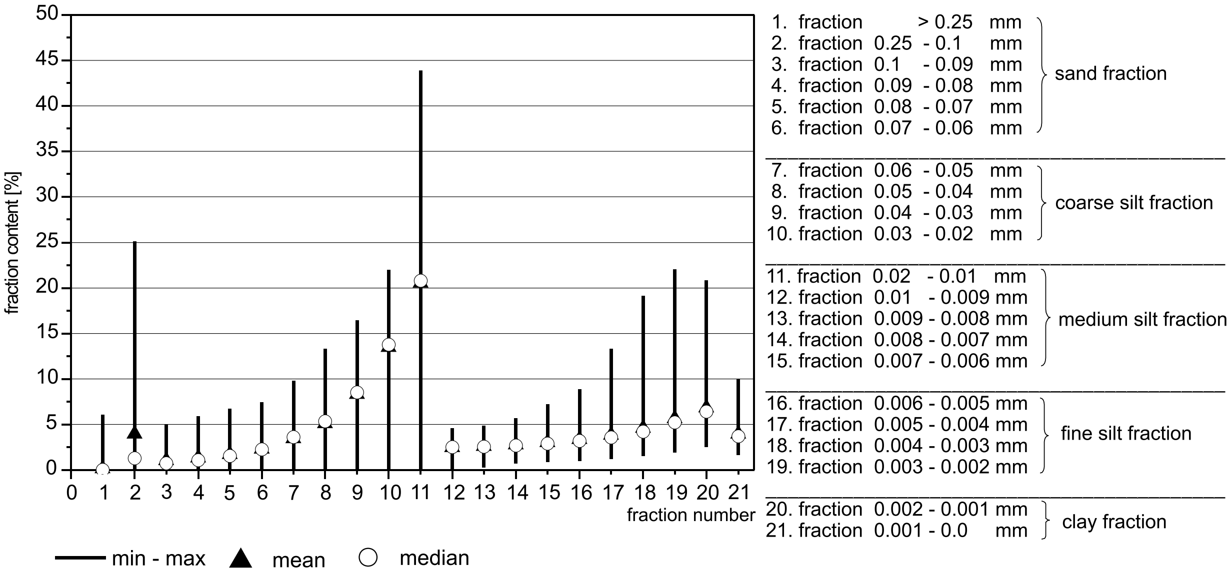

Fig. 2. Percentage contents of the fractions distinguished in the deposits

median values in particular size intervals are almost the same, except for the 0.25–0.1 mm fraction. The 0.02–0.01 mm fraction is modal. The consistency between the obtained mean and median values indicates that the grain size pattern of the deposits examined resembles a normal distribution. However, the null hypothesis of a normal distribution of that random variable, as shown by a Chi-square test, was rejected.

The highest percentage contents are those of the 0.02–0.01 mm fraction (20.5%), the 0.03–0.02 mm fraction (13.5%), and the other coarse silt fractions at 0.06–0.03 mm. Among the sand fractions, the highest content is of the 0.25–0.1 mm fraction (3.9%), and among the clay fractions, it is the 0.002–0.001 mm fraction (6.8%) (Fig. 2).

The contents of particular fractions within each of the lithogenetic units distinguished in the profile are shown in Figure 3A. The ninth position represents the minimum, maximum, and mean values calculated for the entire profile (174 samples). The highest clay content (≤0.002 mm) occurs in unit 3. The contents of fine silt fractions reach several percentages in particular units. The contents of medium silt fractions are similar, except that of the 0.02–0.01 mm fractions (14–29%). The percentage content of particular coarse silt fractions are different. The content of the 0.03–0.02 mm fraction ranges from 11 to 17%, and that of the 0.04–0.03 mm fraction from 6 to 9%. The other coarse silt fractions (0.05–0.04 mm and 0.06–0.05 mm) reach several percent, as do the contents of sand fractions, except for the content of the 0.25–0.1 mm fraction, which varies from 1 to 16%.

The contents of sand, silt (divided into subfractions), and clay fractions in particular units are shown in Figure 3B according to the British Standards (BS) 1377 (1990) and ISO 14688 (2002). In the samples examined, the medium silt fraction (0.02–0.006 mm) and coarse silt fraction (0.06–0.02 mm) reach the highest contents. A high sand content (29%) occurs only in unit 6.

Statistical grain size and sorting parameters were calculated according to the method described by Folk and Ward (Racinowski *et al.*, 2001) on the basis of grain-size distributions in the loess samples, determined using the laser method. The results were calculated using a computer programme purpose-devised by Dr Wach of the Silesian University, and shown graphically in Figure 4. The variation in grain-size parameters across the entire profile is shown as histograms in Figure 5, as a comprehensive diagram (Fig. 6), and in individual units as mean, median, minimum, and maximum values (Fig. 7):

— the median of grain diameter (*Md*) is mainly in the interval 5.4–6.6 phi;

— the mean grain diameter (*Mz*) ranges from 5.4 to 7.2 phi;

— the material examined is poorly sorted, and the sorting index (σ_1) is mainly in the interval 1.3–2.3;

— the skewness in the samples examined is asymmetric and moderately positive (Sk_1 = 0.06–0.36);

— the kurtosis index (K_G) of the deposits examined is variable. Grain-size distributions are platykurtic (0.67–0.90) or mesokurtic (0.90–1.11).

The results of simple grain-size analysis carried out on other profiles at Kolodiiv using an areometric method after disintegration of mineral aggregates (compare Seul, 2007) are comparable with, though not identical to, the results of laser analysis for the Kolodiiv 2 profile. The mean grain diameter varies from 4.8 to 5.4 phi, and shows the greatest differences (from 0.6 to 1.8 phi). Other grain-size parameters are similar: the sorting index ranges from 1.4 to 2.1, the skewness from 0.19 to 0.33, and the kurtosis from 1.07 to 1.24.

The rate of deposition at Kolodiiv can be deduced from the diagrams showing relations between the parameters. Comparing *Mz* with σ_1 and *Mz* with Sk_1 (Fig. 8A, B), most of the projection points represent a narrow range of *Mz* values with a considerable scatter of σ_1 and Sk_1 values. Slightly more variable values of *Mz* are found only for units 2 and 3. Next, comparing Sk_1 and σ_1 values (Fig. 8C) a of points was obtained, indicating a weak correlation: the sorting index increases when the skewness decreases. In general, material

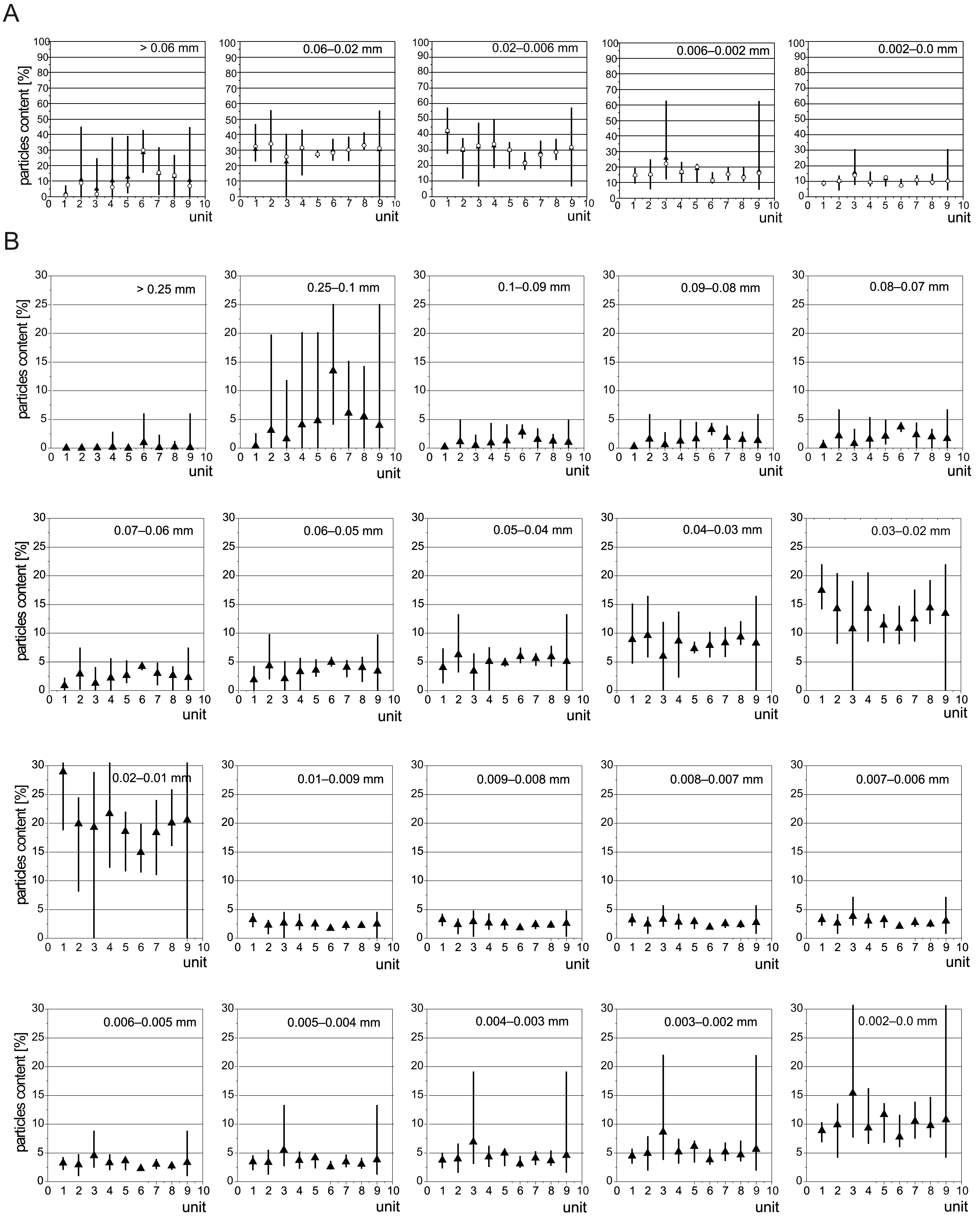

Fig. 3. A — percentage contents of all fractions distinguished in individual lithogenetic units (the ninth position represents the values calculated for the entire profile); B — percentage contents of selected fractions in individual lithogenetic units (the ninth position represents the values calculated for the entire profile)

For explanations see Figure 2

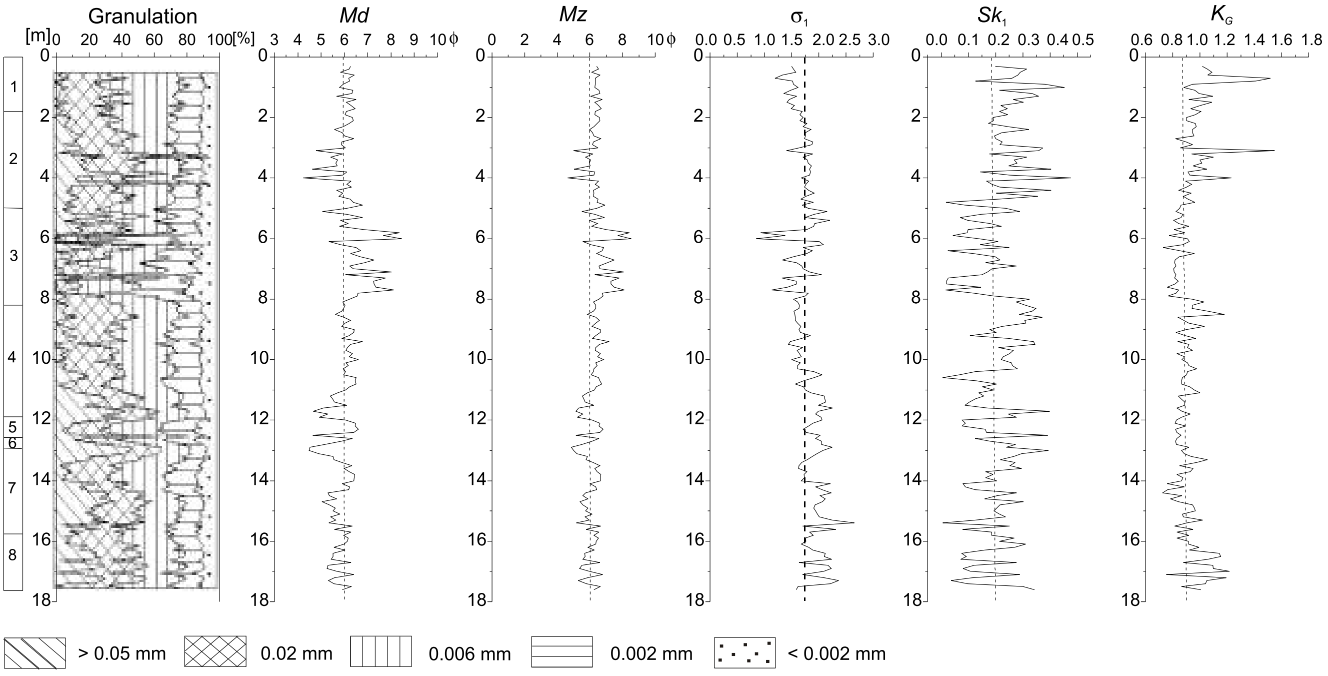

Fig. 4. Grain-size distribution and grain-size parameters

Md — median of grain diameter, *Mz* — mean grain diameter, σ_1 — sorting index, Sk_1 — skewness, K_G — kurtosis index, 1–8 — lithogenetic units

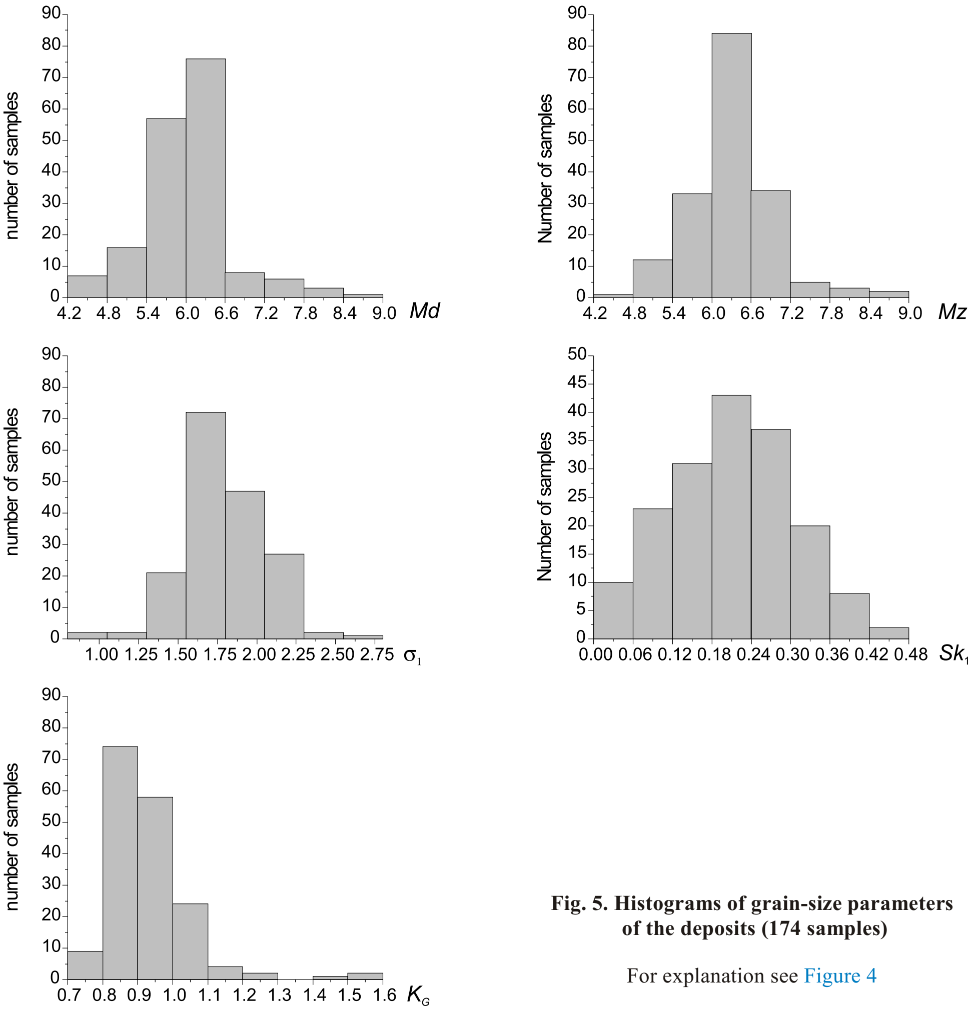

Fig. 5. Histograms of grain-size parameters of the deposits (174 samples)

For explanation see Figure 4

composing the deposits of the Kolodiiv 2 succession was transported from a short distance by wind of constant velocity. However, it seems that environmental dynamics were more variable during accumulation of the upper part of the deposits while the lower part formed under generally stable conditions.

The types of deposits defined according to PN-86/B-02480 (Table 1) in the eight units are shown in Table 2 as numbers of samples representing individual types and their percentage content in relation to all samples examined. Silty loams and silts prevail.

The number of samples with dominant silt fractions, and the percentage contents of these fractions in each of the eight units are given in Table 3. Size intervals are taken according to British Standard BS 1377 (1990):

coarse silt — 0.06–0.02 mm,
medium silt — 0.02–0.006 mm,
fine silt — 0.006–0.002 mm.

The ISO 14688-1 standard (2002) gives slightly different intervals, i.e. 0.063 and 0.0063 mm instead of 0.06 and 0.006 mm, respectively. It appears that in 92 samples (from a total of 174) coarse silt predominates, and in 77 samples medium silt prevails. Fine silt is represented by only 5 samples.

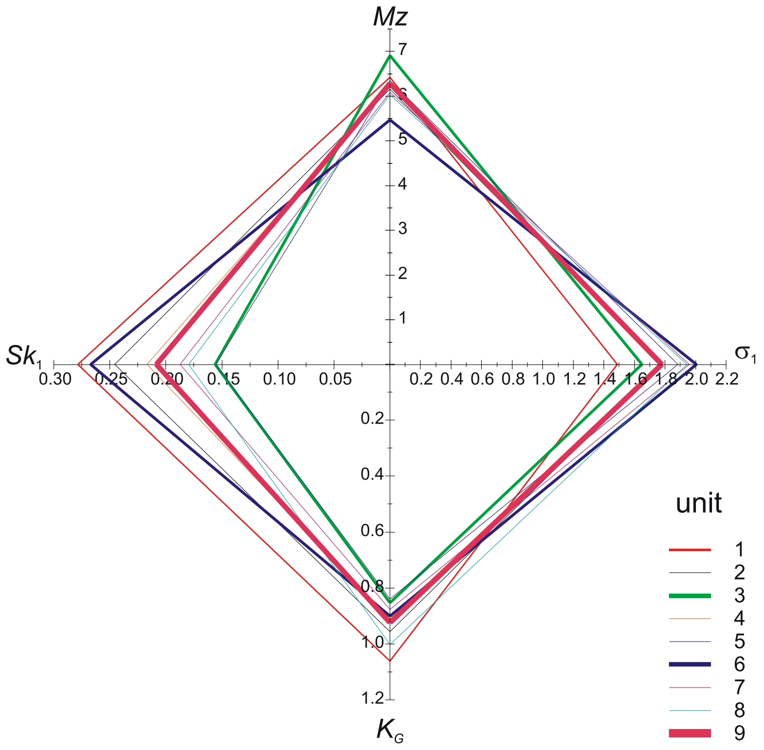

Fig. 6. Comprehensive diagram of grain-size parameters of the deposits (the ninth position represents the values calculated for the entire profile)

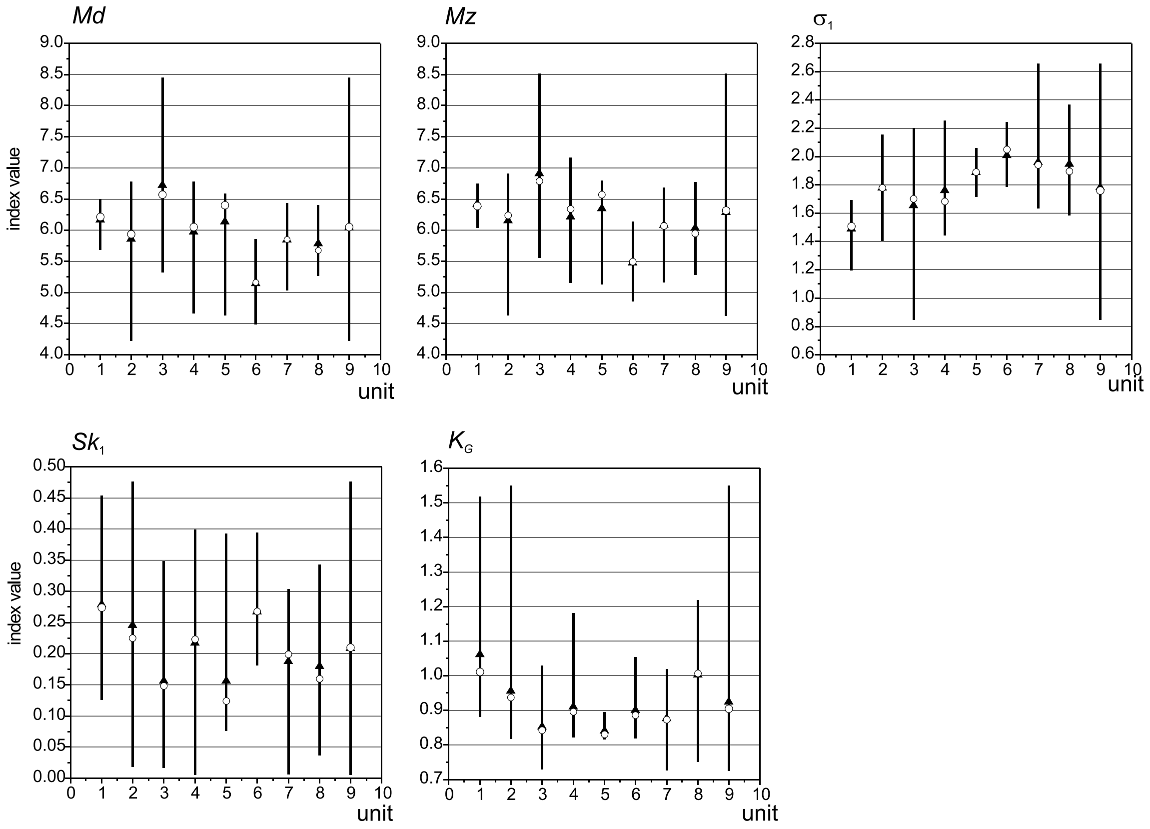

Fig. 7. Grain-size parameters in particular lithogenetic units (the ninth position represents the values calculated for the entire profile)

For other explanation see Figure 2

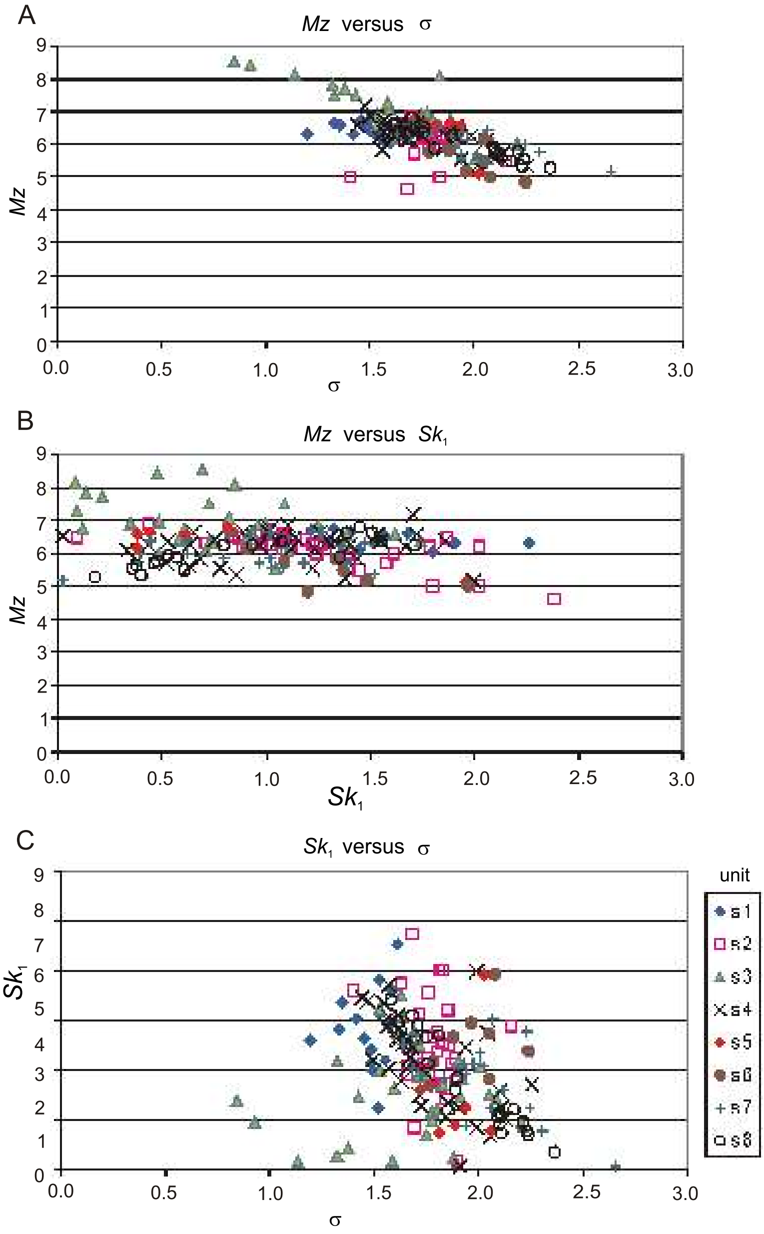

Fig. 8. A — relation between Mz (mean grain diameter) and σ_1 (sorting index) parameters in individual lithogenetic units; B — relation between Mz (mean grain diameter) and Sk_1 (skewness) parameters in individual lithogenetic units; C — relation between Sk_1 (skewness) and σ_1 (sorting index) parameters in individual lithogenetic units

GRAIN-SIZE INDEX

In order to study the changes in grain-size distribution in the Kolodiiv 2 profile, the grain-size index (Ding *et al*., 1994) was calculated for each of the 174 samples. This is the ratio between the percentage contents of additional (<0.005 mm) and main (0.01–0.05 mm) fractions. The grain-size index is considered to be a good indication of changes in the sedimentary environment (especially with respect to wind velocity). It agrees well with other granulometric parameters, and precisely shows differences in grain-size distribution between soil and loess layers. Fractions for calculation of this index were selected in such a manner as to be representative for a definite loess deposit. Therefore, if the content of the 0.002–0.05 mm and >0.05 mm fractions were low in the loess samples, the following fractions were chosen: an additional <0.002 mm, and a main >0.01 mm fractions. The contents of representative fractions in a particular sample should be high enough, i.e. 20–30% for the additional fraction, and 40–60% for the main fraction (Ding *et al.*, 1994). The grain-size indices described above are denoted by the symbols I_{gs1} and I_{gs2}, and calculated from the following formulae:

$$I_{gs1} = \frac{< 0.005\ \text{mm}\ [\%]}{0.01\text{-}0.05\ \text{mm}\ [\%]} \qquad [1]$$

and

$$I_{gs2} = \frac{< 0.002\ \text{mm}\ [\%]}{> 0.01\ \text{mm}\ [\%]} \qquad [2]$$

Variability of both indices in vertical section is shown in Figure 9, and their mean contents of main and additional fractions are given in Table 4. The first index, I_{gs1} is certainly representative of the profile, as its mean content of the additional (<0.005 mm) fraction is 24% and the main fraction (0.01–0.05 mm) is 48%, so they occur within the required intervals. It appears that the I_{gs1} index is representative of each individual unit (only two units — 3 and 6, have mean contents of additional fractions slightly outside the required interval). The second index (I_{gs2}) does not meet the criteria of being representative.

The value of the I_{gs1} index is the highest in unit 3 (composed of palaeosols) indicating a considerably higher content of additional (finer) fraction in relation to the coarser fraction, in comparison with the other units. This feature distinctly differentiated this unit from the overlying and underlying, several metres-thick, loess beds. The differences are distinct both in Figure 9 and in Table 4, especially when comparing the contents of the finer fraction. The two next highest mean values of the I_{gs1} index were calculated for units 5 and 7, i.e. also for palaeosols, and unit 5 occurs between two loess beds. Therefore, the highest mean values of the I_{gs1} index represent palaeosols (unit 5) or palaeosol sets (units 3 and 7) adjoining loess layers. The internal differentiation of units 3 and 7 into separate palaeosols is very well seen in Figure 9. Unit 1 (Holocene soil) is characterized by the lowest values of this index.

The greatest differences in grain-size distribution occur between units 3 and the rest, especially the adjacent units 2 and 4, between units 5 and the adjacent units 4 and 6, and also between

Table 1

Selected types of deposits defined according to Polish Standard PN-86/B-02480

Type of deposit	Symbol	Content of fraction [%]		
		f_p	f_π	f_i
sandy silt	πp	30–70	30–70	0–10
silt	π	0–30	60–100	0 –10
loam	G	30–60	30–60	10–20
silty loam	Gπ	0–30	30–90	10–20
consistent silty loam	Gπz	0–30	50–80	20–30
silty clay	Iπ	0–20	50–70	50–50

f_p — sand fraction, f_π — silt fraction, f_i — clay fraction

Table 2

Number of samples representing particular types of deposits (defined according to Polish Standard PN-86/B-02480), and their percentage contents (in brackets)

Unit	Type of deposit					
	πp	π	G	Gπ	Gπz	Iπ
1		12 (6.9)		4 (2.3)		
2	4 (2.3)	10 (5.7)		19 (10.9)		
3		5 (2.9)		21 (12.1)	5 (2.9)	1 (0.6)
4	5 (2.9)	20 (11.5)		11 (6.3)		
5	1 (0.6)			6 (3.4)		
6	4 (2.3)	2 (1.1)		1 (0.6)		
7	3 (1.7)	6 (3.4)	1 (0.6)	14 (8.0)		
8	2 (1.1)	9 (5.2)		8 (46)		
Σ	19 (10.9)	64 (36.8)	1 (0.6)	84 (48.2)	5 (2.9)	1 (0.6)

For explanations see Table 1

Table 3

Number of samples with dominant silt fractions, and mean contents of silt fractions (their size intervals according to British Standard BS 1377)

Unit (number of samples in the unit)	Number of samples with dominating silt fraction mean content [%]		
	0.06–0.02 mm	0.02–0.006 mm	0.006–0.002 mm
1 (16)	4 43.5	12 45.2	–
2 (33)	22 37.2	11 35.2	–
3 (32)	10 33.5	17 36.2	5 46.9
4 (36)	17 33.6	19 35.6	–
5 (7)	2 26.6	5 32.2	–
6 (7)	7 29.6	–	–
7 (24)	15 31.0	9 33.8	–
8 (19)	15 34.1	4 34.7	–
Σ (174)	92 34.1	77 36.7	5 46.9

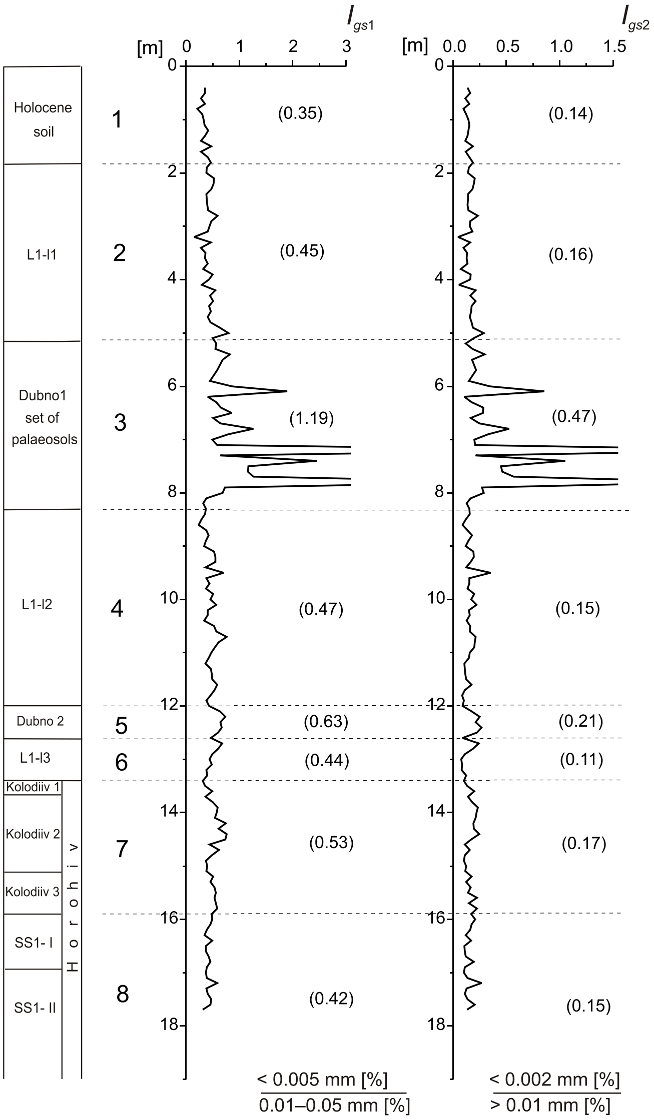

Fig. 9. Vertical variability of grain-size indexes I_{gs1} and I_{gs2} in the Kolodiiv 2 profile

unit 1 and the rest. In other sections of the profile examined, the changes of grain-size index are less distinct indicating a generally similar grain-size distribution. Almost identical values of the I_{gs1} index in units 2, 4, and 6 are noticeable. In these loess beds they are 0.45, 0.47, and 0.44, respectively.

The stratigraphic differences between mean values of the I_{gs1} index indicates that the upper part of the profile (units 1–3) seems to be more variable than its lower part (units 4–8).

The data gathered prompt the following remarks:

— the highest values of grain-size index are found in unit 3,

— the highest mean values of grain-size index occur in units 3, 5, and 7 (palaeosols),

— lower and almost identical values of grain-size index are typical of loess beds represented by units 2, 4, and 6,

— the lowest mean value of grain-size index in unit 1 (Holocene soil) shows its individual nature.

Table 4

The mean percentage contents of the additional and main fractions, and mean values of the grain-size indices I_{gs1} and I_{gs2} in individual units and through the entire profile

Units		Fractions in mm [%]		Index I_{gs1}	Fractions in mm [%]		Index I_{gs2}
		Additional < 0.005	Main 0.01–0.05		Additional < 0.002	Main > 0.01	
1		20.5	59.3	0.35	8.9	63.3	0.14
2		22.1	50.0	0.45	9.9	65.1	0.16
3		33.4	42.1	1.19	14.4	49.4	0.47
4		22.6	49.7	0.47	9.4	63.2	0.15
5		27.0	42.2	0.63	11.7	58.1	0.21
6		18.8	40.1	0.44	8.5	70.7	0.11
7		23.3	44.7	0.53	10.5	63.8	0.17
8		21.1	49.7	0.42	9.8	66.8	0.15
174 samples	min.	8.8	8.3	0.15	4.1	8.3	0.05
	max.	64.4	67.2	7.54	26.4	87.3	3.00
	median	23.2	48.9	0.47	10.2	63.4	0.16
	mean	24.1	47.9	0.59	10.5	61.8	0.21

STATISTICAL ANALYSIS

To find differences or similarities of grain-size distribution (expressed as mean grain diameter) between the eight lithogenetic units distinguished, two methods were used:

— the Kolmogorov-Smirnov test (“D” test);
— the Spearman rank correlation coefficient.

In both methods, the number of samples of definite mean grain-size within the intervals of particular silt subfractions (from 4 to 9 phi; 10 intervals every 0.5 phi) were compared in each pair of units.

KOLMOGOROV-SMIRNOV TEST
(“D” TEST)

This test enables the comparison of two random samples such that their elements are paired (Puchalski, 1973), and it has already been used in geological studies of loess (Racinowski *et al.*, 2003). The percentage sets of cumulative values are compared, and then relative differences between corresponding classes of elements for those two random samples are calculated. The greatest difference is a test statistic denoted as D_0 (%), and is compared with a critical value D (%) at the significance level $\alpha = 0.05$, which is calculated from the following formula (Puchalski, 1973):

$$D = 136\cdot\left[\frac{n_1 + n_2}{n_1 + n_2}\right]^{0.5} [\%] \qquad [3]$$

where: n_1, n_2 — numbers of elements in compared random samples 1 and 2.

If the greatest difference between percentage points of cumulative number of elements (the value of the test statistic D_0) of the compared samples is higher than the critical value D, the null hypothesis that differences between the sets are not statistically significant is rejected, and it is assumed that the differences are significant (Puchalski, 1973).

All possible pairs among the eight deposit units were compared using the “D” test in order to examine grain-size similarities or differences for each pair of deposit units. There were 10 intervals of mean grain diameter Mz for silt subfractions, in which cumulative proportions (%) of samples in a given unit were determined. The results obtained for each pair of units are shown in Table 5 (critical value D) and Table 6 (test statistic D_0). As a final result, pairs of units which show similarities or differences are distinguished using a grey scale in Table 6.

Table 5

Critical values D [%] at the 0.05 significance level in the Kolmogorov-Smirnov test for each pair of deposit units

Unit	1	2	3	4	5	6	7	8
1		41.43	41.64	40.86	61.63	61.63	43.89	46.15
2			33.74	32.78	56.59	56.59	36.48	39.17
3				33.04	56.75	56.75	36.72	39.39
4					56.18	56.18	35.84	38.56
5						72.70	58.42	60.13
6							58.42	60.13
7								41.76
8								

Table 6

Empirical values of the test statistic D_o [%] in the Kolmogorov-Smirnov test counted as the maximum of differences between cumulative values of each deposit unit

Unit	1	2	3	4	5	6	7	8
1		25.57	34.38	25	27.68	85.71	45.83	52.63
2			47.44	9.6	53.25	61.47	21.59	28.39
3				37.85	34.38	79.96	40.63	46.38
4					43.65	60.71	20.83	27.63
5						71.43	46.43	50.38
6							48.81	41.35
7								7.46
8								

Pale grey — significant differences, grey — no significant differences, dark grey — no significant differences but very near the critical value, white — negative correlation is not present

On the basis of the test the following can be noted:

— significant differences between units occur only in 10 from among the 28 pairs, and in two other pairs of units (2–5 and 5–6) the values obtained are very close to the critical value,

— from among the eight deposit units distinguished, 1, 3 and 6 differ from the highest number of the other ones,

— from among successive units, significant differences occur between units 2–3 and 3–4,

— distinct differences in grain-size distribution occur between the upper part of the profile represented by units 1 and 3, and the three lowest units (6–8),

— unit 6 differs from all overlying units, and is similar to the underlying ones (7 and 8).

SPEARMAN RANK CORRELATION COEFFICIENT

Rank correlation methods are especially important in geological studies because they provide possibilities for comparison of qualitative and quantitative features that are not characterized by normal distributions. The most commonly used (also in geology) rank correlation coefficient is the Spearman coefficient (Alexandrowicz and Krawczyk, 1982; Aczel Amir, 2000).

Preparation of data for evaluation of the rank correlation coefficient involves assigning a rank order to quantitative features: sorting the series of features of each unit (i.e. ten intervals of mean grain diameter *Mz* with numbers of samples, notched into the interval) in ascending order, and assigning ordinal rank numbers to all sorted features. A rank order was assigned to quantitative features of each unit and then all units were paired to conduct the correlation. Assuming that there are not the same ranks (the same quantitative features) within the single series, the Spearman coefficient is calculated from the following formula (Aczel Amir, 2000):

$$r_s = 1 - \left[\frac{6\cdot\sum d^2}{n\cdot\left(n^2-1\right)}\right] \qquad [4]$$

where: r_s — Spearman coefficient, n — number of paired elements, d — difference between the ranks of corresponding intervals of two compared units.

This coefficient is usually in the interval from –1 (negatively correlated variables) to +1 (positively correlated variables). However, in each of the the eight units, it was necessary to include into the formula the corrections for the occurrence of the same ranks. The corrections were calculated from the formula [5] and Spearman coefficient with the corrections for connected ranks from the formula [6] (both formulae after Alexandrowicz and Krawczyk, 1982):

$$T = \sum\left[\frac{2}{12}\cdot\left(t^3-t\right)\right] \qquad [5]$$

where: T — correction, t — number of ranks of which connected ranks were created in the series.

Table 7

Values of the Spearman rank correlation coefficient r_s evaluated for each pair of units

Unit	1	2	3	4	5	6	7	8
1		0.49	0.48	0.49	0.45	–0.01	0.37	0.37
2			0.33	0.75	0.55	0.49	0.73	0.73
3				0.55	0.33	–0.32	0.33	0.33
4					0.58	0.29	0.75	0.75
5						0.13	0.45	0.45
6							0.42	0.42
7								0.79
8								

For explanations see Table 6

$$r_s = 1 - \left[\frac{6\cdot\left(\sum d^2 + T_x + T_y\right)}{n\cdot\left(n^2-1\right)}\right] \qquad [6]$$

where: T_x, T_y — corrections evaluated for two compared series, for other explanation see formula [4]

In Table 7 the values of Spearman rank correlation coefficient obtained for all pairs of the deposit units are shown. Significance assessment was conducted by comparison of these values with the critical value ($r_s = 0.564$) of the Spearman coefficient taken from adequate tables (Aczel Amir, 2000) at the significance level 0.05 and $n = 10$. The correlation of two units is positive (similarity) if the calculated coefficient is higher than the critical value 0.564, and occurs in the interval from –1 to +1. Pairs of units which show similarities or differences are distinguished using a grey scale in Table 7. The values of Spearman rank correlation coefficient obtained show that only seven pairs of deposit units, i.e. 2–4, 2–7, 2–8, 4–5, 4–7, 4–8, and 7–8, show similarity in respect of mean grain-size. The values obtained for the rest of pairs are lower than the critical value, so these pairs show statistically significant differences. In two cases (pair 1–6 and 3–6) negative values of Spearman coefficient were obtained, though those values are not in the rejection region (from –0.564 to –1) so the coefficient is not significant and we may conclude that negative correlation does not occur.

COMPARISON OF THE RESULTS OBTAINED FROM THE KOLMOGOROV-SMIRNOV TEST AND THE SPEARMAN RANK CORRELATION

Based on the results of mean grain-size comparison among deposit units, obtained by the two statistical methods, it may be shown that:

— the Spearman rank correlation coefficient shows considerably greater differences between the units examined than does the Kolmogorov-Smirnov test ("*D*" test). The values of Spearman coefficient obtained allows recognition of similarity in a much smaller number of pairs (only 7) of deposit units than the results of the "*D*" test, which indicated 18 pairs as similar,

— all seven pairs of units with similarity confirmed by the Spearman coefficient method (2–4, 2–7, 2–8, 4–5, 4–7, 4–8, and 7–8) belong to the group of 18 pairs where similarity was found by means of the "*D*" test,

— the Spearman rank correlation coefficient method seems more precise (gives stricter criterion for similarity of two sets) than the "*D*" test because it recognized as similar only those 7 pairs of units, that in the "*D*" test obtained values of the test statistic D_0 with considerable reserve below the critical value D.

CONCLUSIONS

LITHOGENETIC UNITS' SIMILARITIES AND DIFFERENCES ON THE BASIS OF GRAIN-SIZE ANALYSIS

Based on the grain-size distributions, the variability of the grain-size index (I_{gs1}) and the results of statistical analysis, i.e. the Kolmogorov-Smirnov test ("*D*" test) and the Spearman rank correlation coefficient, the following conclusions about similarities or differences between individual units in the Kolodiiv 2 profile may be made:

— unit 3 (Dubno 1 set of palaeosols) and unit 1 (Holocene soil) are most individual as regards grain-size in the entire profile,

— units 2 and 4 (loess layers several metres thick, separated by the Dubno 1 unit) are very similar,

— the upper part of the profile (represented by units 1–3) differs in grain size from the lower part (represented by units 4–8). Statistical analysis shows that units 1 and 3 differ from almost all the other units, and the mean values of grain-size index indicate that the upper part of the profile is much more variable as regards grain size (mean values of I_{gs1} from 0.35 to 1.19) than the lower part (mean values of I_{gs1} from 0.42 to 0.63),

— almost all adjoining units differ in grain size. Units 7 and 8 are exceptional as statistical analysis indicated their distinct similarity. Units 4 and 5 are also exceptional because statistical analysis revealed similarity in this pair, though near the critical value. Taking into account the results of other analyses (grain-size distribution and values of I_{gs1}), observable differences between these units can be recognized,

— variability of the mean values of grain-size index (I_{gs1}) in the profile examined indicates that three soil layers (units 3, 5 and 7) differ from three loess layers (units 2, 4 and 6). Analysis of the grain-size distribution indicates considerable similarity between the soil units indicating that silty loam predominates in their composition.

STRATIGRAPHY AND PALAEOGEOGRAPHY COMMENTS BASED ON GRAIN-SIZE ANALYSIS

The lithogenetic units distinguished in the Kolodiiv 2 profile have been correlated with climatic changes during the last interglacial-glacial cycle as reflected in oxygen-isotope stages (Table 8). The history of transformation of the depositional environment was deduced from the grain-size distributions.

The grain-size distribution of the loess deposits in profile 2 varies, with a considerable dominance of the silt fractions (Table 8). The content of silt is lower only in soil layers. These deposits were probably deposited from winds that changed little in intensity, and which transported silt material over a short distance. Heavy minerals analysis published by Racinowski (2007) indicates that the main source area was the valley plain of the Dniester River flowing only 3 km away from the site. The estuary of the narrow, deep, and asymmetrical valley of the Sivka River is perpendicular to the Dniester River valley, which generally runs NW–SE. The steep, right side of the Sivka River valley is covered with loess and exposed to the NW. Loess-forming winds in the East Carpathian Foreland were generally westerlies (Chlebowski *et al*., 2004, Nawrocki *et al*., 2006). It seems that local relief additionally controlled wind direction around Kolodiiv site.

The Upper Pleistocene palaeosol units of high (interglacial) and low (interstadial) rank are characterized by a higher rela-

Table 8

Deposit-forming processes and pedogenic transformation of deposits in the profile Kolodiiv 2 profile

OIS	Lithogenetic units	Deposit type	Dynamics of environment	Deposition type	Pedogenesis	Chronostratigraphy		
1	1. Holocene soil	silt	stabilization of environment		meadow-forest soil	Holocene		
2	2. loess	silt	variable dynamics of environment	predominant subaerial dust deposition, subordinate gravitational deposition	incipient	Upper	PLENIGLACIAL	VISTULIAN
3	3. Dubno 1 set of palaeosols	mixed	variable dynamics of environment (alternation with phases of stabilization)	periodic gravitational redeposition, weak subaerial dust deposition	multiple pedogenetic process (tundra gley, weak brown soil, pedosediment)	Middle		
	4. loess	silt	little differentiated dynamics of environment	subaerial dust deposition, gravitational deposition	incipient			
	5. Dubno 2 palaeosol	mixed	stabilization of environment		weak brown soil			
4	6. loess	silt-sand	little differentiated dynamics of environment	weak subaerial dust deposition, gravitational redeposition	incipient	Lower		
5	7. Kolodiiv set of palaeosols	mixed	little differentiated dynamics of environment/alternation with phases of stabilization	gravitational redeposition, weak subaerial dust deposition	steppe-forest (?) soils, pedosediment	early glacial		
	8. Horohiv ss set of palaeosols	silt	stabilization of environment	gravitational redeposition	double forest soil	Eemian		

tive content of the fine fraction (Fig. 9). This is a result of pedogenesis and probably of cryogenic processes. In the case of the interstadial palaeosols it seems that this phenomenon was not caused by deposition of finer silt in an environment of weaker dynamics (compare Jary, 2004) because the diagrams of grain size parameters (Fig. 4), and especially those of grain size index (Fig. 9) show distinct deflections on the borders between particular palaeosols within the Dubno 1 (unit 3) and Kolodiiv (unit 7) sets of palaeosols.

Those palaeosols occurring in the upper parts of units 3, 5, 7, and 8 are usually covered by loess mixed with material that originated during soil destruction, which was spread over the slope by solifluction and washdown processes. A predominance of slope processes over aeolian deposition can be concluded from the similarity of the adjoining units 8 (Horohiv set of palaeosols) and 7 (Kolodiiv set of palaeosols). This is less visible in the case of unit 5 (Dubno 2) and 4 (loess bed) as the latter is very thick.

The variability of grain-size distribution in the adjoining units 3–5, which together represent the Middle Pleniglacial (OIS 3), reflects the climatic heterogeneity of this period that has been observed by many researchers. This variability progressively became more marked, and reached a maximum during the formation of the unit 3 deposits, i.e. in the younger part of the Interpleniglacial characterized by a series of small climatic fluctuations.

From among the three loess units examined in the Kolodiiv 2 profile only unit 6 does not show similarity with any other unit as shown by the results of statistical analysis. This individuality seems to be associated with climatic distinctiveness of the Lower Pleniglacial (OIS 4). This was a long period; in the initial cold though wet part of the Vistulian Glacial (Łanczont and Boguckyj, 2007) the deposition rate was lower, and accumulated material was redeposited many times on slopes. Moreover, numerous erosion surfaces found in the loess of this unit in other exposures in the terrace scarp of the Sivka River valley suggest that the Kolodiiv 2 profile contains probably only part the succession, and so is not representative for the whole of this interval.

The dynamic conditions of the aeolian processes forming the loess deposits in the Kolodiiv 2 profile were generally stable (Table 8). Only the loess of unit 2 shows a grain-size distribution that varies significantly (Figs. 2 and 9), on the basis of which three depositional cycles can be distinguished. The initial cycle/phase was characterized by the deposition of finer silt and by lighter winds. Traces of solifluction and other slope processes, visible in the loess structure, suggest possible mixing with material from the erosion of underlying deposits. This stage reflected climatic cooling and increased humidity in the early phase of the Upper Plenivistulian. The deposition of coarse-grained loess in the middle phase probably indicates generally stronger winds but small, rhythmic fluctuations in the proportion of the >0.5 mm fraction (Fig. 4) indicate that distinct, short-term oscillations of environmental dynamics occurred in this interval representing climatic determination in the Upper Pleniglacial. Winds became weaker and more stable in the last phase.

Unit 1, i.e. Holocene soil, reveals a grain-size distribution opposite in trend to the palaeosols. It is distinguished by the lowest mean values of grain-size index in the entire profile (Fig. 9). This may indicate that this soil does not represent the entire Holocene epoch. It is probably a product of very young (Late Holocene) pedogenesis and so the initial material has been only weakly transformed.

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