VERSITA

Acta Palaeobotanica 53(1): 9–21, 2013
DOI: 10.2478/acpa-2013-0002

# Depositional environment of a fan delta in a Vistulian proglacial lake (Skaliska Basin, north-eastern Poland)

BARBARA WORONKO[1*] and KATARZYNA POCHOCKA-SZWARC[2]

[1]Department of Geomorphology, Faculty of Geography and Regional Studies, University of Warsaw, Krakowskie Przedmieście 30, 00-927 Warszawa, Poland; e-mail: bworonko@uw.edu.pl

[2]Polish Geological Institute – National Research Institute, Rakowiecka 4, 00-975 Warszawa, Poland; e-mail: katarzyna.pochocka-szwarc@pgi.gov.pl

[*]corresponding author

Received 20 February 2013; accepted for publication 8 May 2013

ABSTRACT. The study reconstructed the environment of a fan delta filling the vast end depression of the Skaliska Basin, and its overlying aeolian deposits. The formation of the large fan delta is associated with the presence of an ice-dammed lake functioning during the retreat of the Vistulian Glaciation (MIS 2). The examined material was collected from five boreholes. Sediments were analysed for their granulometric composition and subjected to analyses of frosting and rounding of quartz grains. Grain size analysis showed that the fan delta deposits are built of sand sediments of very low lateral and vertical variability. The fan delta was supplied with fluvioglacial sediments. Accumulation of sediments occurred in shallow water with a very low-gradient slope. The exposed fan delta became a site conducive to aeolian processes after the lake waters fell and the Skaliska Basin depression dried. Dune deposits overlying the fan were affected by short-distance transport so they did not acquire features typical for aeolian deposits.

KEYWORDS: fan delta, dune, grain size analysis, Vistulian glaciation, Skaliska Basin, Poland

## INTRODUCTION

Glacial environments are very complex systems. Glacial melt water plays an important role because it affects sediment transfer, glacier dynamics, and erosion and creation of distinct landforms (Eyles et al. 1987, Russell 2007, Liermann et al. 2012). Proglacial lakes are also crucial elements of this system. They capture much of the material transported by proglacial meltwater, thus recording the history of glaciation of the area as well as the processes that took place within the lake and its catchment (Orton & Reading 1993, Eissemann 2002, Winsemann et al. 2007, Hasholt et al. 2008, Liermann et al. 2012). Very often this type of lake is accompanied by the accumulation of large deltas (e.g. Zieliński & Brodzikowski 1992, Hasholt et al. 2008, Liermann et al. 2012). A deltaic system is very sensitive to any changes in even a single element of the environment. This may be reflected in the sediments forming a delta or in the delta's morphology (Orton & Reading 1993). The configuration of the drainage basin, depth of water, transport and accumulation of sediments as well as the nature of processes in the subaquatic environment are major factors of the environment that affect the functioning of such a system (Orton & Reading 1993, Rodriguez et al. 2000). Orton and Reading (1993) suggest that the grain size of the sediment load supplying a delta plays a key role in the shape and size of a delta. Thus grain size is an essential aspect of sedimentary facies and facies sequences.

The Skaliska Basin in north-eastern Poland, functioning during the Pomeranian phase of the Vistulian (Weichselian) glaciation, is an example of such a proglacial lake. The meltwater lake flowed out after the retreat of the ice sheet, when the meltwater outflow pathways that had previously been blocked by an ice dam (Pochocka-Szwarc 2013) were cleared, uncovering an extensive sand deposit on which dunes developed.

In the present work the sedimentation conditions of the deposits forming the vast delta which filled the Skaliska Basin, are reconstructed, and factors responsible for the shape and size of the delta identified. The intensity and duration of the aeolian processes that operated when the lake fell dry are determined.

## GEOGRAPHICAL AND GEOLOGICAL SETTING

The Skaliska Basin is a vast flat-bottomed depression extending to the north-east of Węgorzewo, on the border with Russia. The northern part of the basin is outside Poland's borders, in the Kaliningrad Region (Fig. 1). In this study the sediments that built the extensive sandy delta, accumulated in a proglacial lake filling the Skaliska Basin were examined. The basin is a depression between successive ridges of recession moraines formed during the retreat of the glacial front in the Pomeranian phase of the Vistulian (Weichselian) glaciation (MIS 2). The lake functioned

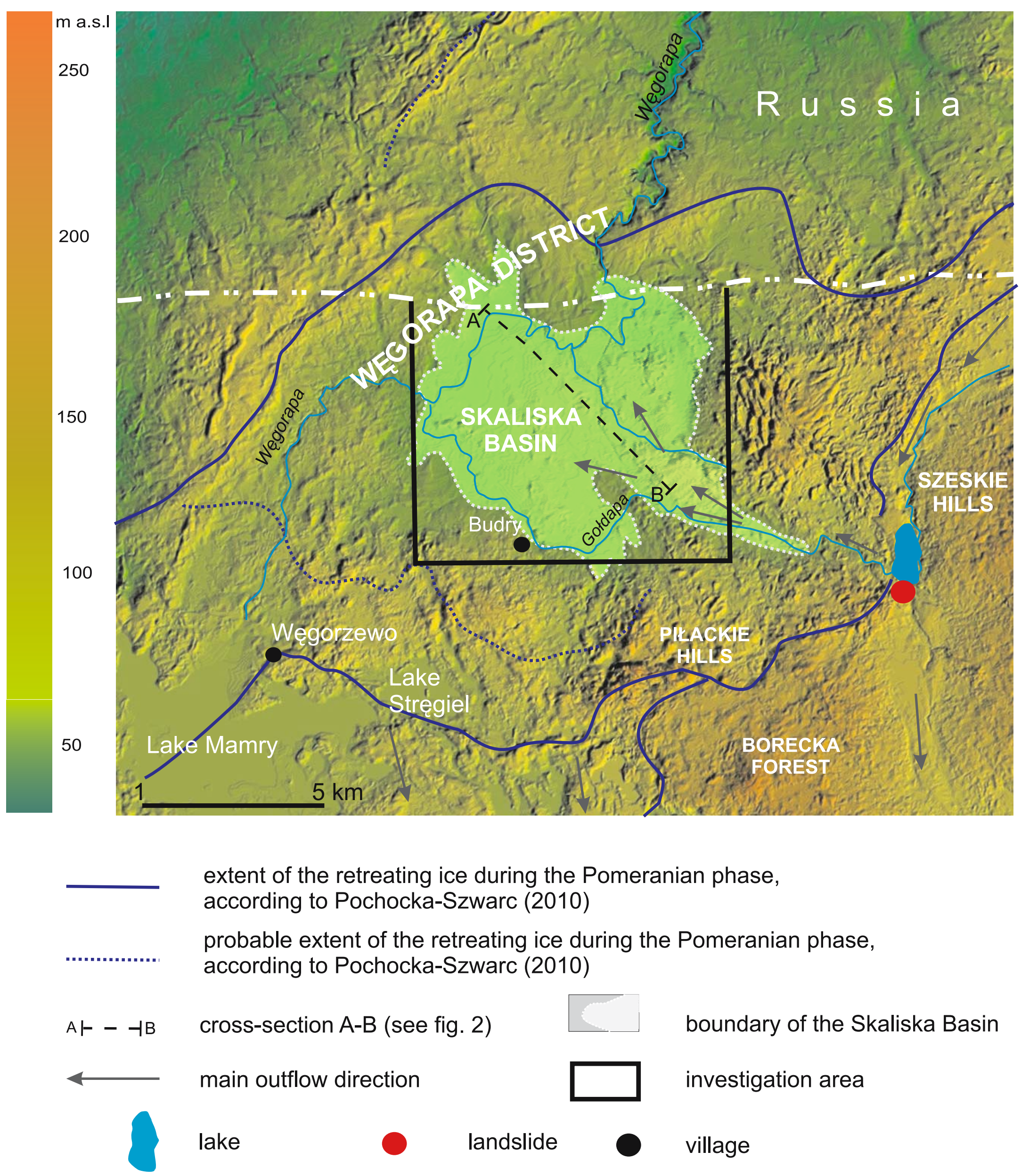


**Fig. 1**. Location of the study area

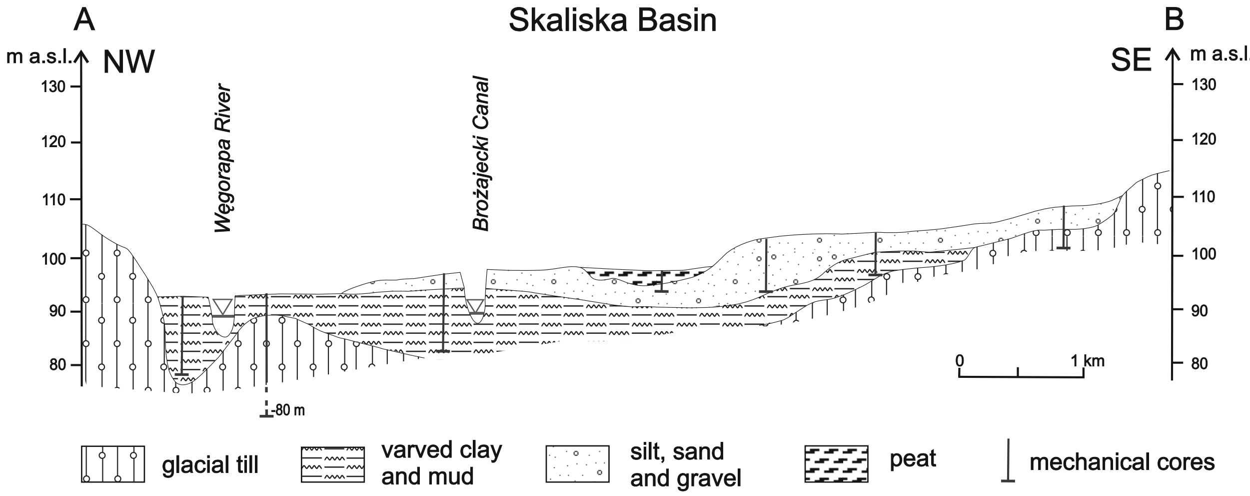


**Fig. 2**. Schematic cross-section A-B through Skaliska Basin

for at least several hundred years and reached a surface area of ca 90 km$^2$ (Pochocka-Szwarc 2010). The occurrence of the lake is recorded in varved clays 1.5–17.8 m thick (Fig. 2). They are overlain by sandy deposits and underlain by glacial till assigned to the ice sheet retreat during the Pomeranian phase (Pochocka-Szwarc & Lisicki 2001, Pochocka-Szwarc 2003, 2010).

Sandy sediments began to accumulate in the lake after glacial meltwater flowing southward on a sandur running along the north and west side of Szeskie Hill became dammed (Pochocka-Szwarc 2003, 2010). Probably the cause of the damming was a landslide, initially forming a stagnant water reservoir and then directing the outflow of fluvioglacial water to the west, to the Skaliska Basin (Fig. 1). At first the flow followed a narrow, deeply indented valley and was breakthrough in character, with erosion as the dominant process. Two to three kilometers further the valley expanded, forming a vast alluvial fan ca 3 km long. These processes formed the delta at the mouths of fluvioglacial streams to the reservoir, near Banie Mazurskie village (Fig. 3). The delta creates a flat, almost radial fan with a maximum radius of ca 6 km (Fig. 3). The sandy sediments forming the delta range from 1.5 to 16.0 m in thickness. In the south-east part of the basin the sand floor of the sediments is at 119–116 m a.s.l., gradually descending westward to ca 100 m a.s.l. (Fig. 3). While the lake existed the front of the ice sheet was 1–2 km to the north (Fig. 1). Regression of the front of the ice sheet resulted in changes in the base level. The withdrawal of the front beyond the line of the Pregoła Valley cleared impediments to northward and subsequently westward outflow of water from the lake (Pochocka-Szwarc 2005). This led to outflow of waters from the ice-dammed lake in the Skaliska Basin (Pochocka-Szwarc 2009, 2010). The delta sediments were overlain by aeolian deposits developed as parabolic dunes forming a north-south belt.

# METHODS

## SAMPLING ORGANISATION

To identify the conditions of transport and sedimentation within the delta that accumulated in the Skaliska Basin, three full-core geoprobe holes (Pochocka-Szwarc 2010) and 19 mechanical drillings, each at least 10–15 m deep, were made. Five boreholes (numbered 1–5) were used for detailed investigations (Fig. 4). Additionally, an outcrop was used to examine sediments down to 2.6 m depth (Fig. 3). Topographic map analyses and geophysical studies preceded drilling. Sampling sites were distributed among locations showing depositional conditions within the delta (Fig. 3), both laterally (from proximal to distal, i.e. SE to W) and in vertical section. The outcrop (DPL) was dug in the crest parts of the parabolic dune overlying the delta. The relative elevation of that form is 5 m.

## GRAIN SIZE ANALYSIS

The material for textural examination of sediments was collected from three boreholes (numbered 1–3) and the outcrop DPL (Fig. 3). The obtained sediments (32 samples) were subjected to grain size analysis. The granulometric composition was determined with an Analysette 22 Comfort Laser Particle Sizer. The results were used to calculate grain size parameters following Folk and Ward (1957): mean grain diameter ($M_z$), standard deviation (sorting) ($\sigma_1$), skewness ($Sk_1$) and kurtosis ($K_G$) (peakedness of a particle size distribution curve). Kurtosis gives information about the

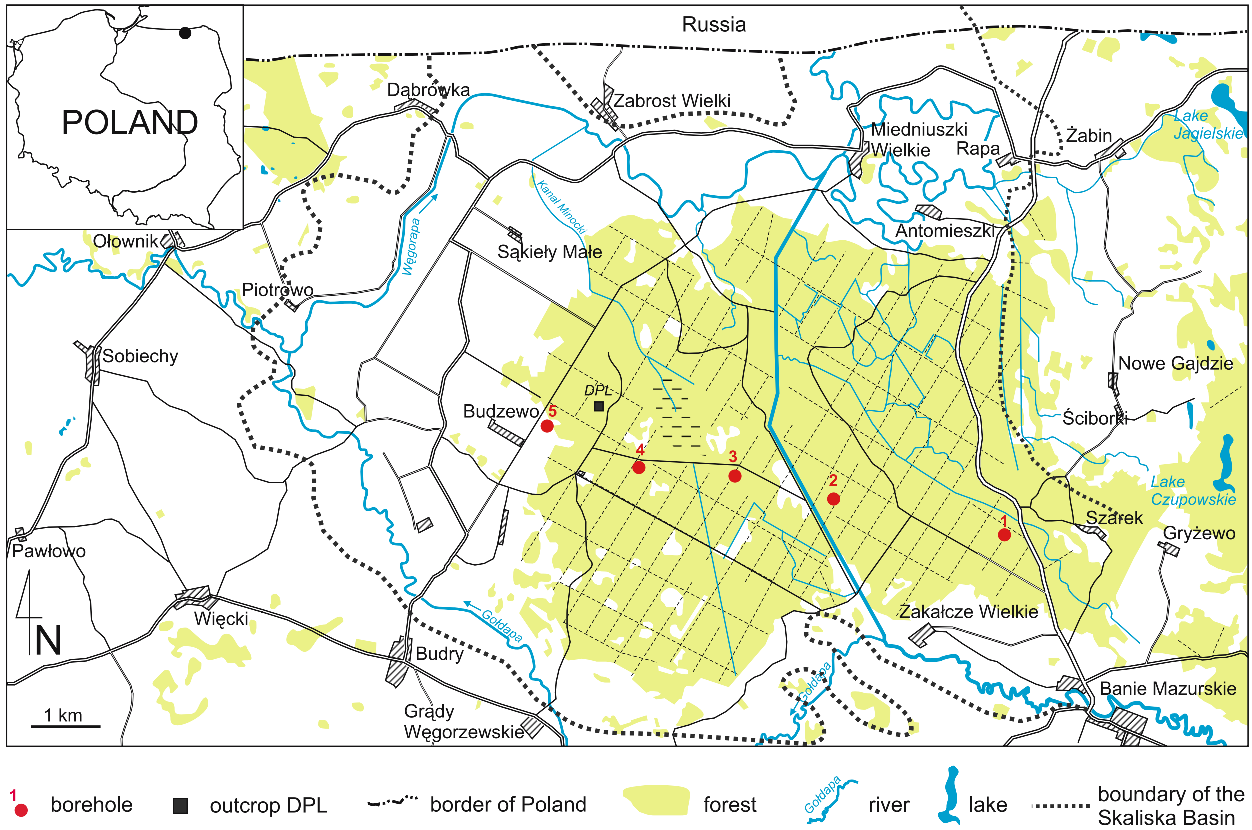


**Fig. 3**. Location of boreholes and outcrop DPL

stability of environmental dynamics: the higher the value of kurtosis, the more uniform the environmental conditions (Racinowski et al. 2002). Frequency and cumulative curves were plotted on a probability scale. The grain size distributions were interpreted according to Visher (1969) "...a sedimentological concept assuming that cumulative curves consist of several line segments, each segment symbolizing categories of particles (populations)" carried in different types of transport (Bartholdy et al. 2007, Opreanu et al. 2007, Mycielska-Dowgiałło & Ludwikowska-Kędzia 2011, Srivastava et al. 2012). All grain size values are presented on the phi scale.

## ROUNDING AND FROSTING OF QUARTZ GRAINS

Additionally, 4 samples from the outcrop DPL (Fig. 3) were analysed for frosting and rounding of quarz grains according to Cailleux (1942) as modified by Goździk (1980) and Mycielska-Dowgiałło and Woronko (1998). The aim of the analysis was to determine whether the quartz grains bore traces of aeolian abrasion, hence how long the sediments were reworked by aeolian processes. Each analysed sample consisted of 100–200 quartz grains of the 1.0–0.8 mm fraction. The analyses assessed quartz grain rounding on the scale of Krumbein (1941) and characterized the grain surfaces. Seven types of grains were distinguished, each associated with a different transport environment or weathering process:

NU – fresh and angular grains with sharp edges, no traces of processing, with rounding degree of 0.1–0.2 following Krumbein (1941). They were likely to be produced by processes operating during, e.g., the action of frost weathering or crushing in a glacial environment;

RM – round, matte grains with a completely frosted surface (0.7–0.9), representing the aeolian environment. The high degree of rounding is an effect of long-lasting abrasion proceeding during transport in saltation in the aeolian environment;

EL – round, shiny grains (0.7–0.9) originating from a high-energy beach or fluvial environment (Woronko & Ostrowska 2009). The very high degree of rounding is an effect of long-term chemical weathering (etching) and abrasion on the grain surfaces;

EM/RM – moderately aeolian grains (0.3–0.6) with mat corners and edges;

EM/EL – shiny grains of an moderately degree of rounding (0.3–0.6). They represent a high-energy beach or fluvial environment (Woronko & Ostrowska 2009);

'other' – grains of various degrees of rounding, the surfaces of which were affected by intensive chemical and mechanical weathering. No effects of abrasion are found on the surface of such grains;

C – broken grains with at least 30% loss of surface (Goździk 1995).

## DATING OF SEDIMENTS

Sediments obtained from the outcrop DPL were also sampled for OSL dating performed at the Luminescence Dating Laboratory of Institute of Physics, Silesian Technical University in Gliwice. Samples were collected from the outcrop at 2.5 and 2.2 m depth.

## RESULTS

### DEPOSITS ACCUMULATED IN LAKE

In borehole 1 (12.0 m depth) during the drilling (Fig. 3), silty sediments were recorded at 8.2–11.0 m depth, overlying a series of laminated clay from the ice-dammed lake. They form the top part of sediments accumulated in the lake, which filled the Skaliska Basin during the Vistulian glaciation (Pochocka-Szwarc 2009). Lacustrine sediments are overlain by sandy material 8.2 m thick (Fig. 4). Grain size analyses indicate that the sand is fine-grained, with low variability of the basic grain size parameters within the section, including mean grain size ($M_z$), and slightly positive skewness ($Sk_1$). This is accompanied by deterioration of sorting ($\sigma_1$) from 0.79 to 0.98 moving up the profile in the 10.0–1.5 m depth range, and $\sigma_1 > 1$ at the 0.5–1.5 m level. The kurtosis values ($K_G$) are 1.08–1.29; that is, the particle size distribution curve goes from normal or mesokurtic to excessively peaked (leptokurtic). The exception is the floor of sandy sediments, at 0.5 m depth, where $K_G$ increases to 1.54, very leptokurtic (Fig. 5). The analyses show dominance of grains of the 0.5–0.063 mm fraction in sandy sediments, varying in proportion from 77.03% at the basal part of the series through 92–96% at 7.7–5.0 m depth to 83.2% in the top part. Cumulative curves are characterized by clear marking of three curve segments indicating different modes of sediment transport: in the bed load (Fig. 6A), by saltation and in suspension (Visher 1969, Opreanu et al. 2007, Mycielska-Dowgiałło & Ludwikowska-Kędzia 2011). In most cases, grains over 1.0 mm in diameter are transported by rolling and sliding. This type of transport involved only ca 5% of the grains. Grains of the 1.0–0.063 mm fraction were transported by saltation. The steeply inclined segment of the saltation curve indicates very good sorting of sediments transported this way. Sediments transported in suspension show the poor sorting typical for that process (Fig. 6A). Good sorting is confirmed by the relatively high-peaked frequency curves (Fig. 6B). At the

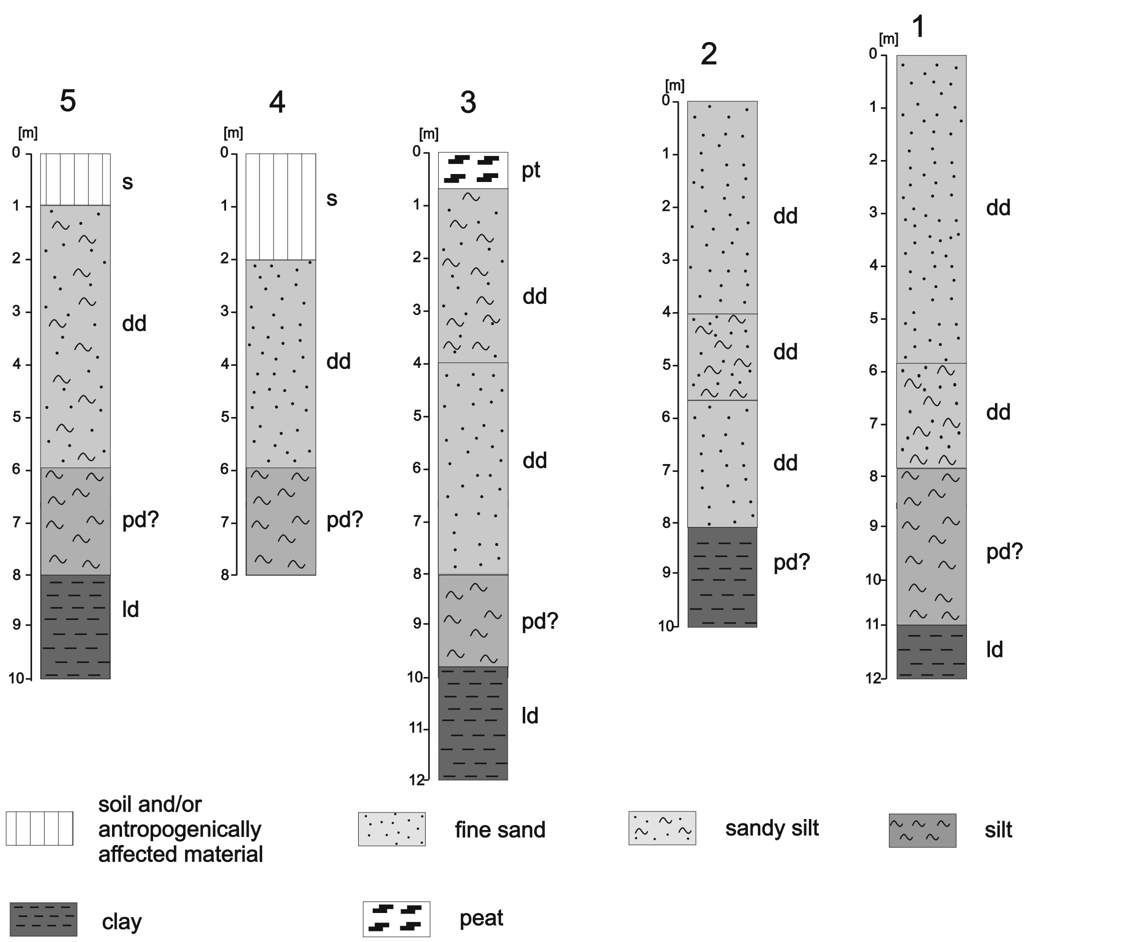


**Fig. 4**. Sections of sediments accumulated in the lake that filled the Skaliska Basin; **dd** – fan-delta deposit, **pd** – prodelta deposit, **ld** – lake deposit, **pt** – peat, **s** – soil and/or antropogenically affected material

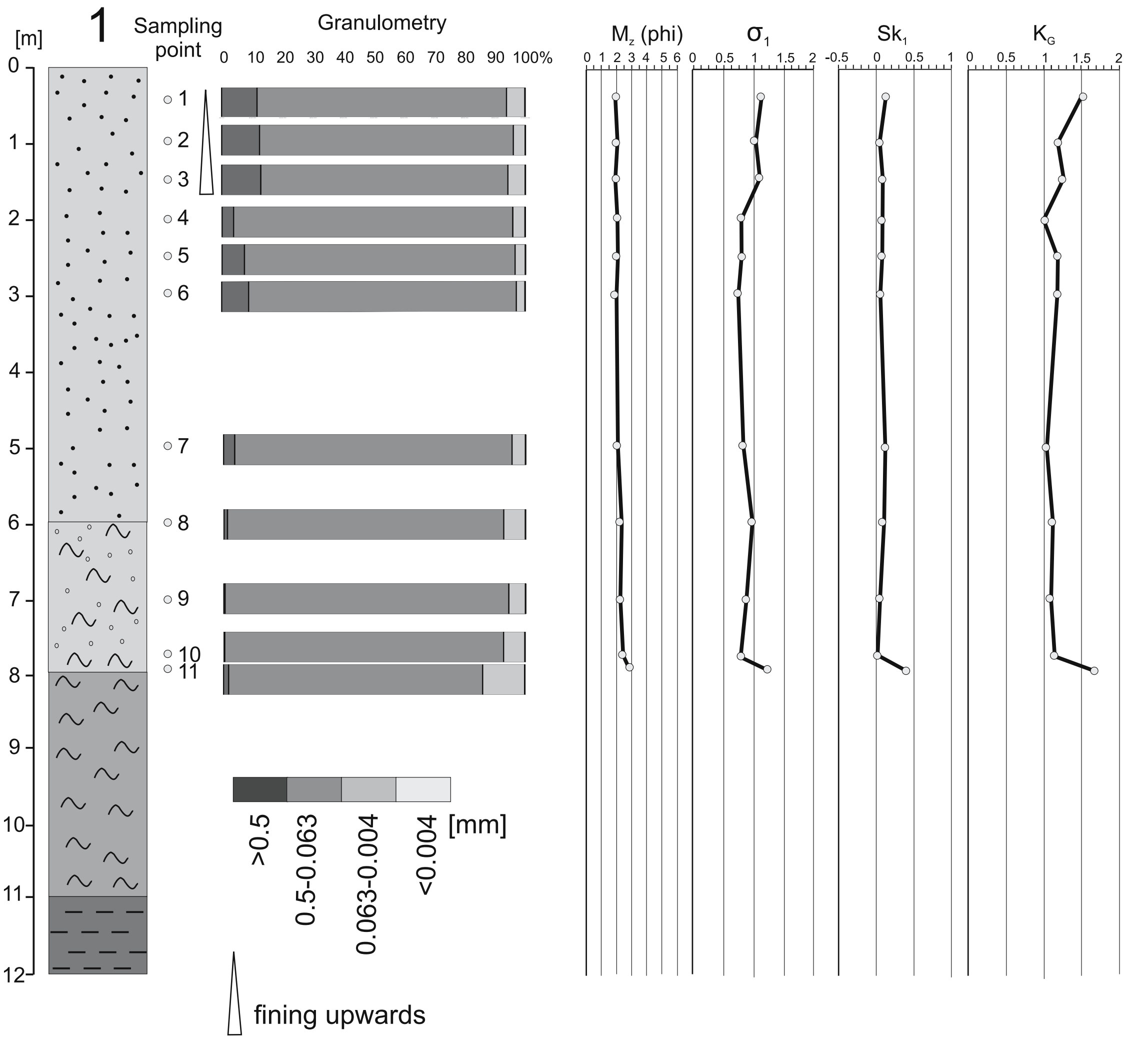


**Fig. 5**. Section of sediments from borehole 1: **Mz** – mean grain size (phi); **$\sigma_1$** – sorting; **$Sk_1$** – skewness; **$K_G$** – kurtosis

same time, upward from 3.0 m depth there are two evident cycles of increase in the share of the >0.5 mm fraction in the sediment (Fig. 5).

In borehole 2, located ca 2 km west of borehole 1 (Fig. 3), the sandy sediments (Fig. 4) attain 8.0 m thickness (depth 0.0–8.0 m). They overlie lacustrine clays in which mean grain size ($M_z$) ranges from 8.41 phi at 9.1 m depth to 6.46 phi in the ceiling (8.1 m depth). Kurtosis ($K_G$) changes from 0.98 (mesokurtic particle size distribution curve) to 1.34 (leptokurtic) in the ceiling (Fig. 7), which corresponds with the course of the frequency curve (Fig. 6D). The basal part of the sandy sediments (7.4 m depth) bears the coarsest material of the entire section ($M_z = 0.75$ phi), is poorly sorted ($\sigma_1 = 1.74$), very negatively skewed ($Sk_1 = -0.308$) and leptokurtic ($K_G = 1.22$). Subsequently the sediment becomes finer ($M_z = 1.84$ phi), moderately sorted ($\sigma_1 = 0.74$) and very positively skewed ($Sk_1 = 0.330$) at 6.0 m depth. The very positive skewness illustrates the frequency curves, with clearly marked tails in small fractions. To the top of the profile, mean particle size ($M_z$) ranges from 1.39 to 1.89 phi, sorting ($\sigma_1$) from 0.61 to 0.86, and kurtosis ($K_G$) from 1 to 1.5 (Fig. 7). For sand deposits the cumulative curves on the probability scale are very similar to those the deposits drilled in borehole 1. They consist of three units with a very steep unit (Fig. 6C) corresponding to saltation (Visher 1969). Such cycles of grain diameter increase followed by fining of sediment are observed at least three times within the section: at 5.0 m, 3.0 m and 2.6 m depths. Each cycle begins with an increase in the share of grains of the >0.5 mm fraction in the sediment (Fig. 7).

Borehole 3 was obtained from the central part of the Skaliska Basin (Fig. 3). At this site the sandy sediments are 8.0 m thick (Fig. 8). As in boreholes 1 and 2, variability of the basic grain size parameters is low. The basal part of the sediments have mean grain size ($M_z$) of 2.91 phi, poor sorting ($\sigma_1 = 1.74$), positive skewness ($Sk_1 = 0.125$) and kurtosis ($K_G$) of 1.37 (leptokurtic), i.e. a curve with a sharp maximum. Moving up the profile, $M_z$ changes in a small range, from 1.51 phi at 4.0 m depth through 2.09 phi at 1.5 m depth to 1.89 phi in the ceiling of sand sediments, Deposit sorting is improved toward the top of the profile, accompanied by a decrease of skewness and kurtosis (Fig. 8). The cumulative curves according to Visher (1969) are marked by a clear unit corresponding to transport by saltation and in suspension (Fig. 6E). On the other hand, frequency curves are high-peaked, confirming the relatively good sorting of sediments (Fig. 6F) Subsequently there is periodicity of sedimentation, indicating supply of coarser material to the basin (Fig. 5). The mineral sediments are underlain by peat.

In boreholes 4 and 5 (Figs 3, 4), located in the most distal part of the Skaliska Basin's sandy deposits, the sediments are developed as in boreholes 1, 2 and 3 under anthropogenically affected material (Figs 4, 5, 7, 8). In borehole 5, clay is overlain by mud deposits 2 m thick (6.0–8.0 m depth). They in turn are covered by silty-sand material 5 m thick. There is no evidence of sandy deposits (Fig. 4). In borehole 4, however, under anthropogenic deposits there

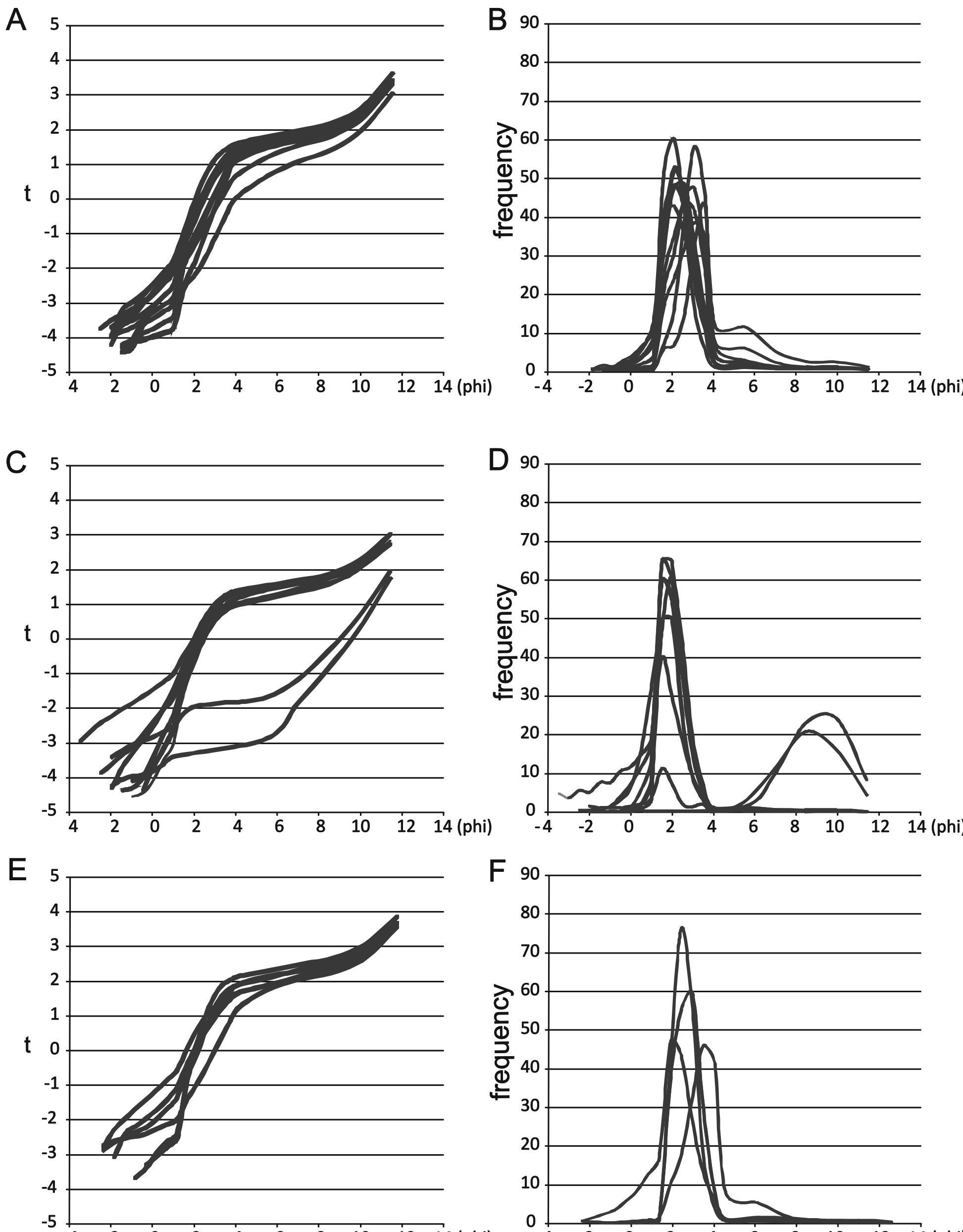


**Fig. 6**. Cumulative curve of sediments deposited in the lake filling the Skaliska Basin: **A** – profile 1; **C** – profile 2; **E** – profile 3. Frequency curves of sediments deposited in the lake that filled the Skaliska Basin: **B** – profile 1; **D** – profile 2; **F** – profile 3

is fine sandy material ca 4 m thick overlying silt sediments, as in all other boreholes except borehole 2.

It is worth noting that the content of the < 0.004 mm fraction does not exceed 0.2%, while the share of silty fraction (0.063–0.004 mm) is 10% in all examined sections of the sediments forming the delta. High homogeneity of sediments is suggested by the shape of the cumulative curves on probability plots. There, two units indicate saltation and sliding or rolling according to Visher (1969).

## DUNE DEPOSITS

All the sediment from the outcrop DPL (Fig. 3, 9) is of massive structure (*Sm*). The 0.75–0.90 m depth interval is marked by a zone enriched in $Fe^{3+}$, the occurrence of which results from soil processes (illuviation zone – E). The dune is formed of fine sand succeeded by medium sand, with the mean grain size ($M_z$) changing from 2.02 phi at 2.0 m depth through 2.50 phi at 1.5 m depth to 2.79 phi at 0.4 m depth. The sediment shows moderate or poor sorting ($\sigma_1$) ranging from 0.88 to 1.20, and positive or very positive skewness ($Sk_1$ from 0.317 to 0.015). The $Fe^{3+}$-enriched zone shows noticeably finer mean grain size ($M_z = 5.41$ phi), very poor sorting ($\sigma_1 = 2.46$), and the lowest value of kurtosis ($K_G = 0.85$ in the profile), i.e. a flat (platykurtic) particle size distribution curve (Fig. 9).

Analyses made according to Cailleux (1942) as modified by Goździk (1980) and Mycielska-Dowgiałło and Woronko (1998) reveal great variability of grain types, representing both aeolian (RM and EM/RM) and fluvial or high-energy beach environments (EL and EM/EL). The proportion of grains with surface subjected to intensive *in situ* weathering ('other') is very high. The content of broken grains (C) was high in all analysed samples (Tab. 1).

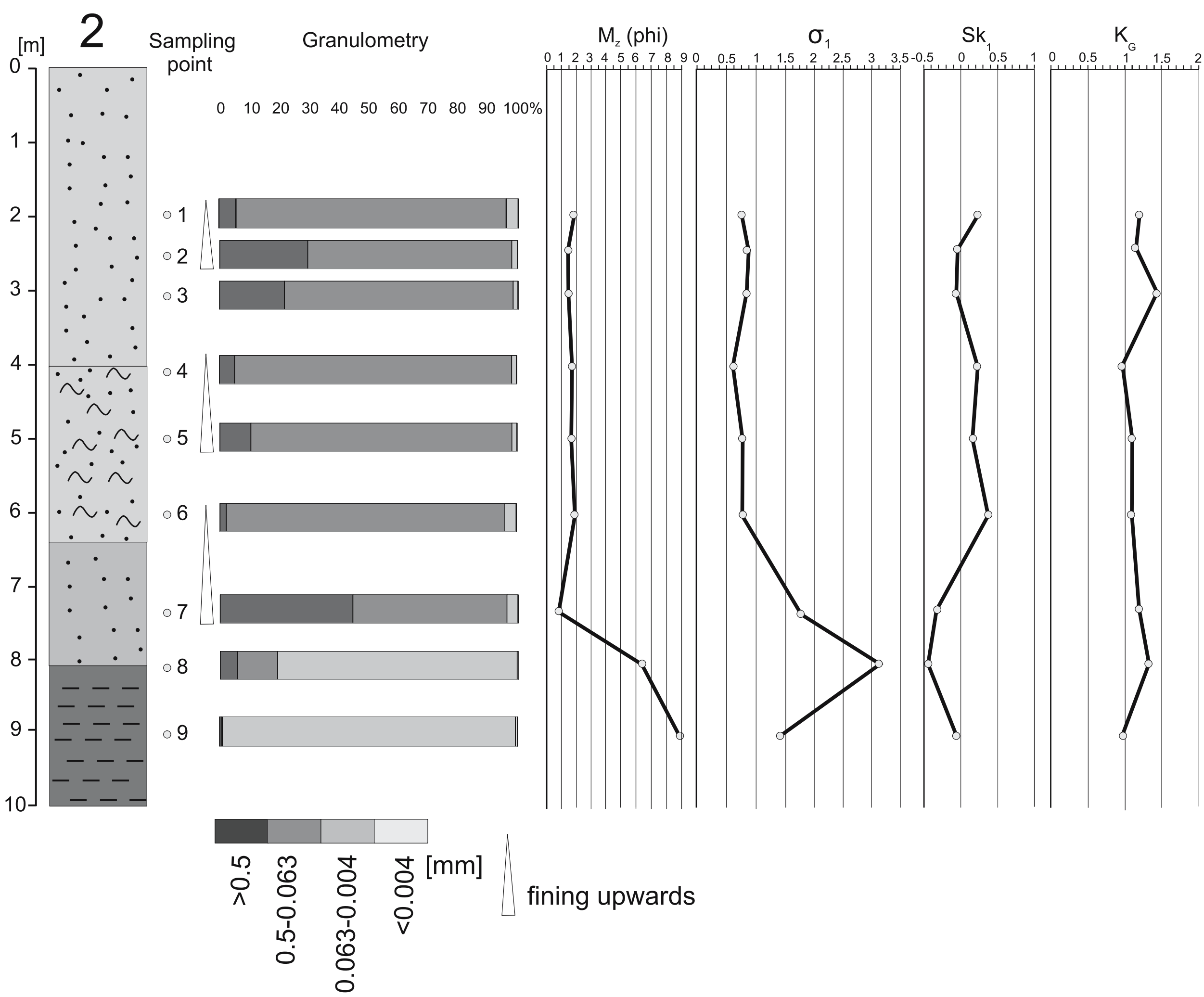


**Fig. 7**. Section of sediments from borehole 2: **Mz** – mean grain size (phi); $\boldsymbol{\sigma_1}$ – sorting; $\mathbf{Sk_1}$ – skewness; $\mathbf{K_G}$ – kurtosis

**Table 1**. Rounding and frosting of quartz sand grains following Cailleux (1942) as modified by Goździk (1980) and Mycielska-Dowgiałło and Woronko (1998), explanations of symbols in main text

| Sample number | NU% | EL% | RM% | EM/EL% | EM/RM% | INNE% | C% |
|---|---|---|---|---|---|---|---|
| 0.5 | 0.0 | 0.0 | 2.4 | 37.9 | 11.3 | 31.5 | 16.9 |
| 1.5 | 0.92 | 0.0 | 0.92 | 29.36 | 23.85 | 29.36 | 15.60 |
| 2.0 | 3.0 | 0.7 | 0.7 | 41.5 | 17.8 | 21.5 | 14.8 |

The OSL dating for the sample from 2.5 m depth is 10.03±4.7 ka (GdTL 1168), and 9.57±4.5 ka (GdTL 1169) for the sample from 2.2 m depth (Fig. 9).

## DISCUSSION

### MORPHOLOGY AND DEPOSITIONAL ENVIRONMENT OF THE DELTA

Sedimentary structure cannot be observed in the sandy deposits of the Skaliska Basin, making it difficult to interpret their depositional environments. The morphology of the form, comprising a long, very gradual slope with a cone accumulated at the most distal part of the sandur, suggests that it should be called a fan delta (Nemec & Steel 1988). The declination of the delta slope probably was the only place where the slope was equal to the angle of repose in the aquatic environment (i.e. 20–30°), as recorded in the sediments (Zieliński & Brodzikowski 1992). Forms of this type are recorded in past proglacial lakes and

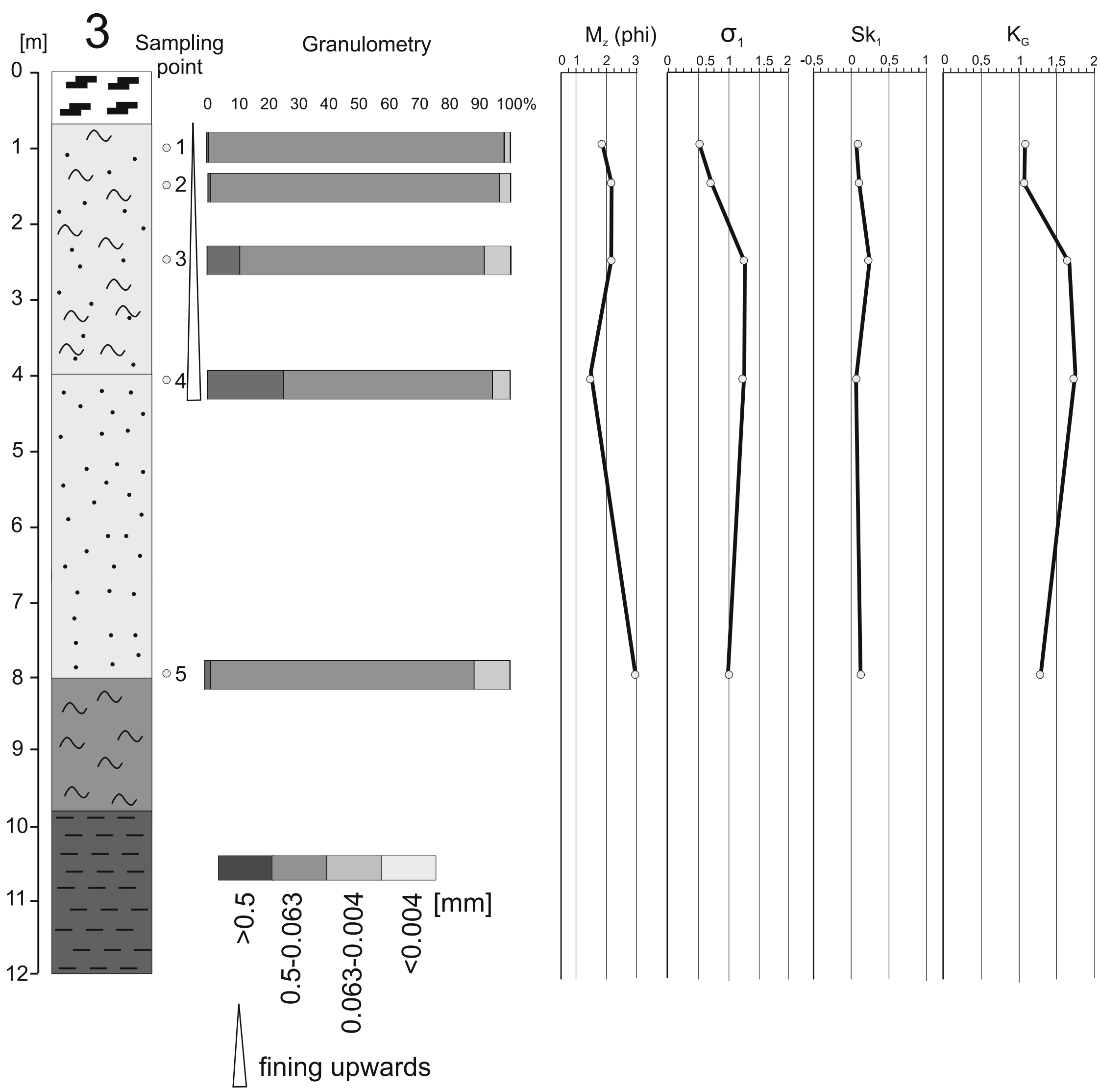


**Fig. 8**. Section of sediments from borehole 3: **Mz** – mean grain size (phi); $\boldsymbol{\sigma_1}$ – sorting; $\mathbf{Sk_1}$ – skewness; $\mathbf{K_G}$ – kurtosis

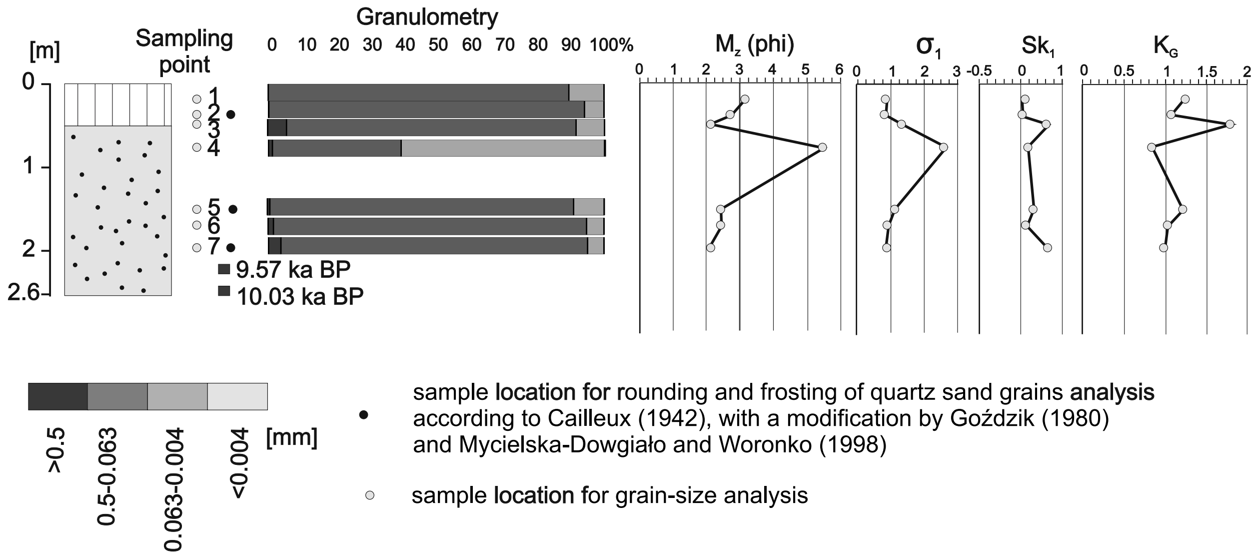


**Fig. 9**. Section of sediments from outcrop DPL: **Mz** – mean grain size (phi); $\boldsymbol{\sigma_1}$ – sorting; $\mathbf{Sk_1}$ – skewness; $\mathbf{K_G}$ – kurtosis

in modern glaciated areas as well (e.g. Zieliński & Brodzikowski 1992, Boyd 2007, Winsemann et al. 2007, Kowalska & Sroka 2008, Liermann et al. 2012).

The fan delta that accumulated in the lake which filled the Skaliska Basin during the retreat of the last glaciation is composed of fine-grained sandy sediments directly underlain by silt and clay materials everywhere within it. The conditions accompanying accumulation were very stable. This is seen in the diagrams plotted for mean grain size ($M_z$)/ sorting ($\sigma_1$), where the spread of points is very narrow (Fig. 10). Such ratios are characteristic of a fluvial environment for current overbank facies (Mycielska-Dowgiałło & Ludwikowska-Kędzia 2011) and most likely associated with migrating current ripples. The high kurtosis values in all analysed profiles (Figs 5, 7, 8) also confirm stable environmental conditions. The cumulative curves of delta sediments indicate that the main mass of sediments was transported by saltation, with only small shares of rolling, dragging, and suspension. Racinowski et al. (2002) suggest that high (leptokurtic) kurtosis indicates that a deposit is in a transit phase. This material has been transported and deposited selectively. In the cumulative curves a clearly visible unit corresponds to particles transported in suspension, and the frequency curves tail toward fine fractions; this indicates reduction of speed resulting in immobilisation of particles transported by saltation and accumulation of material from suspension (Racinowski et al. 2002). However, there are small changes in the particle diameter distribution along the vertical profiles, showing the features of a sequence of normal grading, for example in borehole 2 (Fig. 7). It is marked by an increase in the share of the >0.5 mm fraction, causing negative skewness (7.0 m, 3.0 m, 2.6 m depths) (Fig. 7). Such a sequence of sediments may be due to small pulsatory discharges of lake sediments, and probably serve as a record of channel environments. They are sites of accumulation of coarser material, which indicates higher energy of discharge. Such a deposit structure may be a record of small fluctuating and periodically waning flow (Zieliński & Brodzikowski 1992, Winemann et al. 2007). Thus it may be the result of individual flood events that take place during the melt season in glacial environments (Winemann et al. 2007).

Sediment grain size does not significantly change with distance from the supply source in

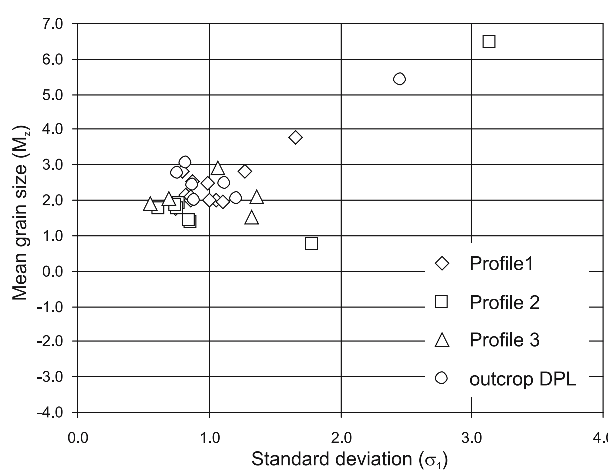


**Fig. 10**. Correlation diagram of the mean grain size (**Mz**) and sorting ($\boldsymbol{\sigma_1}$)

the south-east part of the Skaliska Basin near Banie Mazurskie village (Figs 1, 3). This may indicate a homogeneous, continuous source of sediment, and may be due to its location in the distal part of the sandur (Figs 4–9), which is dozens of ca 20 km long. Probably this stretch of distance was the site of fluvioglacial deposit sorting, where grains are fined along the transport (Orton & Reading 1993, Fernendez et al. 1988). Coarser grain fractions can be accumulated entirely on the delta in an alluvial fan (Liermann et al. 2012). Probably the recharge of sediments from the sometimes steeply sloped hills surrounding the sandur was not significant. That may also form a very small concentration of clay and silt particles. According to Smolska (2010), within a delta there are no interdistributary bay areas where mud of the type transported along a sandur can accumulate. In the distal parts of a sandur such transported material comprises small amounts of clayey and silty fractions.

Perhaps the accumulation of sediments occurred in shallow water. This suggestion is supported by geological surveys (Pochocka-Szwarc 2003) which estimate the depth of the reservoir in which the fan delta formed. Depths ranged from ca 7 m at the mouth of the proglacial braided channel to the lake near Banie Mazurskie to ca 10 m in the centre of the Skaliska Basin. Geophysical surveys also indicate that the lake bottom is not flat; this probably is related to the melting of dead ice (Pochocka-Szwarc 2009). At the same time, the shallowness of the reservoir increased resedimentation processes and expansion of mouth bar deposits (Nichols 2009). The series of mud deposits (Fig. 4) directly underlying the sandy ones, likely to form the prodelta, remains an open issue.

## ENVIRONMENTAL CONDITIONS OF THE DUNE

Analyses following Cailleux (1942) suggest that the material forming the dune displays features of fluvioglacial sediments, typified by great variability of grain types presented in Table 1 (Woronko 2001). The shape of the form, typical of parabolic dunes, indicates that the structure should be considered a dune, but transport of grains most likely was very short-range, as evidenced by the small share of grains processed in an aeolian environment – RM and EM/RM (Tab. 1). The source sediments included the fluvioglacial sediments commonly found in the western part of the Skaliska Basin (Pochocka-Szwac 2003) and sediments forming the fan delta. Equally low shares of quartz grains processed in an aeolian environment were reported in aeolian sediments infilling wedges from the central part of the Kolno Plateau (Korotaj & Mycielska-Dowgiałło 1982) and in the northern part of the Podlasie region at the Jałówka site (Woronko et al. 2013). These two sites are located in the foreground of the Weichselian ice-sheet. Such features of aeolian deposits may be caused by high moisture of sediments blown by the wind, among other factors. The high share (> 14%) of broken grains (C) with fresh edges in the dune sediments may be the result of postsedimentological frost weathering (Woronko & Hoch 2011, Woronko 2012) and crushing in a glacial environment (Gomez & Small 1983, Gomez et al. 1988, Mahaney 1995).

OSL dating indicates that accumulation of aeolian deposits began ca 10.3 ka BP (Fig. 9), corresponding to the dune transformation period of Dryas 3 and the Early Preboreal, dated to 10.800–9.500 ka BP, when new dunes were formed from the Netherlands in the west to Great Poland in the east (e.g. Kozarski 1978, Kasse 1999, Schirmer 1999). In Dryas 3 the culmination of aeolian activity is recorded "*…from the area closely extramarginal to the Pomeranian glacier stage…*", where the withdrawal of the ice sheet was initiated ca 15 ka (Schirmer 1999).

## CONCLUSIONS

Analyses of the grain size of fan delta sediments accumulated in a proglacial lake of the Skaliska Basin during the Weichselian glaciation show very little variability in grain features, neither laterally nor along the vertical profile. Probably this is related to the supply of homogeneous material into the lake, which before forming the fan delta was sorted along a sandur ca 20 km long. The fan delta is built of fine sandy sediments lying on laminated clay from an ice-dammed lake. Accumulation most likely occurred in shallow water and with a large amount of material supplied to the basin along the sandur. The large sediment supply to the lake caused the fan delta to have a low slope gradient. Small changes in sediment grain parameters observed in the drilled boreholes may reflect low variability of flow in the proglacial river that provided material into the reservoir.

Once the lake water of the Skaliska Basin depression was gone, the exposed delta became a site affected by aeolian activity, which resulted in the formation of belts of small dunes in the Younger Dryas. However, aeolian processes in this area were of short duration, recorded only in the relief, not in the textural features of deposits.

ACKNOWLEDGEMENTS

We thank Professor A.J. (Tom) van Loon for critically reviewing the paper and making valuable suggestions. The study was carried out as part of an interdisciplinary research project funded by the Ministry of Science and Higher Education in Poland (grant No. PO 4 D 024 29).

## REFERENCES

BARTHOLDY J., CHRISTIANSEN CH. & PEDERSON J.B.T. 2007. Comparing spatial grain-size trends inferred from textural parameters using percentile statistical parameters and those based on the log-hyperbolic method. Sediment. Geol., 202: 436–452.

BOYD M. 2007. Early Postglacial History of Southeastern Assioniboine Delta, Glacial Lake Agassiz. J. Paleolimn., 37: 313–329.

CAILLEUX A. 1942. Les actiones éoliennes périglaciaires en Europe. Mm. Soc. Géol. France, 41: 1–176.

EISSMANN L. 2002. Quaternary geology of eastern Germany (Saxony, Saxon–Anhalt, South Brandenburg, Thuringia), type area of the Elsterian and Saalian Stages in Europe. Quatern. Sci. Rev., 21: 1275–1346.

EYLES N., CLARK B.M. & CLAGUE J.J. 1987. Coarse-grained sediment gravity flow facies in a large supraglacial Lake. Sedimentology, 34: 193–216.

FOLK R.L. & WARD W.C. 1957. Brazos River bar, a study in the significance of grain size parameters. J. Sediment. Petrol., 27/1: 3–26.

FERNANDEZ L.P., AUGEDA J.A., CALMENDERO J.R., SALVADOR C.I. & BARBA P. 1988. A coal-bearing fan-delta complex in the Westphalian D of the Central Coal Basin, Cantabrian Mountains, northwestern Spain: implications for recognition of humid-type fan-delta: 286–302. In: Nemec W. and Steel R.J. (eds), Fan Deltas: Sedimentology and Tectonic Setting. Blackie, Glasgow.

GOMEZ B. & SMALL R.J. 1983. Genesis of englacial debris within the Lower Glacier de Tsidjiore Nouve, Valais, Switzerland, as revealed scanning electron microscope. Geografiska Annaler, 65A: 45–51.

GOMEZ B., DOWDESWELL J.A. & SHARP M. 1988. Microstructural control of quartz sand grain shape and texture: implication for discrimination of debris transport pathways through glaciers. Sediment. Geol., 57: 119–129.

GOŹDZIK J. 1980. Zastosowanie morfometrii i graniformametrii do badań osadów w kopalni węgla brunatnego Bełchatów. Studia Regionalne, IV (IX). PWN Warszawa-Łódź: 101–114.

GOŹDZIK J. 1995. Vistulian sediments in the Bełchatów open cast mine, central Poland. Quat. Stud. Pol., 13: 13–26.

HASHOLT B., KRÜGER J. & SKJERNAA L. 2008. Landscape and sediment processes in a proglacial valley, the Mittivakkat Glacier area, Southeast Greenland. Geogr. Tidsskr.-Dan. J. Geogr., 108(1): 97–110.

KASSE C. 1999. Late Pleniglacial and Late Glacial aeolian phases in The Netherlands. GeoArchaeo-Rhein, 3: 61–82.

KOROTAJ M. & MYCIELSKA-DOWGIAŁŁO E. 1982. Würmian periglacial processes in the Kolno Plateau in the light of sedimentological investigations with the use of scanning electron microscope. Biul. Perygl., 29: 53–76.

KOWALSKA A. & SROKA W. 2008. Sedimentary environment of the Nottinghambukta delta, SW Spitsbergen. Pol. Polar Res., 29(3): 245–259.

KOZARSKI S. 1978. Das Alter der Binnendünen in Mittelwestpolen: 291–305. In: H. Nagl (ed.), Beiträge zur Quartär- Und Landschaftsforschung (Festschrift J. Fink), Wien.

KRUMBEIN W.C. 1941. Measurement and geological significance of shape and roundness of sedimentary particles. J. Sediment. Petrol., 11: 64–72.

LIERMANN S., BEYLICH A.A. & van WELDEN A. 2012. Contemporary suspended sediment transfer and accumulation processes in the small proglacial Sćtrevatnet sub-catchment, Břdalen, western Norway. Geomorphology, 167–168: 91–101.

MAHANEY W.C. 2002. Atlas of sand grain surface textures and applications. Oxford University Press.

MYCIELSKA-DOWGIAŁŁO E. & LUDWIKOWSKA-KĘDZIA M. 2011. Alternative interpretations of grain-size data from Quaternary deposits. Geologos, 17(4): 189–203, doi: 10.2478/v10118-011-0010–9

MYCIELSKA-DOWGIAŁŁO E. & WORONKO B. 1998. Analiza obtoczenia i zmatowienia powierzchni ziarn kwarcowych frakcji piaszczystej i jej wartość interpretacyjna. Prz. Geol., 46: 1275–1281.

NEMEC W. & STEEL R.J. 1988. What is a fan delta and how do we recognize it?: 3–13, In: Nemec W. & Steel R.J. (eds), Fan Deltas: Sedimentology and Tectonic Settings. Blackie, Glasgow.

NICHOLS G. 2009. Sedimentology and Stratigraphy. Second edition. Wiley-Blackwell, Chichester.

OPREANU G., OAIE G. & PĂUN F. 2007. The Dynamic Significance of the Grain Size of Sediments Transported and Deposited by the Danube. Geo-Eco-Marina Coastal Zone Processes and Management. Environmental Legislation, 13: 111–119.

ORTON G.J. & READING H.G. 1993. Variability of deltic processes in terms of sediments supply, with particular emphasis on grain size. Sedimentology, 40: 475–512.

POCHOCKA-SZWARC K. 2003. Szczegółowa mapa geologiczna Polski w skali 1: 50 000 ark. Banie Mazurskie i Mażucie. Centr. Arch. Geol. Państw. Inst. Geol. Warszawa.

POCHOCKA-SZWARC K. 2005. Zagadka zaniku jeziora skaliskiego w Krainie Wielkich Jezior Mazurskich. Prz. Geol., 53(10): 873–878.

POCHOCKA-SZWARC K. 2009. Rekonstrukcja deglacjacji północnej części Krainy Wielkich Jezior Mazurskich u schyłku ostatniego zlodowacenia z wykorzystaniem wybranych metod teledetekcyjnych. PhD thesis: 1–127.

POCHOCKA-SZWARC K. 2010. Zapis glacilimnicznej sedymentacji w basenie Niecki Skaliskiej – północna część Pojezierza Mazurskiego. Prz. Geol., 58(10): 1014–1022.

POCHOCKA-SZWARC K. 2013. Some aspects of the last glaciation in the Mazury Lake District (northeastern Poland). Acta Palaeobot., 53(1): 3–8.

POCHOCKA-SZWARC K. & LISICKI S. 2001. Szczegółowa mapa geologiczna Polski w skali 1: 50 000, ark. Budry z objaśnieniami. Centr. Arch. Geol. Państw. Inst. Geol., Warszawa.

RACINOWSKI R., SZCZYPEK T. & WACH J. 2002. Prezentacja i interpretacja wyników badań uziarnienia osadów czwartorzędowych. Wydawnictwo Uniwersytetu Śląskiego, Katowice.

RODRIGUEZ A.B., HAMILTON M.D. & ANDERSON J.B. 2000. Facies and evolution of the modern Brazos Delta, Texas: wave versus flood influence. J. Sediment. Res., 70(2): 283–295.

RUSSELL A.J. 2007. Controls on the sedimentology of an ice-contact jökulhlaup-dominated delta, Kangerlussuaq, west Greenland. Sediment. Geol., 193: 131–148.

SCHIRMER W. 1999. Dune phases and soils In the European sand belt. In: Schirmer W. (ed.) Dunes and fossil soils. GeoArchaeoRhein, 3: 11–42.

SMOLSKA E. 2010. Cechy uziarnienia aluwiów rzek roztokowych a zapis litofacjalny. In: Kostrzewski A., Paluszkiewicz R. (eds), Geneza, litologia i stratygrafia utworów czwartorzędowych, 5: 517–533.

SRIVASTAVA A.K., INGLE P.S., LUNGE H.S. & KHARE N. 2012. Grain-size characteristics of deposits derived from different glacigenic environments of the Schirmacher Oasis, East Antarctica. Geologos 18(4): 251–266, doi: 10.2478/v10118-012-0014-0.

VISHER G.S. 1969. Grain size distribution and depositional processes. J. Sediment. Petrol., 39: 1074–1016.

WINSEMANN J., ASPRION U., MEYER T. & SCHRAMM CH. 2007. Facies characteristics of Middle Pleistocene (Saalian) ice-margin subaqueous fan and delta deposits, glacial Lake Leine, NW Germany. Sediment. Geol., 193: 105–129.

WORONKO B. 2001. Stopień eolizacji osadów czwartorzędowych na stanowisku Dębe k/Warszawy: 59–64. In: Mycielska–Dowgiałło E. (ed.), Eolizacja osadów czwartorzędowych jako wskaźnik stratygraficzny czwartorzędu. Pracownia Sedymentologiczna WGiSR UW, Warszawa.

WORONKO B. 2012. Micromorphology of quartz grains as a tool in the reconstruction of periglacial environment: 111–131. In: Churski P. (ed.), Contemporary Issues in Polish Geography, Bogucki Wydawnictwo Naukowe, Poznań.

WORONKO B. & HOCH M. 2011. The Development of Frost-weathering Microstructures on Sand-sized Quartz Grains: Examples from Poland and Mongolia. Permafrost and Periglacial Processes 22, Issus 3: 214–227. DOI: 10.1002/ppp.725.

WORONKO B. & OSTROWSKA M. 2009. Wpływ środowiska fluwialnego na charakter powierzchni ziarn kwarcowych – dyskusja. In: Kostrzewski A., Paluszkiewicz R. (ed.), Geneza, litologia i stratygrafia utworów czwartorzędowych, 5: 605–622.

WORONKO B., RYCHEL J., KARASIEWICZ M.T., BER A., KRZYWICKI T., MARKS L. & POCHOCKA-SZWARC K. 2013. Heavy and light minerals as a tool for reconstructing depositional environments: an example from the Jałówka site (northern Podlasie region, NE Poland). Geologos, 19(1): 47–66. doi: 10.2478/v10118-012-0019–8.

ZIELIŃSKI T. & BRODZIKOWSKI K. 1992. Cechy przykładowych sukcesji osadów glacilimnicznego subśrodowiska przyujściowego: 143–157. Materiały Letniej Szkoły Sedymentologicznej. Problemy sedymentacji glacilimnicznej. Zakład Geologii Instytutu Geografii Fizycznej i Kształtowania Środowiska Uniwersytetu Łódzkiego, Łódź.