

Depositional conditions on an alluvial fan at the turn of the Weichselian to the Holocene – a case study in the Żmigród Basin, southwest Poland

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Abstract

Presented are the results of research into the fluvio-aeolian sedimentary succession at the site of Postolin in the Żmigród Basin, southwest Poland. Based on lithofacies analysis, textural analysis, Thermoluminescence and Infrared-Optical Stimulated Luminescence dating and GIS analysis, three lithofacies units were recognised and their stratigraphic succession identified: 1) the lower unit was deposited during the Pleni-Weichselian within a sand-bed braided river functioning under permafrost conditions within the central part of the alluvial fan; 2) the middle unit is the result of aeolian deposition and fluvial redeposition on the surface of the fan during long-term permafrost and progressive decrease of humidity of the climate at the turn of the Pleni- to the Late Weichselian; 3) the upper unit accumulated following the development of longitudinal dunes at the turn of the Late Weichselian to the Holocene; the development of dunes was interrupted twice by the form being stabilised by vegetation and soil development.

Keywords: climate change, periglacial environment, fluvial processes, aeolian processes, luminescence dating

1. Introduction

The Weichselian decline (25–10 kyr) was characterised by rapid climate change, which led to the disappearance of the ice sheet in the area of northern Poland, and – in the periglacial zone – the

degradation of permafrost (Bohncke et al., 1995; Kozarski, 1995; Van Huissteden & Kasse, 2001; Rinterknecht et al., 2006; Kolstrup, 2007; Renssen et al., 2007; Zieliński et al., 2014a). This conditioned the evolution of sedimentary processes within the extra-glacial river valleys (Bohncke et al., 1995; Huijzer & Isa-

rin, 1997; Kasse et al., 1998; Huijzer & Vandenberghe, 1998; Krzyszkowski et al., 1999; Mol et al., 2000; Van Huissteden & Kasse, 2001; Schokker & Koster, 2004; Rinterknecht et al., 2006; Kolstrup, 2007; Renssen et al., 2007; Zieliński et al., 2011). The most complete record of these phenomena can be found in the areas occupied by dune fields on the meadow terraces or alluvial fans at the mouth of small, presently often dry valleys. One of the best areas of dune fields developed in that way in Poland is the Silesian Lowland (Nowaczyk, 1986).

Previous research on the aeolian forms of this area has focused mainly on morphometric characteristics of the forms and textural characteristics of sediments (Pernarowski, 1950/1951, 1958, 1959), or has been conducted when determining the chronology of events in the Odra valley (Szczepankiewicz, 1959, 1966). The results of these earlier studies determined the aerodynamic and lithological conditions of the dune development and attempted to establish their age.

Given the development of new research methods since the last 25 years (lithofacies, morphoscopic and GIS analysis as well as dating methods; see Żabinko key site described by Kozarski & No-

waczyk, 1995; Zieliński et al., 2011) and directions associated with the analysis of aeolian sands (in particular the participation of aeolian sands in Plenian-Weichselian sediments; Mycielska-Dowgiałło & Woronko, 2004) the revival of research in this area seemed justified. For the present study a dune field was selected in the Żmigród Basin in the Silesian Lowland (Fig. 1A), developed on alluvial sediments of the last glaciation.

The aim of the present study is to deliver: a) characteristics of the fluvio-aeolian sedimentary succession at Postolin, a site that is representative of the study area, and on this basis b) a reconstruction of depositional environment volatility that took place during the Weichselian decline.

2. Study site and research methods

The Postolin site is located within the dune (Fig. 1B). In the northern dune rampart there is a sandpit, where it is possible to trace dune sediments and their substrate.

The analysis of sediment lithological features was performed at outcrop (their texture and struc-

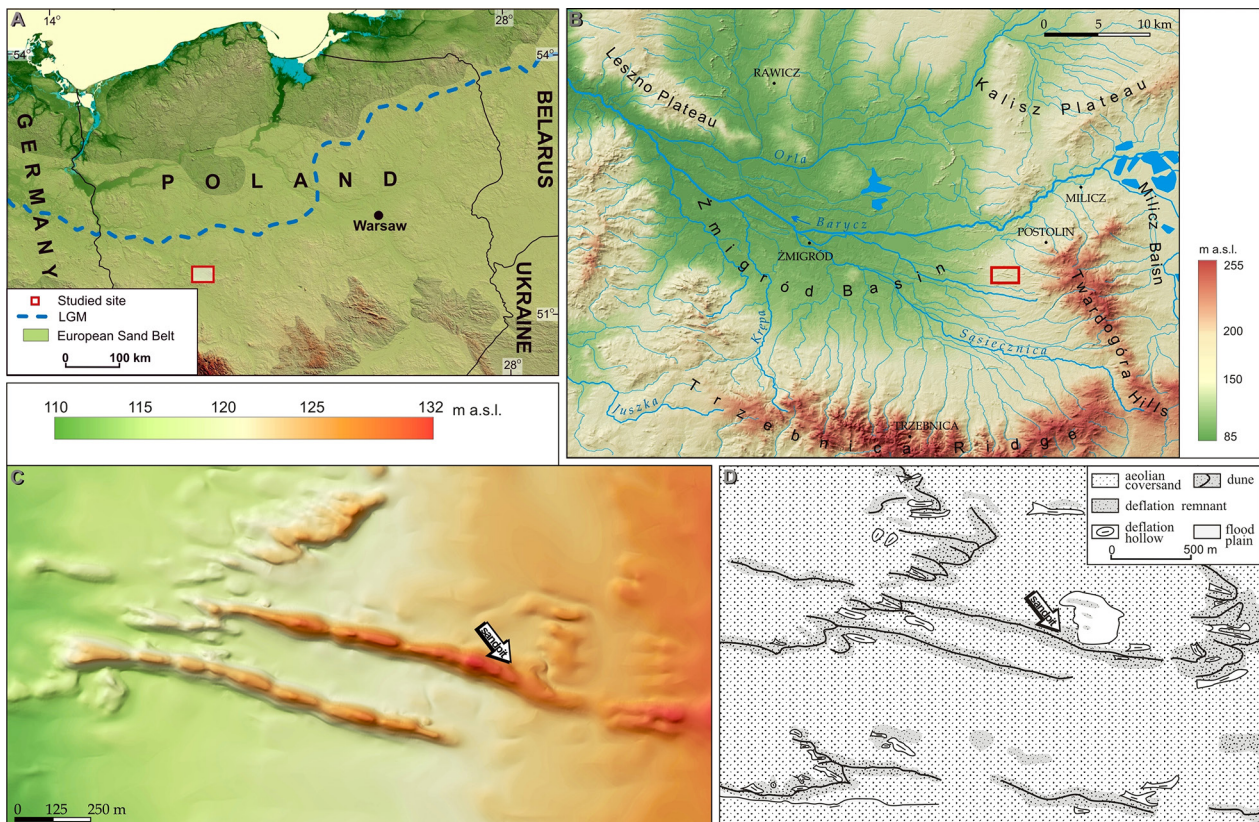


Fig. 1. Location of the study site against the background of: **A** – The extent of the Sand Belt in central Europe according to Koster (1988) and Kasse (1997); **B** – DEM of the Żmigród Basin; **C** – DEM of the study area; **D** – geomorphological sketch.

Table 1. Type of rounding and frosting of quartz sand grains (after Woronko et al., 2015).

Type of grain	Roundness of grain (Krumbein, 1941)	Description	Processes responsible for grain formation
RM	0.7–0.9	Very well-rounded with completely mat surface	Very long duration of abrasion in aeolian environment
EM/RM	0.3–0.9	Moderately rounded, mat surface only on convex parts of grains	Short-time abrasion in aeolian environment marked only on convex parts of grains
EL	0.7–0.9	Very well-rounded, entire surface smooth and shiny	Combination of abrasion and solution in fluvial or beach environment. 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. Only crushed surface fresh, remaining parts with microstructures typical of transport or weathering	Crushing in all types of environments but with highest intensity in subglacial environment or as effect of frost weathering
NU	0.1–0.2	All surfaces fresh: corners sharp and angular	Crushing and abrasion in glacial environment; mechanical weathering <i>in situ</i> , e.g., frost weathering
O (other)	0.1–0.9	Very intensively weathered surface by silica precipitation or solution <i>in situ</i> ; traces of transport invisible	Solution or precipitation in soil profile, hot desert or periglacial environment

ture were defined, and the directional elements of their structures were measured), periglacial structures and levels of fossil soils were documented, and samples were collected for detailed textural laboratory analyses of the sediments (granulometric and morphoscopic). The TL age of the deposits analysed was established at the University of Gdańsk (Fedorowicz, 2006), and the IR-OSL dating was done at the Research Laboratory for Quaternary Geochronology (RLQG) at Tallinn University of Technology (Molodkov & Bitinas, 2006). Digital Elevation Models and Digital Terrain Models analyses were made.

Quartz grains were examined to identify their rounding, according to the 9-degree classification by Krumbein (1941), and surface type, following the Cailleux (1942) method as modified by Goździk (1980) and Mycielska-Dowgiałło & Woronko (1998). In each sample, taken from the size fraction of 710–1,000 μm , 100–150 grains were analysed and assigned to one of seven types (Table 1).

3. Geomorphology of the study area

The Postolin site includes two parallel longitudinal dune forms of a WNW-ESE orientation, which are spaced approx. 300 m (Fig. 1B). Their length reaches up to 2 km while the maximum relative height is 7 m. The surroundings of the dune consist of an aeolian sand cover with deflationary de-

pressions and outliers. This is particularly evident on the western side of the elongated forms, where there are also arc dunes in various stages of blow off. Similar forms are also located in the eastern part of the study area, at the contact of the aeolian cover and slope of the moraine upland (Fig. 1C, D; Winnicka, 2007, 2008).

The contact of the upland (part of the Twardogóra Hills) with the base of the Żmigród Basin is an area slightly inclined towards the WNW. The slope direction is identical with the direction of the current fluvial outflow from the Twardogóra Hills (Fig. 1B). This surface is built of Weichselian fluvial sands (Winnicka, 2007, 2008). A similarly developed surface, transitional between the Twardogóra Hills and the base of the Żmigród Basin by Winnicka (2008), are alluvial fans. These fans developed in stages, following formation of the Twardogóra Hills at the end of the Saalian Glaciation (Szczechaniewicz, 1989). The last episode of their formation probably took place during the Last Glacial Maximum (Winnicka, 2008).

4. Lithological characteristics and age

The section exposed enabled the delimitation of three lithofacies units: fluvial, fluvio-aeolian and aeolian (Figs 2, 3), separated by vast erosion/deflation surfaces.

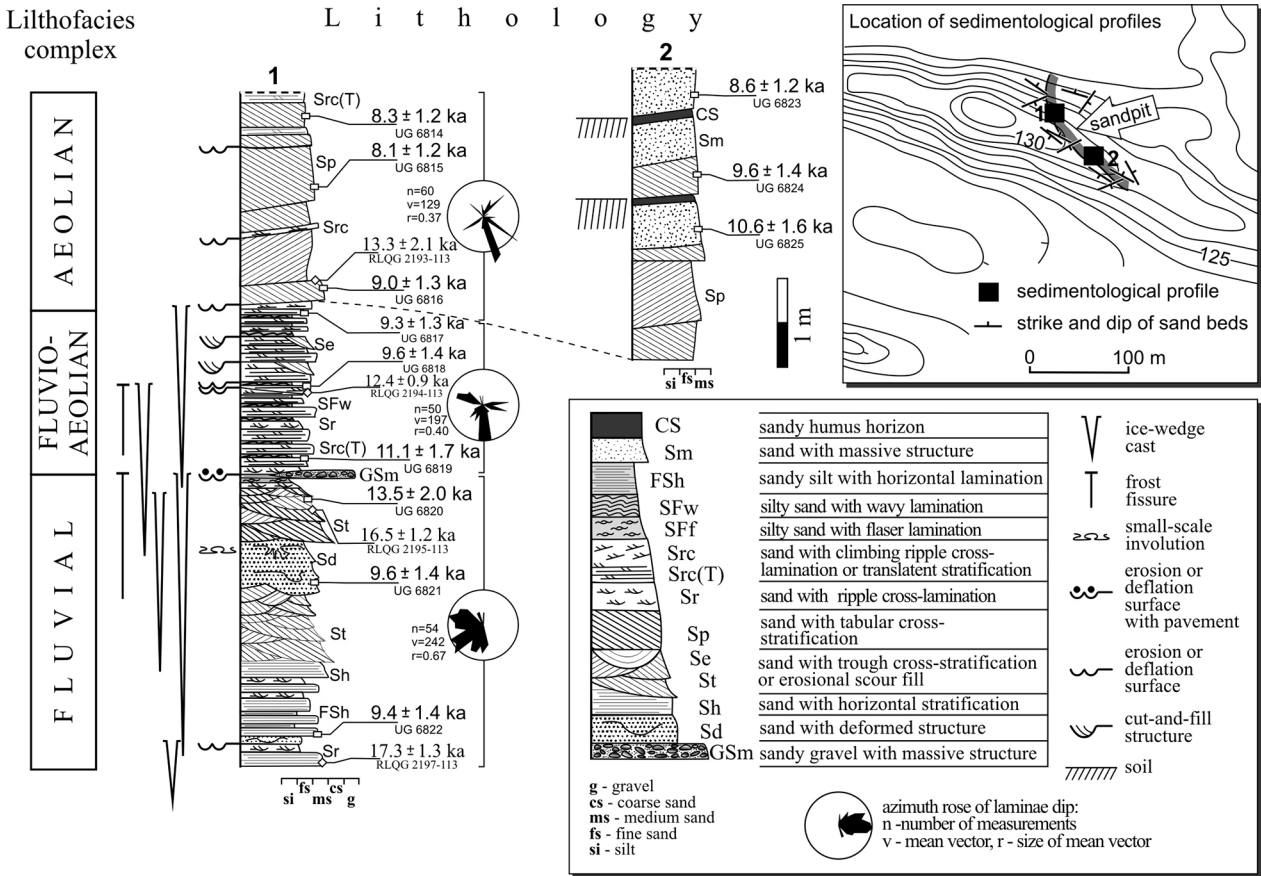


Fig. 2. Sedimentary successions studied.

4.1. Fluvial unit

The fluvial unit is composed of two sets of lithofacies (Figs 2, 3C). The lower set comprises horizontally stratified sands (Sh), with accessory ripple stratification (Sr) and inclusions of sandy silt of horizontal lamination (FSh). The upper set consists of sands of trough cross stratification (St), turning into sands of ripple lamination (Sr) and silty sands of flaser lamination (SFf).

The middle section of the set contains the level of sediment of disturbed structure (Sd), within which there are small-scale involution (finger like) structures (Fig. 3C). There are also two generations of syngenetic pseudomorphs after ice wedges and accompanying thermal contraction structures (Fig. 3E). The first generation refers to the top of the lower lithofacies set, while the other does so to the top of the fluvial unit. Structural directional elements are arranged in a sector with a span of just over 120° and the resultant vector indicates a southwesterly direction (Fig. 2).

Sediments representing the alluvial unit are medium-grained sands, which are characterised by a relatively small, but variable (in the vertical

profile of the unit) average particle diameter of 0.31 to 0.17 mm. This unit shows average sorting of the sediment (σ_1 = from 0.71 to 0.86) and a negative or symmetrical skewness value Sk_1 (-0.29 to 0.02) practically throughout the entire unit (Fig. 4A). The relation of grain-size parameters σ_1/Mz shows that, irrespective of grain diameter (Mz), the sorting of sediment takes a similar value (Fig. 4B). This trend is perfectly in line with the third co-ordinate system of Mycielska-Dowgiałło & Ludwikowska-Kędzia (2011). A similar trend is observed at Sk_1/σ_1 , where a skewness value change (Sk_1) is accompanied by a more or less constant sorting value (σ_1) (Fig. 4C). In contrast, the relationship of Sk_1/Mz indicates that the more fine-grained sediments are, the more negative skewness is (Fig. 4D). In the CM diagram the samples are arranged in the fields VI and V, incidentally in I, and are also clustered around the segment P (Fig. 4E).

The results of the analyses of rounding and frosting of quartz grains surface show that this unit is characterised by a marked predominance of particles with an intermediate degree of rounding and frosting visible only on the most convex parts (EM/RM 72-81%; see fig. 4A). Their variability in the

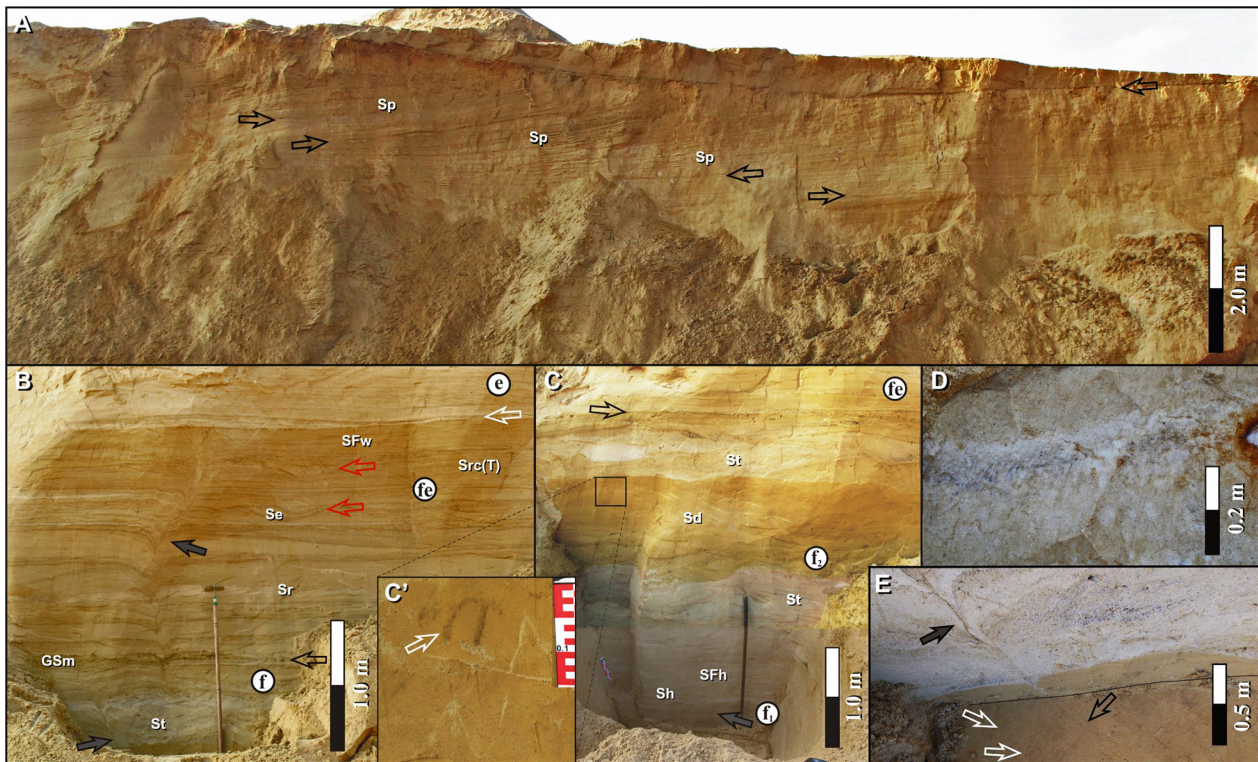


Fig. 3. Depositional succession at the Postolin site: **A** – Aeolian unit with numerous reactivation/ deflation surfaces (black arrows); **B** – Fluvio-aeolian unit (fe) with ice-wedge casts (grey arrows); the fluvio-aeolian and fluvial unit (f) are separated by erosional/ deflation surface (black arrow) with deflation pavement, this and aeolian unit (e) separated by extensive deflation surface (white arrow); **C** – Fluvial unit consisting of two lithofacies associations: (f₁) lower one with ice-wedge cast (grey arrow) and (f₂) upper with finger-like structures (white arrow on C'); black arrow marks erosional surface with deflation pavement in the basal fluvio-aeolian unit (fe); **D** – Older fossil soil; **E** – Ice-wedge cast in top part of fluvial unit: view of vertical (grey arrow) and horizontal section (black arrow), as well as associated frost fissures (white arrows).

profile of the series is small. Larger variations are shown in grain content of a high degree of rounding and frosting visible over the entire surface of grains (RM 6–20%).

Furthermore, there is a downward tendency up the unit in favour of glossy grains of a medium degree of rounding (EM/EL up to 10.5%) and other types of grains (from 2.3 to 6.7%, fig. 4A).

The age of the units specified by the IR-OSL date: 17.3 ± 1.3 ka at the base and 16.5 ± 1.2 ka at the top. The TL dates are significantly different: 9.4 ± 1.4 ka at the base and 13.5 ± 2.0 ka at the top (Fig. 2; Table 2).

4.2. Fluvio-aeolian unit

The base of this unit is a non-continuous level of ventifacts (fine gravels in size). The remainder of the unit consists of sands of translant stratification or climbing ripple cross-lamination (Src), which in places are interbedded with sands of ripple lamination (Sr) or silty sands of wavy lamination (SFw). Cut-and-fill structures are quite numerous (Figs 2, 3B).

What was also found were numerous syngenetic pseudomorphoses after ice wedges dissecting the lower unit (Fig. 3B). Directional structures within the unit show a large scatter, with the greatest frequency being in a southerly direction (Fig. 2).

The fluvio-aeolian unit, similarly to the fluvial one, consists of medium-grained sand, with relatively small grain size variability. The average particle diameter (M_z) varies from 0.27 to 0.31 mm, with the exception of the top of the series where the deposit is slightly finer ($M_z = 0.2$ mm) and of the base, where the M_z values are the highest (0.53). This small variation of sediment is also indicated by the standard deviation values (σ_1).

Noteworthy is the skewness parameter of the deposits. At the base it takes on a negative value, while in the middle and upper parts of the series it is positive, and at the same time shows the least variation in the whole section analysed (Fig. 4A). The relationship of grain-size parameters σ_1/M_z shows that the increase in average particle diameter (M_z) is accompanied by an increase in sediment sorting (σ_1) in the first co-ordinate system according

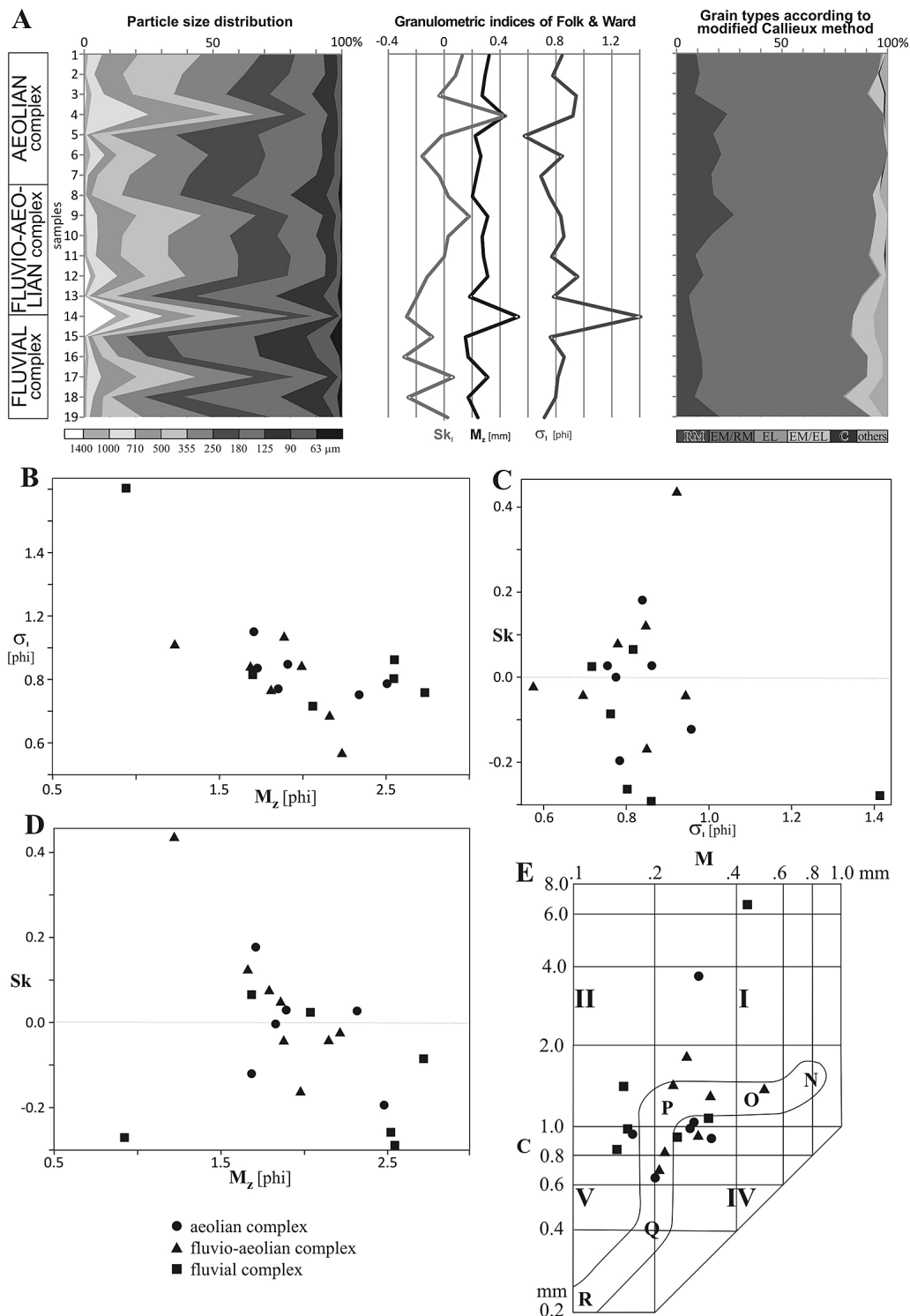


Fig. 4.A – Results of grain-size and morphoscopic analyses at the Postolin section; parameters of grain size distribution after Folk & Ward (1957): mean grain size (M_z), sorting (σ_i), skewness (Sk_i); frosting and rounding classes of quartz grains by modified Cailleux's method (Mycielska-Dowgiałło & Woronko, 1998): rounded and frosted grains (RM, rounding degree: 0.7–0.9, following Krumbein, 1941), (2) moderately rounded and frosted grains (EM/RM, rounding degree: 0.3–0.6), rounded and shiny grains (EL, rounding degree: 0.7–0.9), moderately rounded and shiny grains (EM/EL, rounding degree: 0.3–0.6), fresh, angular grains (NU, rounding degree: 0.1–0.2), cracked (C); **B-D** – Comparison of parameters calculated after Folk and Ward (1957): **B** – mean grain size (M_z) to sorting (σ_i); **C** – sorting (σ_i) to skewness (Sk_i); **D** – mean grain size (M_z) to skewness (Sk_i); **E** – Results of grain-size analysis in a CM Passega diagram.

Table 2. Luminescence and radioactivity data for samples analysed in the present study.

Samples	No lab. UG	²²⁶ Ra [Bq / kg]	²³² Th [Bq/kg]	⁴⁰ K [Bq/kg]	Dose rate d_r [Gy/ka]	Equivalent dose d_e (Gy)	TL age [ka]
POS-01	6814	3.50±0.2	2.16±0.1	161±6	0.55±0.06	4.6±0.4	8.3±1.2
POS-02	6815	3.61±0.2	2.06±0.1	152±5	0.52±0.06	4.2±0.4	8.1±1.2
POS-03	6816	3.55±0.2	2.16±0.1	179±6	0.61±0.06	5.5±0.5	9.0±1.3
POS-04	6817	3.75±0.2	2.19±0.1	173±6	0.59±0.06	5.5±0.5	9.3±1.3
POS-05	6818	3.71±0.2	2.12±0.1	150±5	0.52±0.05	5.0±0.5	9.6±1.4
POS-06	6819	4.28±0.3	7.13±0.4	249±9	0.92±0.09	10.2±1.0	11.1±1.7
POS-07	6820	3.62±0.3	2.11±0.1	156±5	0.54±0.05	7.3±0.7	13.5±2.0
POS-08	6821	4.07±0.4	2.29±0.1	232±8	0.77±0.08	7.4±0.7	9.6±1.4
POS-09	6822	3.86±0.3	2.25±0.1	205±6	0.70±0.07	6.6±0.6	9.4±1.4
POS-10	6823	3.75±0.3	2.15±0.1	162±5	0.56±0.05	4.8±0.5	8.6±1.2
POS-11	6824	3.55±0.3	2.23±0.1	159±5	0.55±0.05	5.3±0.5	9.6±1.4
POS-12	6825	3.64±0.2	2.20±0.1	182±6	0.62±0.06	6.6±0.6	10.6±1.6

Samples	No lab. RLQG	U [ppm]	²³² Th [ppm]	⁴⁰ K [%]	Dose rate d_r [mGy/ka]	Equivalent dose d_e (Gy)	IR-OSL age [ka]
POS-01	2192-113	0.26	0.36	0.47	1441	18.0	12.5 ± 0.9
POS-02	2193-113	0.08	0.68	0.53	1426	19.0	13.3 ± 2.1
POS-03	2194-113	0.30	0.52	0.49	1323	16.4	12.4 ± 0.9
POS-04	2195-113	0.36	0.30	0.53	1443	23.8	16.5 ± 1.2
POS-05	2196-113	0.34	0.61	0.56	1468	25.3	17.2 ± 1.3
POS-06	2197-113	0.20	0.57	0.67	1455	25.2	17.3 ± 1.3

to Mycielska-Dowgiałło & Ludwikowska-Kędzia (2011). In contrast, the more negative value the skewness index (Sk_l), the more fine-grained sediment becomes. In the case of the indicators Sk_l/σ_l a lack of clear trends in sorting and skewness is observed (Fig. 4B-D). In the CM diagram by Passega these sediments are arranged around the segment P (Fig. 4E).

In terms of the nature of the surface of quartz grains, the unit is similar to the alluvial one. The sediment is dominated by EM/RM grains. In contrast, a different tendency is shown in the content of round matt grains (RM), which at the top of the unit reaches the maximum value (27.4%); it is also the highest value in the entire section. However, the proportion of glossy grains with a medium degree of roundness (EM/EL) is at the level of a few percent only and drops to zero towards the top of the series (Fig. 4A).

From this unit three TL dates were obtained, ranging in age from 11.1±1.7 at the base to 9.3±1.3 ka at the top. The one IR-OSL datum point shows 12.4±0.9 ka (Fig. 2; Table 2).

4.3. Aeolian unit

This unit is composed of sands with a large-, medium- and small-scale tabular cross-stratifica-

tion (Sp), and accessory translent stratification (Src(T)). There are numerous reactivation surfaces, often of a deflationary character. Structural directional elements are concentrated in two main sectors, the northeast and southeast (Fig. 2).

In terms of grain size distribution the unit is characterised by a small variation in average particle diameter (M_z) in the section, forming at the level of 0.26 mm, with the exception of reactivation surfaces, which are connected with an M_z increase. The sorting of the deposits is average, and the skewness in the entire unit is negative, with the exception of the top, where it takes positive values (Fig. 4A). The relationship of grain-size parameters σ_l/M_z , Sk_l/σ_l and Sk_l/M_z and the Passega CM diagram show similar trends as those observed in the fluvial unit (Fig. 4B-E).

In terms of morphoscopy, the section shows dichotomy (Fig. 4). At the base almost 100% is reached by frosted grains, with a significant advantage of medium roundness (EM/RM up to 88%), with over 20% of round grains (RM). However, at the top the participation of RM grains falls below 10%, and the percentage of glossy grains (EM/EL) and other grains increases (Fig. 4A). A sudden leap of the content of each group refers to the surface of the reactivation.

Sediments of the aeolian unit are divided by two layers of buried soils at 1.9 and 2.7 m below

the present-day surface (Fig. 3D). The older (lower) soil has only one horizon, consisting of whitish and light beige mottles with small light grey spots. This zone can be described as a weakly developed BC horizon of an initial sandy soil: arenosol.

The younger soil has two layers, the upper one consisting of dark grey and whitish patches. The arrangement of these patches suggests that this layer is an effect of primary soil horizon mixing, respectively: a humic A horizon (dark grey patches) and an eluvial E horizon (whitish patches). The lower layer of the younger soil has a pale orange colour and constitutes a weakly developed illuvial horizon Bs of iron accumulation. That soil represents remnants of a weakly podzolised soil with the top part altered post-genetically by external factors.

Due to lack of charcoals or other organic remains, the dating of buried soils by the radiocarbon method was not possible. Based on TL datings of underlying, intermediate and overlying sediments both soils, it is possible to conclude that they formed during a relatively short period (c. 1–1.5 kyr).

The age of the unit is specified by the TL date between 10.6 ± 1.6 and 8.1 ± 1.2 ka and the one obtained in IR-OSL – 13.3 ± 2.1 ka (Fig. 2; Table 2).

5. Reconstruction of environments

The sediment succession at the Postolin site resulted from a gradual transition from a fluvial (alluvial) to an aeolian sedimentation.

5.1. Fluvial unit

The presence of a rhythmic succession of the lithofacies Sh → SFh(Sr) at the top of the lithofacies set can be interpreted as sedimentation cycles resulting from the flow in the shallow sandy riverbeds of the waning current (Smith, 1970; Zieliński, 1993) or within the floodplain (Ghazi & Mountney, 2009). However, in the upper set, lithofacies St are a record of the operation of a deep riverbed with winding megaripples.

The succession of lithofacies St → Sr(SFf) can be interpreted as a record of falling flood cycle (Miall, 1996; Zieliński, 1998). The structural directional elements indicate that outflow generally was in a westerly direction (Fig. 2). A small thickness of individual lithofacies and cycles indicates shallow flows turning into sheet flows. Such a situation is typical of the middle and distal parts of stream-dominated alluvial fans (Collinson, 1986; Ridgway & DeCelles, 1993; Blair & McPherson, 2009). The lower part of

the section was deposited under conditions of sheet flows (rhythmite Sh → Sr; Krüger, 1997; Zieliński, 2014). The fluvial facies of the St type occurring in the top part of the unit developed within small tributary channels (Ridgway & DeCelles, 1993).

The presence of syngenetic ice-wedge cast and thermal contraction cracks indicates the presence of permafrost (Fig. 5). This is also confirmed by deformation structures, with the presence of finger-like structures, suggesting the development of a permafrost active layer (Huijzer & Vandenberghe, 1998; Vandenberghe, 2007) (Fig. 3C).

The development of these structures can be explained by strong waterlogging of the underlying sandy sediments at the presence of impermeable, frozen ground. This allows the overlying silt deposits, characterised by greater cohesion, to plunge (Van Vliet-Lanoë et al., 2004; French, 2007; Shiklomanov & Nelson, 2007). The presence of the level of deformation structures also shows a break in building up of deposits, long enough for these structures to develop. The reason for the development of this level may be a shift of the current into a different part of the valley and/or an increase in climatic aridity.

The lack of flow favoured the aggradation of permafrost, which encroached onto the exposed parts of the valley (Vandenberghe & Woo, 2002). These conditions indicate the nival discharge regime (Kasse et al., 2003), probably associated with spring thawing of the snow cover and active layer. In periods of no flow dry sediments underwent aeolian redeposition, which is indicated by significant aeolisation (more than 70% of grains are matt) of the material of the alluvium (Fig. 4; Isarin et al., 1997; Lewkowicz & Young, 1991; Van Huissteden et al., 2000; Blair & McPherson, 2009; Woronko, 2012). At the same time, the results of particle size, in particular the relationship between mean grain size (Mz) and standard deviation, i.e., the sorting parameter (σ_1), show that they are characteristic of sandy sediments which form active parabolic dunes (Mycielska-Dowgiałło & Ludwikowska-Kędzia, 2011). This indicates that the activity of the fluvial environment was not very large, and thus particle size characteristics acquired in the aeolian environment did not disappear. Short-distance transport and intense aggradation predominated.

These features suggest that the sedimentation of the fluvial unit took place under harsh climatic conditions, with a mean annual temperature (MAAT) below -4 or -8°C and a mean annual precipitation (MAP) below 300 mm/y (Vandenberghe & Pissart, 1993). The conditions prevailing at the time were similar to those of a polar desert (Guiter et al., 2003).

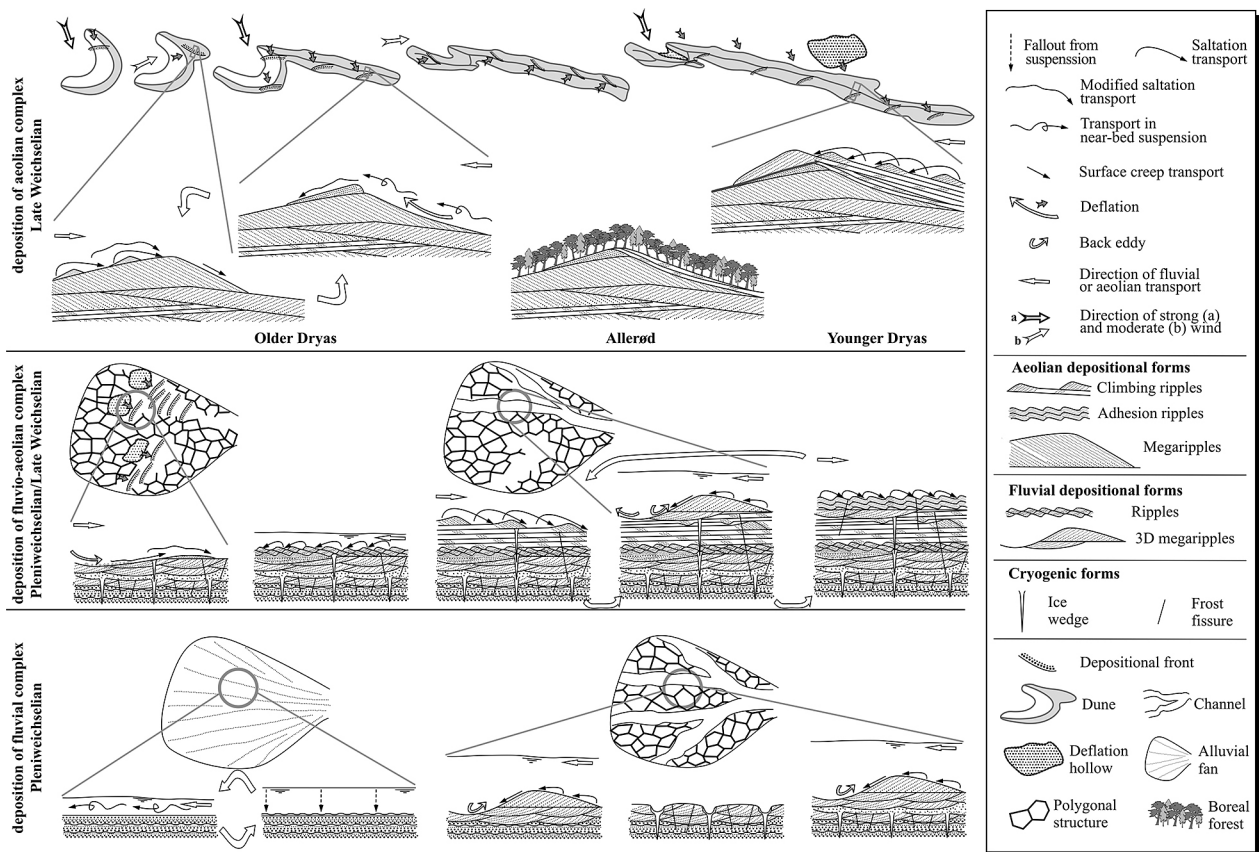


Fig. 5. Model of depositional environments.

The absence of vegetation (or thin cover) was conducive to providing large amounts of sediment by small rivers flowing from the western slopes of the Twardogóra Hills (Fig. 1B). Large fluctuations of flows facilitated the formation of alluvial fans at the foreland of moraine hills, a situation which has also been recorded from other parts of the European Lowland (Roskosch et al., 2012; Meinsen et al., 2014).

The geological and morphological situation, i.e., inclination of the surface towards the west-northwest, the presence of a morainic upland on the eastern side, the nature and direction of the outflow and the existence of permafrost during sedimentation of the unit, indicates that the sedimentation of this series took place in an environment of shallow sand-bed braided river (Cant & Walker, 1976, 1978; Zieliński, 1993; Miall, 1996; Vandenberghe, 2001). The river functioned in the middle part of the alluvial fan, leading to deposition in the Żmigród Basin under periglacial conditions.

5.2. Fluvio-aeolian unit

The deposition of this unit was preceded by deflation, as indicated by extensive deflation surface with

the pavement showing signs of influence of the aeolian environment (Fig. 3B). The presence of the deflation surface demonstrates prolonged exposure to the wind actions (Seppälä, 2004; Antczak-Górka, 2007), increased average wind speed, and – above all – increased aridity of the climate. This was accompanied by a decrease in flow volume. Increasing aridity of the climate during the deposition of the fluvio-aeolian sediments was also described for localities in the Netherlands and Germany (Kasse, 1997, 2002; Vandenberghe et al., 2013; Meinsen et al., 2014).

The deflation pavement consists of sands of lithofacies Src (T) and Src, which are a record of deposition induced by migration of aeolian ripples (Hunter, 1977; Schwan, 1988; Lea, 1990). Periodically, wind-deposited sediment was redeposited by subcritical flows – lithofacies Sr, or sudden, concentrated, short-term flows – i.e., the cut-and-fill structures (Fig. 3B). The period of fluvial redeposition was followed by aeolian deposition on the wet surface as demonstrated by adhesive structures – SFw (Kocurek & Fielder, 1982; Good & Bryant, 1985; Kasse, 2002; Schokker & Koster, 2004).

These processes are indicative of an alternating operation of aeolian and fluvial environments. The orientation of sedimentary structures shows a wide

range of variation (Fig. 2). Preferences of structures associated with the aeolian environment can help reconstruct the wind sector from the NNE through W to WSW. However, the direction of the fluvial drainage was generally westwards (in the sector from the northwest to southwest).

The presence of numerous syngenetic pseudomorphs after ice wedges indicates the existence of permafrost in the substrate during deposition of the unit. The climatic conditions were very similar to those under which the fluvial unit formed. However, the change in deposition style, i.e. a clear reduction in fluvial components in favour of aeolian ones, may indicate an increase in climatic aridity. This is supported by the increase of participation of RM grains and a maximum value in this unit (Fig. 4A; Kasse, 1997; Van Huissteden et al., 2000; Woronko, 2012). However, grain-size parameters, in particular σ_1/M_z , are arranged in a way that is typical of environments with highly variable dynamics (Mycielska-Dowgiałło & Ludwikowska-Kędzia, 2011) (Fig. 4B-D). This is most characteristic of the fluvial environments (especially river-bed subenvironments). In contrast, this is rarely found in sediments of the aeolian environment (Mycielska-Dowgiałło & Ludwikowska-Kędzia, 2011). Most probably, the flow almost came to a halt under these conditions. Only occasionally did channel incision occur (Murton & Belshaw, 2011).

5.3. Aeolian unit

Numerous deflation and reactivation surfaces, tabular sets and two clearly separated directions in the distribution of structural elements, as well as the inclination of sandy layers, indicate considerable similarity of lithological features of this unit to the structure of longitudinal desert dunes (Figs 2, 3A; Bagnold, 1954; McKee & Tibbitts, 1964; Tsoar, 1982; Bristow et al., 2000).

Large-scale tabular sets indicate the emergence of the depositional face within the dune slope, while sand lithofacies of small- and medium-scale translational and diagonal tabular stratification document the exposure of the dune slope to wind of medium velocity: 4–8 m/s documented through translational beds and 8–12 m/s through the tabular sets, respectively (Zieliński & Issmer, 2008).

Periodic subjection of the dune slope to wind activity is further confirmed by the existence of deflation surfaces, suggesting a significant increase in wind velocity (> 15 m/s). This is also expressed as an increase in average diameter of the aeolian unit (Fig. 4). The lithological characteristics and their directional structures indicate that this series was de-

posited at periodically changing bidirectional wind and at variable wind speeds.

The wind from the southwesterly sector is characterised by a generally lower speed than that from the northwesterly sector. The wind parameters interpreted in this way indicate they should be identified with the deposition conditions typical of seif dunes (see Bagnold, 1954; Tsoar, 1983, 1984; Bristow et al., 2000).

A geomorphological analysis of the study area showed the presence of two parallel dune ramparts (Fig. 1B). This would indicate dune development by the model of Landsberg (1956) and Galon (1959), i.e., through transformation of the arms of parabolic dunes into longitudinal dunes through blowing the dunes' front.

However, the lack of deflation outliers between longitudinal dunes developed from blowing the front of parabolic dunes, the measured variable directions of palaeotransport in the dune (Fig. 2) and the dichotomy of the morphoscopic characteristics of quartz grains within the aeolian unit (Fig. 4) indicate different, material-rich feeding areas. Initially, the deposit could have undergone a repeated wind redeposition as demonstrated by a high content of RM grains (Fig. 4; Table 1). Large differences in the dynamics of the transport medium (both its strength and direction) seem to confirm a significant dispersion in grain size characteristics, as seen in the tables of granulometric indices and in the CM Passega diagram.

Next, the percentage of material from the underlying sedimentary units increases, as demonstrated by a distinct decline in RM grain content and an increase in the glossy grain content. Such a clear change in indicators suggests an increased material supply, which rules out the possibility of dune blowing. This allows us to interpret the analysed dunes as longitudinal forms developed according to the model proposed by Lancaster (1980), except that the form converted into a longitudinal dune was a parabolic dune, whose remains are visible at the west end of the form in question (Fig. 1B).

Deposition of the aeolian unit took place under conditions of progressive degradation of permafrost, which led to increased infiltration and thus desiccation of the subsurface layers. This resulted in a greater availability of material for aeolian transport (Kasse, 1997; Van Huissteden et al., 2000; Zieliński et al., 2009; Woronko, 2012).

The improvement in climatic conditions is also indicated by fossil soil levels. Both soils show a weak developmental stage; however, the younger one is morphologically significantly better expressed than the older one.

The older soil, arenosol, documents an initial stage of plant succession. The presence of small light grey spots shows that pedogenic obliteration of sedimentary structures by pedogenic processes was accompanied by extremely poor accumulation of organic matter. Thus, climatic conditions were sufficient to allow pioneer vegetation, not necessarily forming a continuous cover.

Morphological features of the younger soil reflect further amelioration of climatic conditions and plant succession progress. Podzolic soils form under coniferous (boreal) forest. Even the poor stage of the younger soil podzolisation advancement proves at least temporary stabilisation of the dune by a vegetation cover.

Buried soils are divided by a 0.8-m-thick series of aeolian sands. This shows a deterioration of climatic conditions and renewal of aeolian activity between the two periods of pedogenesis. Also after formation of the younger soil aeolian processes restarted, causing its burial and indicative of climate deterioration. The obtained TL dates indicate that the lower soil level developed at the start of the Holocene, at the turn of the Younger Dryas to the Preboreal. The date TL 8.6 ± 1.2 ka suggests that the last dune-forming episode occurred during the Preboreal. However, the fact that the TL dates from the fluvial and fluvio-aeolian units are younger than the IR-OSL dates suggests that the dates of the aeolian unit may also have been rejuvenated. Thus, these sediments could be a bit older than suggested by the results of the TL dating obtained so far. This dilemma could be settled by results of the ^{14}C dating of the lower fossil soils (in progress).

6. Chronostratigraphy and palaeoenvironmental changes

Our interpretation of the structural and textural analyses of sediments clearly indicates that their accumulation took place under harsh climatic conditions. The fluvial and fluvio-aeolian units formed under conditions of continuous permafrost (Fig. 5). In contrast, between the deposition of the fluvio-aeolian and aeolian units falls permafrost degradation. The resultant IR-OSL and TL dates indicate that the deposition of the tested sediment took place during the latest Weichselian and early Holocene (Fig. 2). However, they do show some discrepancies (Table 2).

The IR-OSL values for the base and top of the fluvial unit date the formation of the unit as latest Pleni-Weichselian (17.3 ± 1.3 and 16.5 ± 1.2 kyr, respec-

tively; Fig. 2; Table 2). The TL dates deviate from the above; they generally indicate an early Holocene age. Only the date obtained from the top of the fluvial unit (13.5 ± 2.0 ka; Fig 2; Table 2) may indicate that it is older. The rejuvenation of these dates, especially the basal ones, may be associated with a slight variation of absorbed energy (in the range of 6.6–7.4 Gy; Table 2); similar values of concentrations of radium and thorium, as well as diversity in the potassium concentration values. These differences in potassium content, as well as its significant increase in the samples POS8 and POS9 causes that the annual dose (\dot{d}_T) is increased by 30%, resulting in the inversion of the lowest lying samples, and thus rejuvenation of the base of the oldest unit. A comparison of these results with similar sedimentary successions, leads to the assumption that the fluvial sediments were deposited during the Pleni-Weichselian (Bohncke et al., 1995; Mol, 1997; Van Huissteden et al., 2000; Kasse et al., 2007; Zieliński et al., 2009, 2011, 2014a, b). The fluvial sediments seen at outcrop represent only the top part of the alluvial fan, the thickness of which can reach up to 10 metres (Winnicka, 2008). Therefore, the obtained dating results document only the late fluvial deposition processes on the alluvial fan. Such a possibility is demonstrated by results of dating of deposits from the alluvial fans in Germany, whose development took place in the interval 28–18 ka (Meinsen et al., 2014; Fig. 13). The formation of alluvial fans started with a clear cooling of the climate during MIS 2 (late Pleniglacial, 27–15 ka; Bos et al., 2001; Guiter et al., 2003).

The fast pace of sediment aggradation on the fan, as well as the prolonged exposure to cold climates was conducive to the development of periglacial structures, numerous in the sediments of the fluvial unit (Figs 3B & E, 5). Presumably their maximum development fell on the cooling peak at about 20 ka (Huijzer & Vandenberghe, 1998; Guiter et al., 2003). This period also saw the maximum development of permafrost which formed almost a continuous cover in central and western Europe (Huijzer & Isarin, 1997; Mol et al., 2000; Kasse, 2002; Zieliński et al., 2014a).

The IR-OSL date (12.4 ± 0.9 ka; Fig. 2; Table 2) obtained from the fluvio-aeolian unit suggests that deposition of this series took place at the end of the Oldest Dryas/Bølling (Fig. 2). However, well-developed syngenetic periglacial structures (Fig. 3B) indicate severe climatic conditions typical of the late Pleni-Weichselian (see Zieliński et al., 2014a and papers cited therein). This allows to accept that the deposition of this unit started probably at about 15–12 ka and was preceded by deflation. This is indicated by the deflation lag preserved at the top of the fluvial

unit (Figs 2, 3C). This pavement can be correlated with the Beuningen Gravel Bed, which in a number of research sites in Germany and the Netherlands separates the fluvial deposits from the fluvio-aeolian series (Kasse et al., 2007; Vandenberghe et al., 2013; Meinsen et al., 2014 and references therein). It developed as a result of deflation of both sandy and finer fractions under polar desert conditions between c. 17 and 15 ka (Kasse et al., 2007). In the case of Postolin its formation took place at around 16–14 ka, as is shown by the dating results (Fig. 2). However, unlike the classic profile of the Netherlands, where the Beuningen Gravel Bed separates the fluvio-aeolian series (Older Coversand I) from the aeolian one (Older Coversand II; compare Kasse, 2002; Vandenberghe et al., 2013), at Postolin the deflation lag separates the fluvial unit from the fluvio-aeolian (Fig. 2). This differentiates profiles from Poland from their counterparts in the Netherlands. This may result from differences in the development of sedimentary environments in western and central Europe. This is indicated by the presence of a deflation pavement in a number of soil sections at the contact between the fluvio-aeolian and aeolian units (Zieliński et al., 2011, 2014b).

A comparison of the development of the fluvio-aeolian Postolin unit with the same type of deposits at other sites, e.g., Żabinko (Zieliński et al., 2011) and Józefów (Zieliński et al., 2014b; Woronko et al., 2015), shows its greater thickness and better-developed periglacial structures. This difference seems to have been rather conditioned by local factors, such as topography, especially exposure to insolation, rather than regional factors, such as climatic conditions. In this case, it was the exposure to the northwest at Postolin, and to the south at Józefów. However, this confirms a certain heterogeneity of the fluvio-aeolian unit at different sites, as well as a varied time of its development (Meinsen et al., 2014; Zieliński et al., 2014a). Climate warming during the Bølling Interphase caused rapid permafrost degradation, increased substrate drainage and the end of fluvio-aeolian-type deposition (Fig. 5). The completion of the deposition of the fluvio-aeolian unit in the Late Weichselian is also supported by the date (10.6 ± 1.6 ka; Fig. 2) of the basal part of the aeolian unit, below the lower fossil soil. It also seems to be confirmed by the development of this soil, indicating its emergence in the Late Weichselian, probably during the Allerød Interphase. This means that the accumulation of sand dunes took place mainly in the Older Dryas, and only a small portion of the form was transformed in the Younger Dryas and Holocene. This is also confirmed by the research at sites in neighbouring regions of western Poland and eastern Germany (Nowaczyk, 1986; Kozarski, 1995; Mol,

1997). However, the model of dune development clearly differs from that commonly seen previously (Wojtanowicz, 1969; Zieliński, 2003; Seppälä, 2004; and references therein), as proposed by Landsberg (1956) and Galon (1959). These authors described the blow off of the parabolic dune face, and its arms forming longitudinal dunes, which are *de facto* deflationary outliers. Such a situation is possible, with constant wind direction and negligible supply of sandy material (Hack 1941; Lancaster, 1995). Meanwhile, the featured model is the same for seif dunes (Bagnold, 1954; McKee & Tibbitts, 1964; Tsoar, 1982; Bristow et al., 2000). Periodically changing bidirectional wind reflects seasonally changing atmospheric pressure centres (Renssen & Isarin, 2001). In contrast, a large delivery of material indicates the affluent alimentation areas, which is the result of an insignificant vegetation cover and relatively deep soil desiccation, following a large drain (Kasse, 1997).

7. Conclusions

The Postolin site is a good example of a typical sedimentary succession in a river valley in the latest Weichselian. This succession begins with fluvial sediments developed in an environment of sand-bed braided river, functioning in the middle part of the alluvial fan accumulated in the Żmigród Basin. These sediments transform into deposits of alternating aeolian and fluvial accumulation associated with episodic, concentrated flows. The succession terminates with aeolian deposition within the longitudinal dunes.

The aeolian processes were stabilised by the development of vegetation, resulting in the creation of soil horizons.

The evolution of depositional environments is the result of climate change:

1. The fluvial accumulation took place under conditions of continuous permafrost, most likely in the Pleni-Weichselian;
2. The deposition of sand covers took place under permafrost conditions, with an increase of aeolian components and incidental flows, most probably at the turn of the Pleni-Weichselian to the late Weichselian;
3. The tested longitudinal dune has enabled us to document a different model of development of longitudinal inland dunes from the one preferred previously. Its development is synonymous with that of desert seif dunes, i.e., shaped by alternating bidirectional wind of 90–120° sector with a considerable supply of sandy materi-

al. This form has been transformed from a small parabolic dune whose remains are located at its western end.

4. The aeolian deposition took place within the dunes during permafrost degradation, with changing, bidirectional wind, mostly from southwesterly and northwesterly directions, during the late Weichselian and early Holocene.

Preservation of continuous permafrost during deposition of the fluvio-aeolian unit was predominantly driven by local factors, mainly the morphology of the area. Final permafrost degradation did not occur until the start of the Bølling Interphase.

The TL dates of the succession studied seem to be generally rejuvenated. It is difficult to say what caused this rejuvenation; perhaps it is the size of the annual dose (d_r), which varies from 0.5 to 0.7 Gy/kyr.

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