

# Aeolian processes records within last glacial limit areas based on the Płock Basin case (Central Poland)



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## Abstract

Formation of dunes in the Płock Basin of the Vistula River valley in Central Poland is connected with the aeolian processes that occurred within the European Sand Belt during the Late Pleistocene. Changes in sedimentation conditions, from fluvial (unit G1), to fluvio–aeolian (unit G2) then to aeolian (unit G3), were respectively recorded in the fluvio-glacial terrace sand dune profiles in the village of Goreń Duży (the Płock Basin, Central Poland). Both fluvial and aeolian processes occurred in the periglacial zone of the last glaciation, the northern limit of which is defined by the Last Glacial Maximum (LGM), being 18.4 ka in the Płock Basin. River and ice-marginal valley terrace sand sediments, in association with glacial deposits, could be the source material for the studied aeolian bedforms. The results of morphoscopic analysis of dunal sand quartz grains indicate that rapid deposition occurred more often than did long-term long-range grain transport. Grain transport genesis begins during the Older Dryas, which is confirmed by optically stimulated luminescence (OSL) dating performed for unit G2: 13.06±0.76 ka and 13.54±0.84 ka. During dune formation, dead-ice blocks remained intact in a subglacial channel until the Allerød, which suggests that aeolian processes continued after block melting, throughout the Younger Dryas. Successional aeolian processes have resulted in the extensive dune fields of the Płock Basin.

Keywords: Aeolian, palaeo-environments, fluvio-aeolian succession; quartz grain morphoscopy, Late Pleistocene, OSL dating

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## 1. Introduction

Aeolian processes occurring during the Late Pleistocene have been extensively described in Europe (Dylikowa, 1967, 1968; Nowczyk, 1986; Zeeberg 1998; Kasse, 2002; Seppälä, 2003; van Huissteden et al., 2001; Koster 2005; Goździk, 2007; Kasse et al., 2007; Bateman, 2008; Kalińska-Nartiša et al., 2016; Woronko et al., 2015; Zieliński et al., 2016). Their effects, aeolian deposits and landforms, wrought elemental features of the north-central European landscape, forming the so-called European Sand Belt that stretches from Great Britain in the west, through Germany and Poland, and spans to Russia and Ukraine in the east (Koster, 1988; Zeeberg, 1998). The aeolian processes were associated with the periglacial conditions (*i.e.*, cold, dry, windy) in the marginal zone of the last Scandinavian Ice Sheet (SIS) (Zieliński et al., 2011) and in areas located in the borderlands of the Last Glacial Maximum (Zieliński et al., 2011, 2015).

When investigating intensity of aeolian processes in Europe, Cailleux (1942) specifically focused on the fraction of highly rounded and completely frosted sand quartz grains with a diameter of 0.4–0.1 mm, described by the author as rounded matt (RM). Very well-rounded and matt surface results from long-lasting and intensive abrasion during the movement (transportation) of grains in the process of saltation in the aeolian environment (Mycielska-Dowgiałło & Woronko, 1998; Mycielska-Dowgiałło, 2001; Goździk, 2007). Cailleux (1942) registered the highest frequency of wind-modified sand grains (RM) in Central Poland. However, the concentration of RM grains in aeolian deposits in Poland varies both in N–S (Goździk, 1998; Zieliński et al., 2015) and W–E directions (Zieliński et al., 2016). In this case, an ice-sheet positional factor had a major and direct impact on the duration of aeolian processes, which resulted in the division of the area of aeolian process development into an ice-free extraglacial zone, occupying the LGM foreland, and newly exposed areas released from under ice cover. An equally important factor driving these aeolian

processes was climate in particular the degree of continentality (Mycielska-Dowgiałło & Woronko, 2004; Zieliński et al., 2016). Based on distribution of dune fields and coversand accumulation during the last Pleistocene glaciation, Zeeberg (1998) distinguishes three types of European aeolian environments: 1) a periglacial zone during the maximum Weichselian ice extent at its foreland from 29 ka to 22.5 ka; 2) an intermediate zone during the ice retreat from 18 ka to 13 ka; 3) deglaciation zone where aeolian processes developed after the ice-sheet retreat between 13 ka to 9 ka. Conditions that would typically facilitate the development of aeolian processes were instead hampered within the second and third zones listed above. Wind action in the latter zones was limited, due to the short timeframe that conditions were favourable for the development of aeolian processes. Aeolian activity was further impeded by the progressive expansion of vegetation into ice-free areas. According to Zeeberg (1998), an example of an area that may represent Zeeberg's second aeolian environment is the Płock Basin located at a midpoint in E–W bounds of the European Sand Belt (Fig. 1a).

The Płock Basin is a vast extension of the Vistula River valley, being the easternmost part of the Toruń–Eberswalde ice-marginal valley (Galon & Roszkówna, 1961; Kozarski, 1965; Skompski, 1969; Pisarska-Jamroży, 2015). The Płock Basin's origin is related to a paleo-ice stream ( $B_3$ ), a branch of the Baltic paleo-ice stream (Punkari, 1997). The maximum range of this ice-sheet occurred during the Poznań phase (LGM) in the Vistula Lobe in the Vistula River valley (Roman, 2010; Wysota & Molewski, 2011; Tylman et al., 2017), which took place approximately 18.4 ka according to optically stimulated luminescence (OSL) and thermal-luminescent (TL) dating (Wysota et al., 2009). The retreat rate of the ice-sheet margin in the Vistula Lobe was about 450 m/a (Wysota et al., 2009). The presence of this paleo-ice stream in the Płock Basin is connected with the system of NW–SE and N–S subglacial channels being parallel to the longer axis of this basin (Lencewicz, 1927). One of the

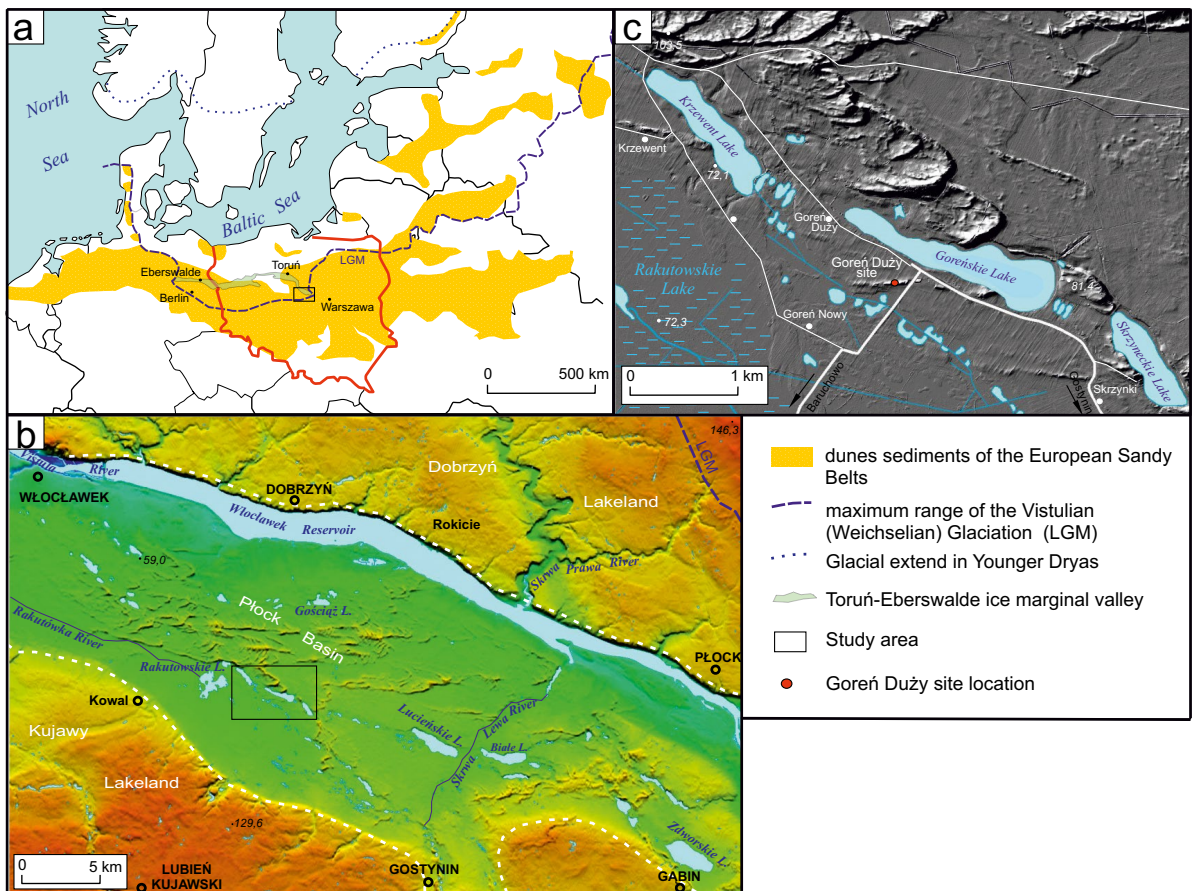


Figure 1. Location of the study area: a) Study area in the European Sand Belt; b) Płock Basin within the maximum range of the Vistulian Glaciation (LGM) (Roman, 2010); and c) Goreń Duży site.

largest subglacial channels in the Płock Basin is Lake Goreńskie with a length of 2 km. According to palynological and  $^{14}\text{C}$  data, the valley bottoms were preserved by dead ice that melted mainly in the Allerød (Ralska-Jasiewiczowa et al., 1998), which had a major effect on aeolian processes in this region (Urbaniak-Biernacka, 1976). This dead-ice melting was connected with permafrost degradation during climate amelioration.

The objective of this study was to: 1) to reconstruct the intensity of aeolian processes in the Płock Basin based on Goreń Duży dune structure and textural features deposit grain size distribution and morphoscopy of its sand quartz grains, 2) compare the activity of aeolian processes developing in the SIS foreland to the area exposed after the ice-sheet

margin retreat in the Vistula Lobe as related to its position in the European Sand Belt (Fig. 1b), and 3) determine the relation between aeolian landforms and associated negative landforms composed in glacial relief, e.g., subglacial channels as viewed in LiDAR imagery.

## 2. Study area and geological setting

The Płock Basin is about 18–20 km wide and has a broad left-bank fluvial terrace of sand. There are numerous postglacial lakes and dunes and a floodplain now substantially inundated as a result of a retention reservoir built here in the late 1960s.

Dunes in the Płock Basin form a belt with a length of about 50 km and a width ranging from 10 km in the west to about 18 km in the east (Urbaniak, 1967) along with a few other smaller dune fields outside this belt. The relative height of individual dunes reaches 35 m. The highest one is a ridge called Patrolowa Góra that has a height of 114.6 m a.s.l.. Aeolian forms are represented by parabolic, longitudinal and irregular dunes (Fig. 1b).

The studied dune in Goreń Duży (52°31'39" N; 19°17'45" E) is located about 180 m south of Lake Goreńskie, the shoreline of which runs at an angle of about 30° in relation to the dune crest (Fig. 1c). It is a narrow longitudinal W–E dune, with a length of approximately 1 km and a relative height of up to 8 m. It is located on the ice-marginal terrace (Skompski, 1969) between a large kettle hole of Lake Rakutowskie in the south and a subglacial channel represented by Lake Goreńskie, Lake Krzewent and Lake Skrzyneckie in the north (Urbaniak, 1962; Urbaniak-Biernacka, 1976; Rychel et al., 2015). Urbaniak (1967) suggested that only distal slopes of dunes were preserved in the Płock Basin. She reported that the dune accumulation from the northern side of Lake Goreńskie was a result of wind blowing from the southern sector. Dunes in the Płock Basin are the dominant element of relief; being very well developed and they cover large areas. Therefore, the regional government legally protected the dune field as part of the Gostynin-Włocławek Landscape Park created in 1986.

### 3. Materials and Methods

Research on the dune in Goreń Duży was carried out in two stages. The first stage included a description of the structural and textural features of the dune deposits along an outcrop wall with a profile height of 10 m revealing dune sediments and their substratum. A detailed structural analysis was performed using a lithofacies code, as proposed by Zieliński & Pisarska-Jamroży (2012). Measurements were then taken of directional

structures. Additionally, 27 samples were collected for further laboratory analysis. In the second stage of research, the textural features of the sediments were analysed and grain size distribution, morphoscopy of quartz grains and loss on ignition were measured. Grain size analysis was performed using sieve and laser methods dry sieve analysis using a set of sieves for the fractions ranging from 2.0 to 0.1 mm and Fritsch Laser Particle Sizer Analysette 22 for the fractions below 0.1 mm. Statistical indices of grain size composition were calculated according to Folk & Ward (1957): average grain diameter ( $Mz$ ), standard deviation ( $\sigma_l$ ) as a measure of sediment sorting, and skewness ( $Sk_l$ ) showing the asymmetry of sediment distribution. For the statistical analysis, the software GRADISTAT\_5\_11\_PL\_beta was used (Blott & Pye, 2001).

Morphoscopic analysis of quartz grains was performed for 0.5–0.8 mm and 0.8–1.0 mm fractions according to the method as proposed by Cailleux (1942) and modified by Mycielska-Dowgiałło & Woronko (1998). This analysis provides information on the genesis of sediments, duration of aeolian processes, dune sediment source areas (alimentary areas), the degree of sediment transformation as well as all post-depositional processes (Mycielska-Dowgiałło & Woronko, 1998). Seven types of quartz grains were distinguished according to the last process marked on the surface of quartz grains (Table 1). In each instance, 100 to 150 randomly selected grains were analysed (after being etched in 10 M HCl, then washed with distilled water).

The organic matter content (OM) was determined based on the weight loss after dry sediment samples were heated at 550°C for 3 hours.

In order to establish the time when aeolian processes began, two samples of sandy sediments were collected to determine their age using OSL, which indicates the time that has elapsed since the last exposure of sediments to daylight (Aitken, 1998). Dating was conducted in the Centre of Excellence GADAM at the Institute of Physics, Silesian University of Technology, in accordance with the procedures applied there (Moska, 2017;

Table 1. Type of roundness and frosting of quartz sand grains (0.8–1.0 mm) according to Cailleux (1942) as modified by Mycielska-Dowgiało &amp; Woronko (1998).

Class of grain	Roundness of grain acc. to Krumbein (1941)	Description	Processes responsible for the formation of grain
RM	0.7-0.9	Very well rounded with completely mat surface	Very long duration abrasion in aeolian environment
EM/RM	0.3-0.6	Moderately rounded, mat surface only on convexed parts of grains	Short time duration abrasion in aeolian environment marked only on convexed parts of grains
EL	0.7-0.9	Very well rounded with smooth, shiny the entire surface	Combination of abrasion and solution in fluvial or beach environment. Very well roundness of grains indicates long duration of processes
EM/EL	0.3-0.6	Moderately rounded, smooth and shiny surface	Combination of abrasion and solution in fluvial or beach environment
C	-	Crushed/Broken	Crushing in all type of environments but the most intensive in subglacial environment or as an effect of frost weathering
NU	0.1-0.2	All surface are fresh, corners are sharp and angular	Crushing and abrasion in glacial environment; mechanical weathering in situ e.g. frost weathering
O	0.1-0.9	In situ very intensive weathered surface by silica precipitation or solution; No visible transport trails	Solution or precipitation in soil profile, hot desert environment or periglacial environment

Table 2). A total of 12 aliquots were conducted for a sample collected at a depth of 8.75 m and 13 aliquots for a sample collected at a depth of 8.1 m. The averaged result is herein provided (Galbraith et al., 1999). Measurements were made using Daybreak 2200 and Risø luminescence readers. The irradiation was performed using a calibrated  $^{90}\text{Sr}/^{90}\text{Y}$  beta source with a power of 3.0 Gy/min. The absorbed dose was determined by the Single Aliquot Regenerative (SAR) method (Murray & Roberts, 1998). The final absorbed dose was determined using the Central Age Model (CAM) (Galbraith et al., 1999).

## 4. Results

### 4.1. Sedimentary structures and age

Based on the structural analysis of sediments at the Goreń Duży site, sediments exposed in the outcrop were divided into three units G1, G2 and G3 with erosional boundaries in between (Fig. 2).

Sediments of unit G1 lie at a depth below 9.6 m. The uppermost (top) layers of this unit are built of cross-bedded sands (Sp) (Fig. 2).

Sediments of unit G2, with a thickness of 1.95 m, lie at a depth of 7.65–9.60 m. Fine- and medium-grained horizontally stratified sand (Sh) and trough cross-stratified sand (St) occur in the uppermost and bottom layers (Fig. 2). The middle part of unit G2 is built of horizontally stratified sand (Sh), massive structure (Sm) and silty sand with wavy lamination (SFw), forming the rhythmite Sh->SFw (Fig. 2a). Accessory lithofacies in the sediments of this unit are represented by massive sand (Se) and massive gravelly sand (SGe), filling a shallow erosional scour with a depth of up to 0.35 m and a varying width, which ranges from 0.10 m to over 0.5 m. At least 5 levels of small-scale involutions were found in the sediments of unit G2, developed at the contact zone of horizontally stratified sandy deposits (Sh), and sand with massive structure (Sm) in the top layer and in the rhythmite Sh->SFw (Fig. 2a). The orientation of the current elements in sediments of unit G2 varied from NNE to SSE at the bottom, to NNW in the central part and at the top (Fig. 2). According to the OSL method, deposits of this unit are dated at:  $13.06 \pm 0.76$  ka (GdTTL-2695) and  $13.54 \pm 0.84$  ka (GdTTL-2696) (Figs 2, 3; Table 2).

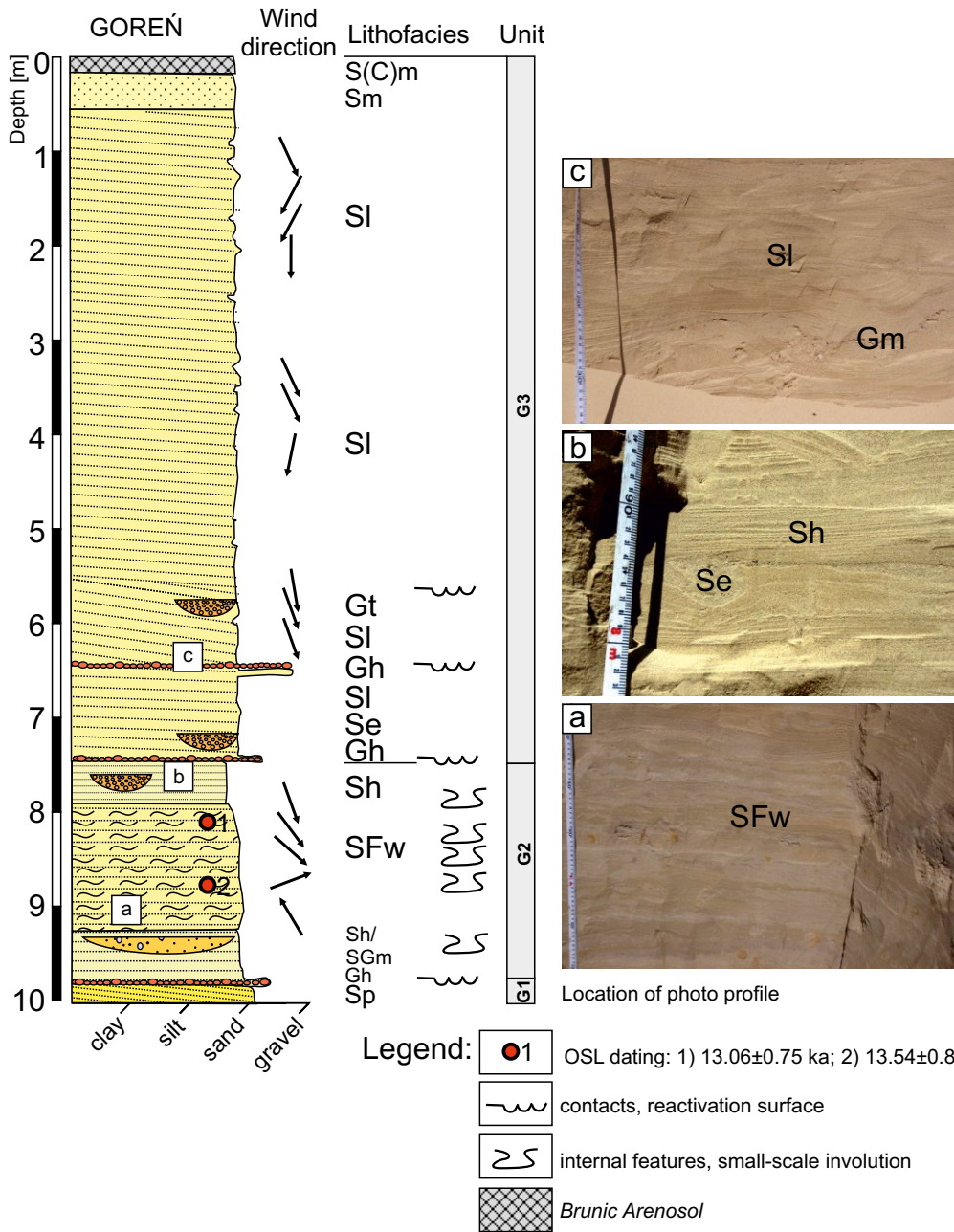


Figure 2. Sedimentological log of deposits in the GOREŃ Duży profile at GOREŃ Duży site: a) silty sand with wavy lamination (SFw) with four generations of small-scale involution structures; b) fine- and medium-grained horizontally stratified sand (Sh) with a small-scale erosion trough filled with trough cross-stratified sand (Se); c) low-angle (<15°), cross-stratified fine sand (Sl) overlaying fine-grained gravel horizon (Gm) along with the reactivation surface.

Table 2. Sample information, dosimetry and luminescence age. The quartz grain fraction was 125–200  $\mu\text{m}$ . Depths are given in metres below the outcrop top. Water content (WC) was calculated as mass of water/mass of dry sediment  $\times 100\%$ . Dose rates were calculated following geochemical analysis of U, Th and K concentrations for each sample, using the conversion factors of Adamiec & Aitken (1998).

Field code	Laboratory code	Sample coordinates	Depth (m)	WC (%)	$^{232}\text{Th}$ ( $\text{Bq kg}^{-1}$ )	$^{238}\text{U}$ ( $\text{Bq kg}^{-1}$ )	$^{40}\text{K}$ ( $\text{Bq kg}^{-1}$ )	$\beta$ dose rate ( $\text{Gy kg}^{-1}$ )	$\gamma$ dose rate ( $\text{Gy kg}^{-1}$ )	Cosmic dose rate ( $\text{Gy kg}^{-1}$ )	Total dose rate ( $\text{Gy kg}^{-1}$ )	$D_e$ (Gy)	Age
Goreń Duży_1_15	GdTL-2695	52°31'39"N 19°17'45"E	8.1	1.5	10.75 $\pm$ 0.49	10.84 $\pm$ 0.29	413 $\pm$ 19	0.951 $\pm$ 0.066	0.462 $\pm$ 0.020	0.0208 $\pm$ 0.0021	1.438 $\pm$ 0.069	18.87 $\pm$ 0.61	13.06 $\pm$ 0.76
Goreń Duży_2_15	GdTL-2696	52°31'39"N 19°17'45"E	8.75	6.7	10.12 $\pm$ 0.49	10.09 $\pm$ 0.33	415 $\pm$ 19	0.947 $\pm$ 0.067	0.452 $\pm$ 0.020	0.0193 $\pm$ 0.0019	1.422 $\pm$ 0.070	19.35 $\pm$ 0.71	13.54 $\pm$ 0.84

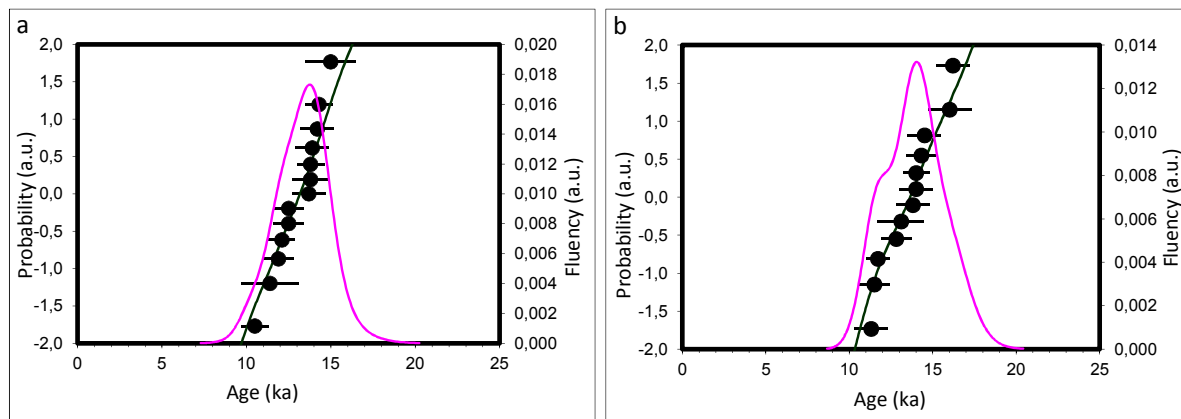


Figure 3. CAM for samples: a – Goreń Duży\_1\_15 (GdTL-2695); b – Goreń Duży\_1\_15 (GdTL-2696).

Unit G3 is represented by low-angle ( $<15^\circ$ ), cross-stratified fine sand (Sl) with a thickness of about 7.65 m (depth 0.0–7.65 m) and an inclination of up to  $10^\circ$ . Small-scale trough cross-stratified sands (Se) occur in the bottom layer of the unit, filling small erosional forms (Fig. 2b), along with the reactivation surface that is characterised by the presence of fine-grained gravel with a thickness of 2–3 mm and change of laminae inclination (Fig. 2c). *Brunic Arenosol* developed in the uppermost part of the deposits at this site. Boundaries between the unit G3 and G2 series are eroded. The orientation of the wind direction slightly varies over the unit, from NNE to NNW (Fig. 2).

#### 4.2. Textural features of the deposits

G1 unit deposits have not been analysed in terms of grain size composition.

Medium-grained sand (0.1–0.25 mm) dominates in the whole G2 unit (depth 7.95–9.60 m).

Their content gradually increases towards the top, ranging 33.9–55.3% in the bottom, and 70–83.05% in the top. The content of the clay fraction ( $<0.063$  mm) in the sediment is only 0.8% and the content of the gravel fraction is correspondingly low (Fig. 4). G2 unit sediments are characterised by the average grain diameter ( $M_z$ ), ranging from 1.96 to 2.76 phi, moderately well sorting—with values between  $\sigma_1=0.60$  and  $\sigma_1=0.93$  and the range of skewness ( $Sk_1$ ) from strongly fine skewed (+0.356) to coarse skewed (-0.174) (Fig. 4). The content of organic matter is very low and ranges from 0.12–0.21% (Fig. 4).

Sediments of G3 unit are fine-grained sand with the main fraction ranging from 0.25–0.1 mm and accounting for 79% at the bottom and up to 89.2% in the middle part and 86% in the uppermost layer. In addition, basic parameters of the grain size composition  $M_z$ ,  $\sigma_1$  and  $Sk_1$  only slightly varies along the vertical profile.  $M_z$  is in the range of 2.67–2.72 phi. This is a well-sorted sediment (0.54–0.65)

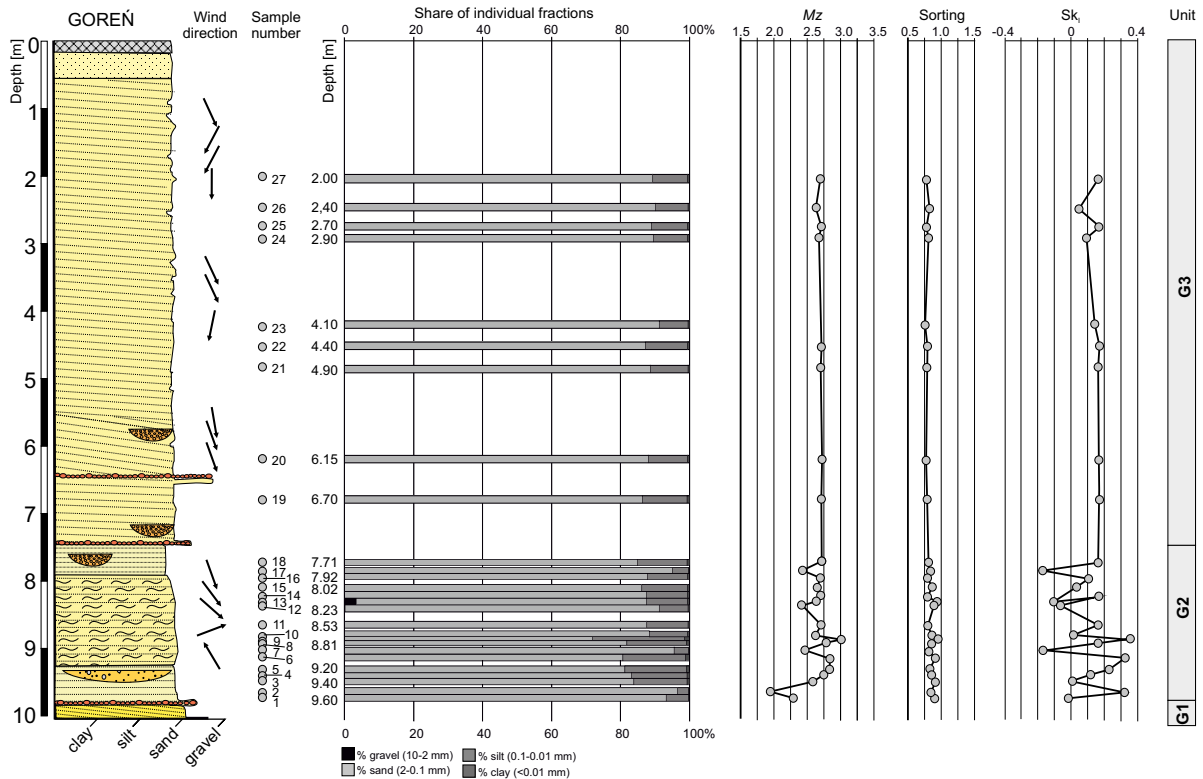


Figure 4. Results of grain-size distribution and OM analyses in the Goren Duży profile: parameters of the grain size distribution after Folk & Ward (1957): mean grain size ( $Mz$ ), sorting or dispersion coefficient ( $\sigma$ ), skewness ( $Sk$ ).

with positive skewness (Fig. 4). These sands basically do not contain organic matter OM (0.16–0.2 %) (Fig. 4).

### 4.3. Morphoscopy of quartz sand grains

The results of Cailleux's (1942) analysis, later modified by Mycińska-Dowgiałło & Woronko (1998), show that the deposits of unit G2 are dominated by EM/RM grains with the roundness of 0.3–0.6 according to Krumbein (1941) and only matt edges and corners, resulting from ongoing abrasion in an aeolian environment. Their content varies from 38.6–75 %. The content of EM/EL grains representing the fluvial environment is also high (from < 20–49.5 %). Conversely, RM grains with a very high degree of roundness (> 0.7

according to Krumbein (1941) and completely matt surface were found in only one sample; their content being below 4 %. Also EL grains were found; being characterised by a high degree of roundness and smooth, glossy surface (from 0.9 % at the bottom to 5 % in the top). Grains with the surface shaped by progressive *in situ* weathering (type O) account for less than 4 % and are not recorded in the sediments (Fig. 5).

The G3 unit is dominated by two types of grains, EM/RM and EM/EL, each type with a different content in the profile. EM/RM grains account for 14.4–76.3 % and EM/EL grains for 16.2–76.4 % (Fig. 5); no RM grains were found. Grains with weathered surface (type O) and cracked grains (C) were also present. The content of the latter did not exceed 2 % (Fig. 5).



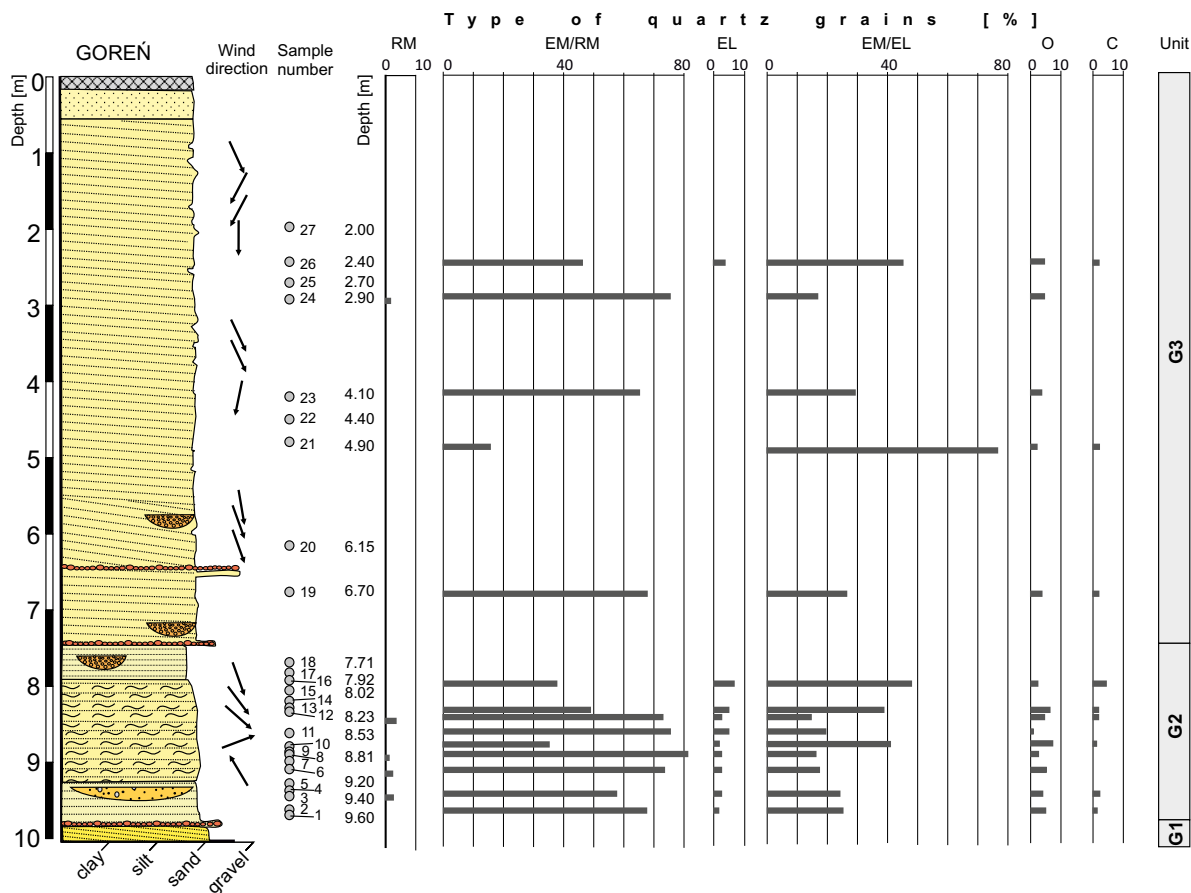


Figure 5. Results of frosting and rounding of quartz grains analysis performed on deposits from the Goren Duzy profile, following the modified method of Cailleux (1942) (Mycielska-Dowgiałło & Woronko, 1998).

## 5. Discussion

### 5.1. Reconstruction of depositional environments

Three units of mineral sediments (G1–G3) distinguished at the site of Goren Duzy (Fig. 2) represent the main morphogenic stages of the Plock Basin development after the last ice–sheet retreat.

Unit G1 (Fig. 2) is associated with a mid-riverbed, being developed as prograding transverse bars and deposition on a slip face (distal slope) of the dune (Miall, 1996; Zieliński, 2014). These forms are characteristic structural elements of braided channels (Zieliński, 2014) which could be associated with the meltwater outflow from beneath

the melting ice-sheet, or with the river water outflow located in the Plock Basin. The uppermost sediment layer of this unit is eroded, being manifested in a thin layer of very poorly rounded clasts of the gravel fraction (Fig. 2).

Unit G2 represents a gradual transition from the fluvial to the aeolian environment. Structural analysis of sediments of this unit proves that the deposition occurred in two different environments: 1) aeolian and 2) fluvial. Lithofacies Sh was associated with shallow and relatively intense flows within the upper plane bed conditions, whereas lithofacies St was deposited within small channelled subcritical flows (Zieliński, 2014). The bottom layer of gravel can be interpreted as lag deposits or deflation pavement, which indicates prolonged

exposure to the wind action (Seppälä, 2003; Antczak-Górka, 2005; Woronko et al., 2015), whereas the middle part of the G2 unit, developed in the form of the Sh→SFw rhythmite the alternating silty sands with wavy lamination (SFw) and horizontally stratified sands (Sh), originated as a result of aeolian accumulation (Hunter, 1977; Zieliński & Issmer, 2008). Lithofacies Sh was deposited in the presence of strong winds, with ripple marks being replaced by a flat depositional surface (Goździk, 1998). Lithofacies SFw was probably deposited on a wet surface at much lower wind velocity (Kasse, 2002; Zieliński et al., 2016). Such sedimentary features are characteristic of fluvio-aeolian deposits, described at many locations in Europe (Kasse et al., 2007; Woronko et al., 2015; Zieliński et al., 2015, 2016). At the same time, the characteristics of G2 unit sediments indicate that the climate became drier, which directly resulted in the reduction of flows in the Płock Basin and in turn increased the activity of aeolian processes (Woronko et al., 2015; Zieliński et al., 2016). Their presence at Płock Basin indicate that wind is the main factor shaping exposed surfaces in vegetation-free areas, and coeval aeolian transport supplied the material to the fluvial environment (Goździk, 2007; Zieliński et al., 2015, 2016; Woronko et al., 2015). This activity is confirmed by the high proportion of sand grains of aeolian origin in the sediments of unit G2 (EM/RM) (Fig. 5). Moisture conditions during deposition varied, both on the dry and/or the humid substrate (Fig. 2). Negative values of skewness ( $Sk_p$ ) coarse along with the increased diameter of grains, and in particular the presence of medium and coarse-grained sands (Fig. 5) all indicate the dominance of deflation processes (wind erosion) with an increased in wind velocity. On the other hand, positive values of skewness ( $Sk_p$ ) of sediments along with the smaller average diameter of grains ( $Mz$ ) and the increased content of silt particles in the sediments indicate that this accumulation occurred at much lower wind velocities. The presence of several levels of small scale involutions/load cast up to 0.2 m and usually 2–5 cm in G2 unit sediments indicates

interruptions in sedimentation and the presence of a humid sediment surface layer in the Płock Basin, which is reflected in the high content of silt particles (Fig. 4) (Pye & Tsoar, 2009). The small-scale involutions documented in the profile (Fig. 2a) were formed under conditions of deep seasonal frost rather than during permafrost aggradation (Kasse, 2002; Zieliński et al., 2016). This indicates the mean annual average temperature (MAAT) was probably about -1 or -2°C (Vandenberghe & Pissart, 1993).

Sediments of the G3 unit represent aeolian deposits that were deposited on the windward slope of the southern arm of a longitudinal dune. Sl stratification is a result of accretion (Hunter, 1977). Single channel structures occurring in the bottom layer of the G3 unit, filled with gravelly sand of massive structure (SGe) or cross-bedded (Sp) fill seems to suggest that those features are small deflation troughs. Several reactivation surfaces are present in the vertical profile of the dune being erosional surfaces characterised by a change of laminae inclination angle or an increase in coarse-grained layers (Fig. 2 c). They reflect the change in the wind direction. The fraction of 0.1–0.250 mm is the main fraction with very small variation of grain size indices ( $Mz$ , sorting) with positive skewness ( $Sk_p$ ) throughout the whole unit (Fig. 4). This indicates relatively stable aerodynamic conditions, with only incidental dominance of deflation over accumulation.

## 5.2. Intensity of aeolian processes

Sand and gravel sediments of Płock Basin River and ice-marginal valley terraces were the source material for aeolian processes (Urbaniak-Biernacka, 1976). EM/RM grains dominate in the G2 and G3 units. RM grains were not registered in the dune sediments of the G3 unit and only a small percentage was found in the fluvio-aeolian unit (G2) (Fig. 5). This indicates that the abrasion period was relatively short and/or the transport distance in this aeolian environment was short too (Mycielska-Dowgiałło, 1993; Kalińska-Nartiša et al., 2015).

By comparison, the RM content in extraglacial zone dune sediments of the Polish sector of the European Sand Belt is up to 50 % (Cailleux, 1942; Goździk, 2007; Woronko et al., 2015; Zieliński et al., 2015, 2016). The presence of EM/EL and EL grains, whose surface is affected by fluvial environment processes, indicates a continuous supply of material for aeolian transport ultimately forming, in example, fluvial, glaciofluvial or glacio-lacustrine deposits. Furthermore, the lack of aeolian environment processing on EM/EL and EL grains along with a varying contribution of EM/RM grains in the vertical profile, indicate that in this depositional environment fast aggradation dominated over long-range transport. In addition, aeolian processes in the G3 unit sediments led to the elimination of the finest (< 0.05 mm) and coarse (> 0.315 mm) fractions recorded in substrate sediments (Fig. 4). At the same time, the variability of types of grain indices in the vertical profile suggests increased desiccation of the surface sediment layer during the process of dune accumulation, which can be related to progressive permafrost degradation. Such conditions resulted in an increased infiltration rate with a commensurate drying of the uppermost layer of sediments, further resulting in increased deflation with the delivery of large amounts of material to the aeolian environment. The small percentage of organic matter in these dune sediments indicates that the soils were poorly developed, and their particles were likely to be removed by wind action. Also noteworthy is that no RM-type grains were found in dune sediments (unit G3). This is contrast to fluvio-aeolian unit G2, which underlies the sediments of the unit G3. This phenomenon may indicate that during the period of dune accumulation in this area, the wind-entrained material was supplied from outside the Płock Basin. Woronko et al. (2015) arrived at similar conclusions.

### 5.3. The age of aeolian deposits

Apart from the dune in Liszyno near Płock, the Płock Basin lacks absolute dating of the activation

of aeolian processes.  $^{14}\text{C}$  dating of the dune in Liszyno revealed that Allerød fossil soil separates two aeolian series a lower one from the Older Dryas and an upper one dated to the Younger Dryas (Kamińska et al., 1986). OSL dating of the aeolian unit base presented in Goreń Duży ( $13.06 \pm 0.76$  ka and  $13.54 \pm 0.84$  ka; Fig. 3; Table 2) indicates that the initial fluvio-aeolian formation should be referred as an Older Dryas deposit. The obtained OSL dates correspond with the deposition of cover sand overlying the Finow soil (about 13.5 ka) in Mecklenburg, NE Germany (Küster & Preusser, 2009), or the first stage of the development of aeolian processes in NE Estonia dated at  $13.3 \pm 1.2$  ka (Kalińska-Nartiša et al., 2015). Moreover, dating results can be related to chronostratigraphic correlations based on the analysis of laminated sediments of Lake Meerfelder and Lake Gościąż (Litt et al., 2001, Ralska-Jasiewiczowa et al., 1998). The Older Dryas is commonly associated with the intensive development of aeolian processes within the European Sand Belt in Poland, Germany, and in the Baltic countries (Manikowska 1985, Nowaczyk 1986, Kasse, 1997, 2002; Zeeberg, 1998; Kasse et al., 2003, Hilgers, 2007; Kaiser et al., 2009, Kalińska-Nartiša et al., 2015, 2016; Zieliński et al., 2016). The overlying fluvio-aeolian sediments of unit G2 and dune sediments of unit G2 are associated with the reactivation of aeolian processes in the Younger Dryas. The beginning of reactivation in this period is marked by the erosional boundary between the units G2 and G3. The Younger Dryas is accepted as the primary dune-forming period in the Toruń Basin, which is adjacent to the Płock Basin (Andrzejewski & Weckwerth, 2010, Jankowski 2012; Zieliński et al., 2016). The presence of unit G3 aeolian process reactivation surfaces results in dune formation by wind from a different direction.

A salient point is the relationship of these dunes to the deep subglacial channels that were preserved for a long time in association with dead ice blocks (Błaszkiwicz, 2011; Błaszkiwicz et al., 2015), which at the same time becomes a useful element in the pursuit of aeolian process age determination.

The main phase of buried, dead-ice melting in the Płock Basin, took place during the Allerød (Ralska-Jasiewiczowa et. al., 1998). In the study area, large parabolic dunes are often “intersected” by subglacial channels. The morphological relationship between the dune forms and the subglacial channels strongly suggests a pre-Allerød (pre-melting phase) age for the aeolian processes that took place within the Płock Basin. Our research fully confirms this thesis, while taking into consideration a subsequent aeolian transformation in the Younger Dryas.

## 6. Conclusions

Sediments of the Goreń Duży profile represent three environments: 1) fluvial unit G1, 2) fluvio-aeolian unit G2 and 3) aeolian unit G3. Each recorded environmental changes in an area that was released from the ice cover around 18.4 ka. The accumulation of the fluvio-aeolian unit was supported through aeolian and fluvial processes. The accumulation of this unit coincides with the Older Dryas. The accumulation of unit G3 occurred during the Younger Dryas. The homogeneous nature of grain size composition throughout the dune profile indicates homoge-

neous wind conditions throughout this sediment accumulation. Aeolian processes during the accumulation of the fluvio-aeolian unit (G2) and dune unit (G3) were short-lived, accompanied by a large supply of the wind-entrainable material, which was conducive to the deposition rather than the deflation (wind erosion). The relationship of dunes to subglacial channels that developed after the melting of dead-ice blocks confirms a pre-Allerød origin of aeolian processes.

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