Research Article

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New approach of clustering of late Pleniglacial Weichselian loess deposits (L1LL1) in Poland

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Abstract: The results of grain size distribution of loess units are suitable for the study of past climate change. There are many methods for the analysis of the grain size, but clustering methods have not been used before. In this article, a new approach in the sediment research, the *k*-median method was used. This method separates the grain size classes of the youngest loess units of three loess-soil profiles in Poland: Biały Kościół, Złota and Tyszowce. In the analysis, only the content for the loess silt fraction (range from 4 to 63 μm) was used. This allowed eliminating the admixtures of sandy and clay fraction, considered as secondary material. For the purposes of this analysis, silt fractions were divided into smaller units using a 1/4 phi interval, resulting in 16 new subfractions. The grain size data from three profiles were combined into one data set. As a result, four classes with a similar internal of grain structure were obtained. The separated classes showed the sedimentological variability of the sediment well. It has been shown that the *k*-median method can be used to classify loess in a fast and objective way.

Keywords: L1LL1 loess unit, loess covers in Poland, *k*-median method, grain-size distribution

1 Introduction

Loess-paleosol sequences are well suited for studying the past climate change. Unfortunately, in most cases, sediment properties cannot be related to a single process. An important condition for extracting climatic

signals from sediments and for further reconstruction of signal-related processes is to study their contemporary spatial variability. The observable properties of the loess material are the result of the interaction of many processes. Depending on their genesis (e.g., soil processes), changes in the original material should show similar characteristics. Therefore, the paleoenvironmental processes save a specific trace in the sediments, which allows them to correlate with each other. For example, during cold and dry climatic conditions that allowed the transport and the sedimentation of the dust fraction, levels of homogeneous loess have been formed. Changing these conditions to more humid and warmer is marked by a change in the grain size distribution and an increase in the proportion of finer fractions by weathering or soil formation. Therefore, the properties of individual archives are not sufficient to decrypt information related to the process or processes responsible for their creation. Thus, with this type of analysis, a wider, regional research area should be considered, not closing to smaller areas showing only local features of the sediments.

Until now loess-paleosol sequences were mainly treated as individual archives, in which the results provided information on local paleoenvironmental conditions. Studies comparing the grain size results in a broader context are still rare. Research covering Central Europe and Central, Eastern and North-West Asia was conducted by Vandenberghe [1]. He attempted to define the characteristic grain size distribution for specific aeolian sediments and to assign them appropriate conditions as well as transport and deposition processes. For this purpose, a combination of visual analysis of grain size distribution curves and the statistical end member analysis (EMMA) was used. The EMMA analysis has proved to be particularly useful for multimodal distributions, whose interpretation is usually qualitative and successful only when subpopulations clearly differ from each other. The EMMA method allows for a quantitative and objective character of the analysis. However, the result of this analysis is to obtain a specific end member that corresponds to the specific grain size.

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The aim of this article is to introduce and check the operation of the objective and automatic clustering method of the loess grain structure. The key was to check the sensitivity of the method to the distribution of data. An important element was the selection of the optimal number of clusters in terms of statistics and checking whether the algorithm can work independently or whether it should be treated as a tool supporting the expert knowledge. Another element was whether the division used corresponds to other methods used in profiles research so far. For the statistical separation of classes, the *k*-median method was used. This method is highly suitable for the multidimensional data, such as grain size results. The *k*-median method is easy, fairly quick, and universal. It was used in the morphometric analysis [2–4] and climate research [5], in search of missing people [6] or in the analysis of depopulation processes [7]. Bhargavi and Jyothi [8] used it to classify soil texture based on soil granulometric properties. The result of the analysis is used to identify ten classes of soil texture. The authors point to the advantages of the method such as its simplicity and systematic structure. The authors of this article made similar observations.

The analysis was limited to the grain size characteristics of the late Pleniglacial loess (L1LL1 according to [9]), least transformed by postsedimentation processes. In the analysis, only the content “typical” for the loess silt fraction (range from 4 to 63 μm) was used. This allowed eliminating the admixtures of sandy and clay fraction, considered as a secondary material. Clay fraction is mainly the result of postdeposition processes. However, the fine sand subfraction is rare in the profiles. Coarser sands are more common, which are certainly associated with the recycled material. For the purposes of the analysis, silt fractions were divided into smaller units using a 1/4 ϕ interval, resulting in 16 new subfractions.

2 Regional setting

Polish loess covers the central area of the northern loess zone in Europe (Figure 1). Due to their transitional location, they are among the most interesting on the continent [10,22]. The authors dealing with problems of loess in Poland suggest that the development of loess covers reflects the contemporary and Pleistocene features of Poland’s climate: continental in the east and more oceanic in the west [12,13]. This study compares the results of the grain size distribution of L1LL1 loess units of three loess-soil sequences: Biały Kościół (Niemcza-Strzelin Hills), Złota (Sandomierz Upland) and Tysowce

(Sokal Plateau-Ridge). These profiles have been repeatedly analyzed, and the results of these analyses are available in many publications (e.g., [11,14–19]). The key element of selection was also the presence of late Pleniglacial loess units and their availability.

2.1 Biały Kościół

The loess section in the vicinity of the village Biały Kościół ($\lambda = 17^{\circ}01'30''\text{E}$, $\varphi = 50^{\circ}43'30''\text{N}$, 193 m a.s.l.) is composed of 9 m interfluve and slope loess facies. The loess profile is situated on the west slope of the Oława river valley at an altitude of approximately 185 m a.s.l. in an old loam pit (Figure 2).

The loess cover in the surrounding area was previously described by Ciszek [20]. The complete loess-soil sequence at Biały Kościół has been excavated and characterized by Ciszek et al. [21].

The results of the multidisciplinary research have been published in numerous scientific papers. A palaeogeographic interpretation was provided by Jary [10,22]. A chronological framework for this site was established by Moska et al. [15,16]. Grain size characteristics of loess sediments were presented by Krawczyk et al. [23]. The stratigraphic and spatial aspects of the differentiation of the chemical composition of this sequence were presented by Skurzyński et al. [24].

2.2 Złota

The investigated loess section is located in the south-eastern part of Poland in the Vistula river valley ($21^{\circ}39'\text{E}$, $50^{\circ}39'\text{N}$), about 20 m above the current level of water. The section was discovered in 2010 in the Złota village on the northern side of the valley. The thickness of the loess cover in this area exceeds 12 m, and the altitude of this place is approximately 170 m a.s.l. (Figure 3). Another loess site, Samborzec, known since the 1980s, is located at a distance of about 100 m westward at the excavation site of former brickworks.

The site was first described by Grygierczyk and Waga [14]. The site was further investigated by Dolecki and Łanczont [25,26], who used the name Polanów Samborzecki. A palaeopedological description of this site was provided by Konecka-Betley et al. [27], and a palaeogeographical interpretation of micromorphological features of the loess-soil sequence was presented by Mroczek [18,28]. The characteristics of the site based on multidisciplinary

Figure 1: Distribution of loess covers in Poland (modified according to refs. [10,12]).

investigations were published by Jary [10]. A chronological framework for this site was established by Moska et al. [29].

2.3 Tyszowce

The Tyszowce loess section ($\lambda = 23^{\circ}42'45''\text{E}$, $\varphi = 50^{\circ}36'30''\text{N}$) is located in the northern part of the Sokal Plateau-Ridge (Figure 4), which is the westernmost part of the Volhynia

Upland [15,30]. The Sokal Plateau-Ridge is a latitudinal cretaceous hump with a thick loess cover [31]. From the north and south, the region is limited by distinct morphological edges to over 10 m high [32]. The loess sequence in Tyszowce is located at the height of 226 m a.s.l. in the northern margin of loess cover, close to the Huczwa River, about 30 m above the modern valley bottom.

The loess deposits at an active brickyard locally reach a thickness of 20 m. The stratigraphy and the

Figure 2: Location (a) and lithological description (b) of Biały Kościół L1LL1 unit (lithological description modified according to ref. [23]).

Figure 3: Location (a) and lithological description (b) of Złota L1LL1 unit (lithological description modified according to ref. [29]).

Figure 4: Location (a) and lithological description (b) of Tyszwce L1LL1 unit (lithological description modified according to ref. [19]).

palaeoenvironmental interpretation of neighboring loess-paleosol profiles in Tyszwce have been presented several times in Polish literature [17,19,32,33].

3 Methods

Research on the profiles can be divided into three basic stages.

3.1 Field work

Field study consisted of careful cleaning of the profile walls, descriptions and sampling for analysis. Before

describing the profiles and sampling, the profile walls were carefully cleaned to expose fresh material. After that the lithological description was prepared. All of these profiles were sampled in vertical continuous sections at close intervals (5 cm) and documented with respect to their sedimentology, paleopedology and stratigraphy.

3.2 Laboratory investigations

Grain size distributions were determined by using a laser diffractometer Mastersizer 2000 (manufactured by Malvern, England) in Soil Laboratory of Department of Physical Geography, University of Wrocław. Before the

measurement, organic matter was removed by H_2O_2 and carbonates by 10% HCl. For better dispersion, sodium hexametaphosphate (calgon) was added to the solution before measurement.

In the analysis, only the silt content (4–63 μm) was used. The fractions were divided into smaller units using a 1/4 phi interval, resulting in 16 new subfractions.

3.3 Statistical analysis – the *k*-median method

The authors searched for a method that provides an analysis of variables collectively, not separately. Therefore, a method that can be used in a multi-dimensional analysis was needed. Clustering is defined as a process of separating data into clusters (groups) of similar types using some physical or quantitative measures [34]. An iterated *k*-median method is one of the clustering methods that divided the data in the disjoint groups (clusters). It is an unsupervised method. The same rules as for the *k*-mean method apply, but the centre of a cluster is determined by using the median instead of the mean function. The standard *k*-means method divides a multidimensional set of data into *k* clusters in the way that the patterns in a cluster are more similar to each other than to patterns in different clusters.

The advantage of this method is the independence from the distribution of data, and it means normal distribution of data is not required. This is very important in the classification of granulometric data, which does not have a normal distribution, and its distribution is not even symmetrical. The *k*-median method is robust to outliers and results in compact clusters, while the *k*-mean is easily affected by outliers. Each variable has the same impact in this clustering. An additional advantage is the possibility of clustering in any number of dimensions, i.e., for many variables at once.

The number of clusters is selected *a priori* [35], which could be a problem if the nature of set of data is not known. Different initial partitions can lead to different final clusters because the algorithm is based on the square-error and can converge to local minima. Therefore, to obtain an optimal solution, several runs must be executed with different initial partitions [36,37]. Usually clustering is done for different *k* values, and then, the optimal solution is chosen from the statistical point of view or based on the expert knowledge.

Table 1: Results of *k*-median analysis

<i>k</i> – number of clusters	BSS – parameter between cluster sum of squares	BSS/ <i>k</i>
3	11.22	3.74
4	15.27	3.82
5	19.40	3.88
6	23.82	3.97

Taking into account the aforementioned advantages, universality and objectivity of the method and the statistical distribution of granulation data, the authors decided to use the *k*-median method to isolate clusters with similar granulation characteristics. In this study, the cluster analysis was performed using Canal software that was specially prepared for clustering, and this was also followed in the previous studies [2,3,5].

4 Results

For the correct separation of grain size classes, the grain size results of younger LILL1 loess in three selected loess-soil sequences have been combined to form one common granulometric database. The data set was classified into three to six classes (Table 1). The obtained statistical parameters (BSS/*k*) gave very similar results. However, after running the program several times, the result for the subdivision of the database into four groups gave the same value 3.82 all the time. Hence, we considered this division to be the most powerful and optimal in terms of interpretation. Taking into account statistical criteria and expert knowledge, the optimal division was considered to be into four classes. They are

Figure 5: Distribution of grain size of four separated groups by the *k*-median method.

Table 2: The number and share of samples in classes in particular analyzed loess sites

Name of class	Total number	Biały Kościół	Tyszowce	Złota	Biały Kościół %	Tyszowce %	Złota %
Class 1	81	18.0	46.0	17.0	22.2	56.8	21.0
Class 2	137	18.0	88.0	31.0	13.1	64.2	22.6
Class 3	165	41.0	39.0	85.0	24.8	23.6	51.5
Class 4	83	—	80.0	3.0	0.0	96.4	3.6

Figure 6: Lithology, *k*-median classes and silt subpopulation content of L1LL1 unit of Biały Kościół loess-soil sequence.

characterized by a similar internal grain structure. The results of the analysis are shown in Figure 5.

The first class (Figure 5.) is characterized by the highest content of fine and medium silt fractions (below 32 μm). The shape of the class chart shows the largest flattening relative to the others. The total number of samples included in this group is 81, and this is the least numerous class. Most samples from class 1 are included in the Tyszowce sequence – over 50% all occurring (Table 2).

The second class, unlike class 1, is characterized by a slight shift in the grain mode toward coarse silt (38 μm level). The graph is less flattened (Figure 5). The content of fine silt is also lower. The number of samples in this class is 137, of which again the largest percentage of them occurs in the profile in Tyszowce – over 60%.

Class 3 is the most common class in results. The course of the curve is similar to that in class 2; however, the content of coarse silt is much higher. This group occurs primarily in the loess-soil sequence in Złota (share over 50%).

Class 4 is distinguished from the others by the largest proportion of coarse silt with a small percentage of fine silt. It appears almost entirely in the profile in Tyszowce (over 90%; Table 2).

The results of *k*-median analysis were compared with the lithological figure of L1LL1 loess-soil sequence in the Biały Kościół and for the distribution of the particle size of the silt subfraction (Figure 6). Over 50% of all tested samples belong to in class 3 (Table 3). This class occurs in the upper part of the described unit, in the place of homogeneous loess (Figure 2). The lower part of the profile (below 3 m) consists mainly of samples qualified for groups 1 and 2. Group 1 occurs at the site with the highest content of fine dust fractions. At this place, a profile of the gley horizon is clearly visible. Above and below the horizons of laminated loess with gley spots are differentiated (Figure 2).

Table 3: Class participation in L1LL1 units as a percentage in particular analyzed loess sites

Name of class	Biały Kościół %	Tyszowce %	Złota %
Class 1	23.4	18.2	12.5
Class 2	23.4	34.8	22.8
Class 3	53.2	15.4	62.5
Class 4	—	31.6	2.2

Figure 7: Lithology, *k*-median classes and silt subpopulation content of L1LL1 unit of Złota loess-soil sequence.

Samples from these levels are characteristic of class 2. This class is characterized by a significant content of fine silt, slightly less than in class 1. The content of both classes in the profile is the same and amounts to 23.4% (Table 3). Class 4 is not distinguished in the described sequence.

The results of the *k*-median analysis compared to the lithological figure and the content of the silt subfraction for the L1LL1 unit of the loess-soil sequence in Złota are shown in Figure 7. This sequence has the largest class 3 share compared to the other profiles. As mentioned earlier, over

Figure 8: Lithology, *k*-median classes and silt subpopulation content of L1LL1 unit of Tysowce loess-soil sequence.

50% of all samples qualified for class 3 comes from this profile (Table 2). In the L1LL1 unit in Żłota, class 3 constitutes over 60% (Table 2). The upper part of the unit (0–5 m) consists of samples classified mainly as class 3. This part of the unit also distinguishes levels classified to other classes in the form of sandy and gley inserts. In places of weak gley horizons (Figure 3), class 2 is distinguished, and in sandy laminates, class 4 is distinguished. The lower part of the L1LL1 loess-soil sequence unit in Żłota is built of a tundra gley horizon. The material from this place was qualified for class 1.

The loess-soil sequence in Tysowce is characterized by the thickest L1LL1 unit (over 12 m) compared to other profiles. The results of the analysis are shown in Figure 8. The upper part of the L1LL1 unit consists mainly of sandy loess with clear, continuous sandy laminates (Figure 4). As a result of the algorithm, this part of the profile (up to approximately 5.5 m) was mostly assigned to class 4, which almost entirely occurs only in this unit.

The middle part of the unit (from 6 to 10.5 m) is classified mostly as class 2, with several levels qualified as class 3 in the upper part of the described level. During fieldwork in this part of the profile, the occurrence of streaked loess and several weak gley horizons (Figure 4) was distinguished. The two best-preserved tundra-gley horizons are described at a depth of 10.5 m and below 12 m. These are the levels with the highest content of fine silt fraction, a characteristic of this type of horizon. In both cases, the material analyzed was classified into class 1.

5 Summary and conclusion

The separated four classes correctly describe the sedimentological variability of loess units. Class 1 occurred primarily in places with the largest share of the finest fractions. At these levels of tundra, gley horizons have been distinguished. Class 2 was distinguished in places of gleyed or laminated loess. The fraction of fine silt is significant here, which is lower than in class 1. Both classes are usually close together. They constitute a significant share in L1LL1 units in the Biały Kościół and Tysowce (Table 3). They occur close to the L1SS1 (description of the unit according to Ref. [9]) fossil soil distinguished in both profiles correlated with MIS 3 [23,17]. This material had to be strongly transformed as a result of postdeposition processes, as indicated by earlier analyses [10,18,23,24]. The result of these transformations is the specific internal grain structure represented by these classes. In places of

homogeneous loess, class 3 has been indicated. It is the characteristic of loess units with the highest content of medium silt, and above all coarse silt. The best example is the L1LL1 unit in Żłota (Figure 7), where this class is the clear majority. The upper part of the mentioned unit is described as an example of loess without a clearly marked structure as noted in the previous studies [11,14]. In its structure, there were often individual samples classified in class 4. In these places, levels with the highest proportion of coarse silt fraction were distinguished. Analyzing lithological figures and the description of the unit, these were often the places of occurrence of sandy laminas or levels of sandy loess. Such features characterize the unit of the late Pleniglacial-Weichselian loess in Tysowce. Its upper part is clearly enriched with material made of a sandy fraction [11,12,19]. Such a large supply of this fraction had to indicate rapid sedimentation from close sources of material [1] as indicated by the obtained dating results [17]. The common database and the algorithm allow even individual samples that were present in a larger structure of another class.

The database was created by combining the grain size results of three L1LL1 units treated comprehensively. The algorithm, not including the depth, allowed the designation of classes without fear of the impact of data neighborhood.

The advantage of the method used is the ability to analyze a multidimensional database regardless of the statistical distribution. It was possible to use the data divided into 16 subfractions instead of the classic division of the silt fraction. By increasing the resolution, the interpretation capabilities of the results have increased significantly.

The weakness of the classification method is the difficulty in choosing the appropriate number of classes that allow objective analysis and interpretability of the results. For the proper analysis, it is necessary to have specific knowledge about the analyzed area and material. This is not a fully deterministic method. It does not guarantee to obtain exactly the same division when you restart the algorithm. However, by running it multiple times and based on the maximum of between cluster sum of square, the separation error is negligible.

To sum up, the *k*-median method can be used to easily classify aeolian sediments such as loess. However, more tests are needed to minimize weaknesses. Further activities on the development of the method will assume taking into account the higher resolution of the database (sample interval from 5 to 1 cm). As mentioned earlier,

the separated classes showed the sedimentological variability of the sediment well. Future research should focus on linking a given class to environmental conditions that shape the specific internal structure of the granulation.

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