

Miocene quartz sands redeposited on subaqueous and alluvial fans during the Saalian: Interpretation of the depositional scenario at Ujście, western Poland

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Abstract

The 14-m-thick sandy succession at Ujście in western Poland formed during the Odranian stadial of the Saalian glaciation, is exceptional in being very well sorted, almost mono-fractional (fine-grained sands) and mono-mineral (mainly quartz grains) and in lacking Scandinavian erratics. The lower sequence (5 metres in thickness) consists of three stacked packages of clinofolds (inclined cross-stratified sands) and is interpreted as having been deposited on a subaqueous fan in a shallow lake during two phases of rising water levels. The upper sand (9 metres in thickness) with (sub) horizontal stratification was redeposited on a subaerial alluvial fan. Distinctive distributary channels that occur in the uppermost part of the subaqueous fan and in the lowermost portion of the alluvial fan may indicate a change in sedimentation style from subaqueous to subaerial. Moreover, the subaerial position of the fan supports the presence of ice-wedge casts that developed under periglacial conditions in the upper part of alluvial fan. The results of granulometric analysis, rounding and frosting of grains and mineral analysis indicate that the sands are derived from Gorzów Formation of Early Miocene age. The only feasible explanation is that the 14-m-thick unit must have been redeposited during the Saalian glaciation.

Key words: proglacial lake, distributary channels, sandy clinofolds, Odranian stadial

1. Introduction

Shape and size of depositional bodies such as alluvial fans, subaqueous fans or deltas accumulated in the lacustrine environment depend on the morphology of the basin, changes of base level, the amount and size of grains supplied to the basin by rivers, the depth of the lake or basin, stream power, climatic conditions and more (compare Boothroyd & Nummedal, 1978; Nilsen, 1985; Rachocki & Church, 1990; Orton & Reading, 1993; Blair & McPherson, 1994; Miall, 1996; Blair, 1999; Harvey et al., 1999; Salamon & Wójcik, 2010; Zieliński, 2014; Zieliński et al., 2016). The majority of Pleistocene lacustrine subaqueous fans and deltas have been described from proglacial environments

(e.g., Kostaschuk & Smith, 1983; Billi et al., 1991; Lunkka & Alhonen, 1996; Lemons & Chan, 1999; Bennett et al., 2000; Gruszka et al., 2004; Lønne & Nemeč, 2004; Hornung et al., 2007; Winsemann et al., 2007; Clemmensen & Houmark-Nielsen, 2008; Winsemann et al., 2009; Ravier et al., 2014; Woźniak & Pisarska-Jamroży, 2018; Woźniak et al., 2018). Such environments explain the coarse-grained or generally polymodal textural features of sediments. In this context, the origin of the present near-unimodal, fine-grained sediment deposited during the Saalian glaciation appears exceptional. The succession studied at Ujście comprises 14 metres of well-sorted, unimodal, fine-grained quartz sands, enriched only locally in fine-grained gravels and armoured mud balls.

The aim of the present paper is fourfold: first, to describe textural and structural features of the sandy succession at Ujście; secondly, to explain sediment genesis in this 14-m-thick succession; thirdly, to identify depositional conditions during erosion of Miocene-aged strata and subsequent transport and redeposition, and lastly, to illustrate features which allow to distinguish between subaqueous and subaerial fans.

2. Geological setting

The Ujście site (co-ordinates 53°02'40"N, 16°41'41"E) is located along the southern margin of the Ujście Basin (= Piła-Ujście Basin; Galon, 1961) near the mouth of the River Gwda towards the Toruń-Eberswalde ice-marginal valley in northwestern Poland

(Fig. 1). This ice-marginal valley drained meltwater from proglacial streams and water from extraglacial areas during the maximum extent of the Pomeranian phase (16–17 ka BP; Marks, 2012; Pisarska-Jamroży, 2015) and the Angermünde-Chojna subphase (14.7±1 ka BP; Lüthgens et al., 2011). These waters eroded the southern margin of the Toruń-Eberswalde ice-marginal valley, where strata of Saalian to Weichselian age are excavated (MIS 8–MIS 2; Pisarska-Jamroży et al., 2019a). Today, the Ujście Basin and adjacent river valleys are occupied by Holocene peat areas and fluvial strata (Fig. 1). Locally, within eroded slopes of the ice-marginal valley, strata of Miocene age that directly underlie those formed during Pleistocene glaciations, are exposed (Bartczak, 2006).

The Ujście site has featured in numerous publications that have dealt mainly with lithostratigraphy (Kasprzak & Kozarski, 1985; Kozarski &

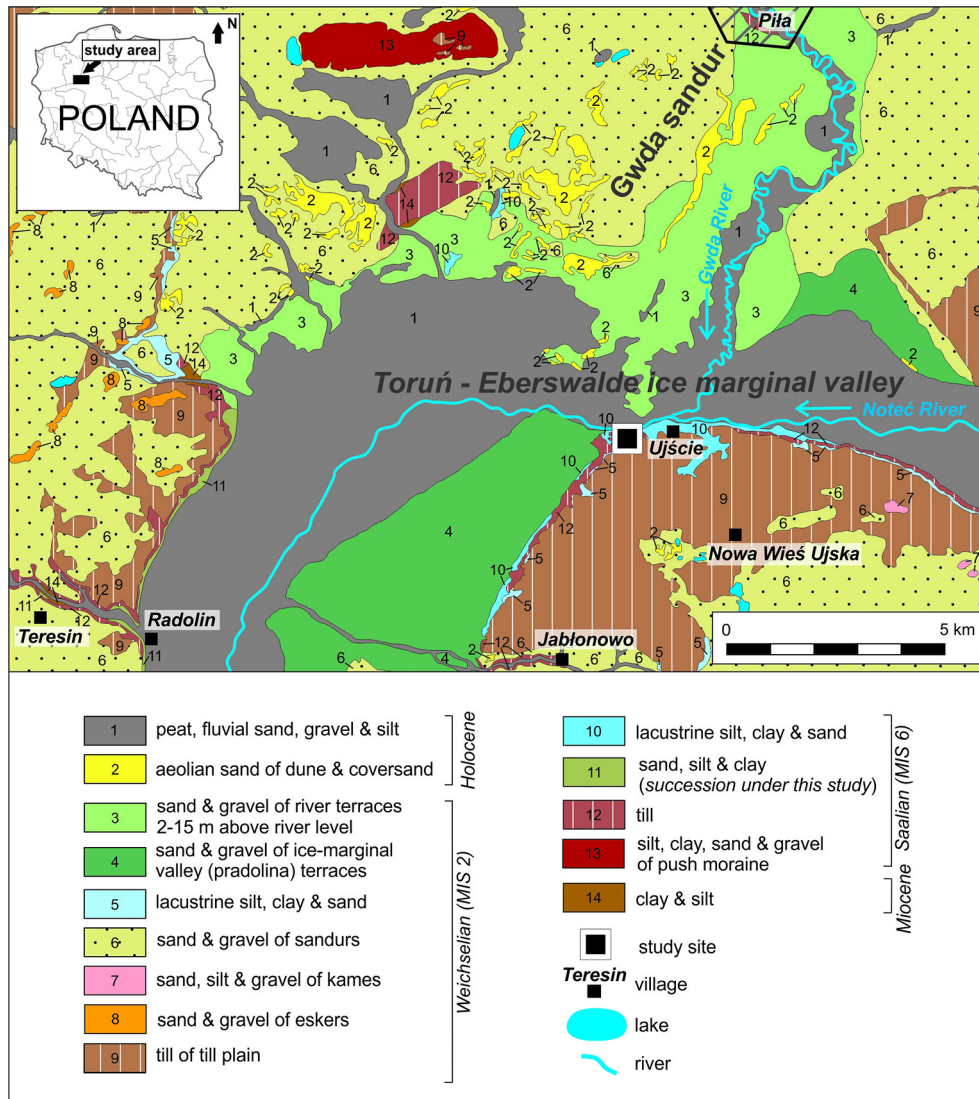


Fig. 1. The study site at Ujście and its geological setting (modified from Bartczak, 2006)

Nowaczyk, 1985; Kozarski & Kasprzak, 1987; Böse & Górska, 1995; Petterson, 1997; Kenig, 2004; Pisarska-Jamroży et al., 2019a), but the origin of the sandy succession in the lowermost part of the 35-m-thick succession at Ujście has never been firmly established. However, Bartczak (2006) did mention that this sandy succession (fine-grained sands and silty sands with intercalations of vary-grained sands and fines of silty- and clayey-fraction) had a 'glaciolacustrine/glaciofluvial origin' and that the sands passed upwards into silty sediments in the vicinity of Radolin and Teresin and into silty/clayey strata near Nowa Wieś Ujska and Jabłonowo (Fig. 1).

Nowadays, the quartz grains (>90%) with inclusions of biotite, muscovite, rutile and zircon (see Bartczak, 2006), commonly referred to as 'glass sands', are used by the glass production firm Ardagh Glass S.A. for green beer bottles, e.g. Budweiser, Heineken and Carlsberg.

3. Methods

Textural and structural features of strata were described using a lithofacies code (Table 1) following Zieliński and Pisarska-Jamroży (2012) and, for the

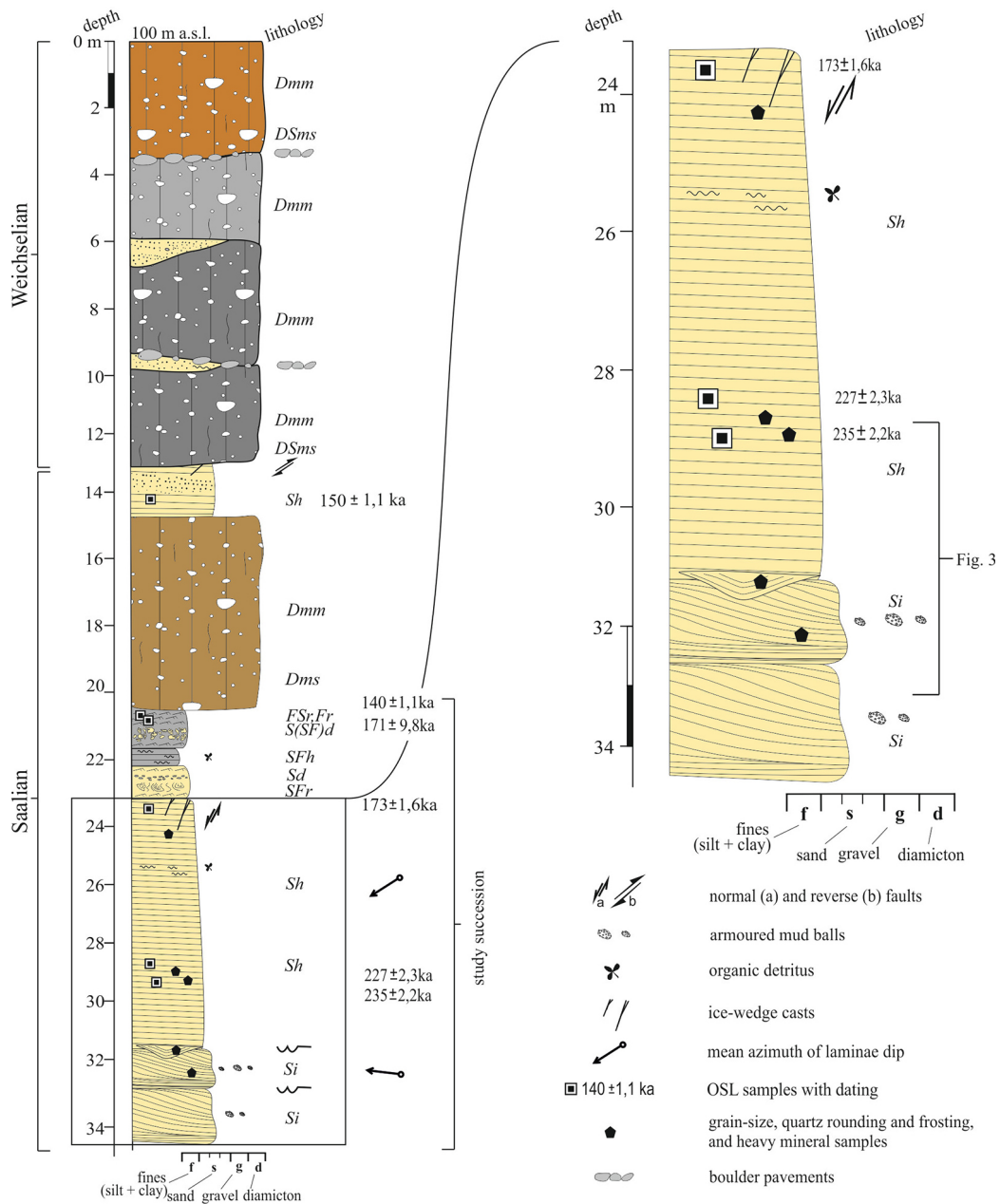


Fig. 2. Sedimentary log for the Ujście site (based on Mleczak et al., 2017). For details see Table 1

Table 1. Textural and structural symbols of lithofacies code used in the present study

Lithofacies	Main features of lithofacies	Interpretation	textural symbols
Si	fine sand low angle (12–17°) sigmoidal cross-stratified	low-angle progradation front of delta	<i>D</i> diamicton <i>S</i> sand <i>SF</i> sand with fines <i>FS</i> sandy fines <i>F</i> fines (silt + clay)
Sh	very fine and fine sand sub-horizontal stratified sheet-like layers	subaqueous, sandy, very shallow sheet-flow	structural symbols <i>m</i> massive structure <i>h</i> horizontal lamination <i>r</i> ripple cross-lamination <i>i</i> inclined stratification <i>d</i> deformed structure <i>e</i> erosional scour fill
Se	fine sand massive or cross-stratified erosional base	erosional scour fill	structural symbols for diamictons <i>mm</i> matrix-supported, massive <i>ms</i> matrix-supported, stratified
SFr, FSr, Fr	very fine sand and fines sheet-like layers	weak currents in nearly stagnant water	
Sd	two horizons of deformed sediment load casts pseudonodules and flame structures	deformation by liquefaction	
S(SF)d	two breccia layers numerous soft-sediment clasts	mudflow	
SFh	very fine sand sheet-like layers	suspension fallout	
Dmm/ Dms	massive diamicton, lower part stratified matrix-supported numerous faults, drag folds and cleavage in lower part extended clasts of unconsolidated sediments	glacial deposits	

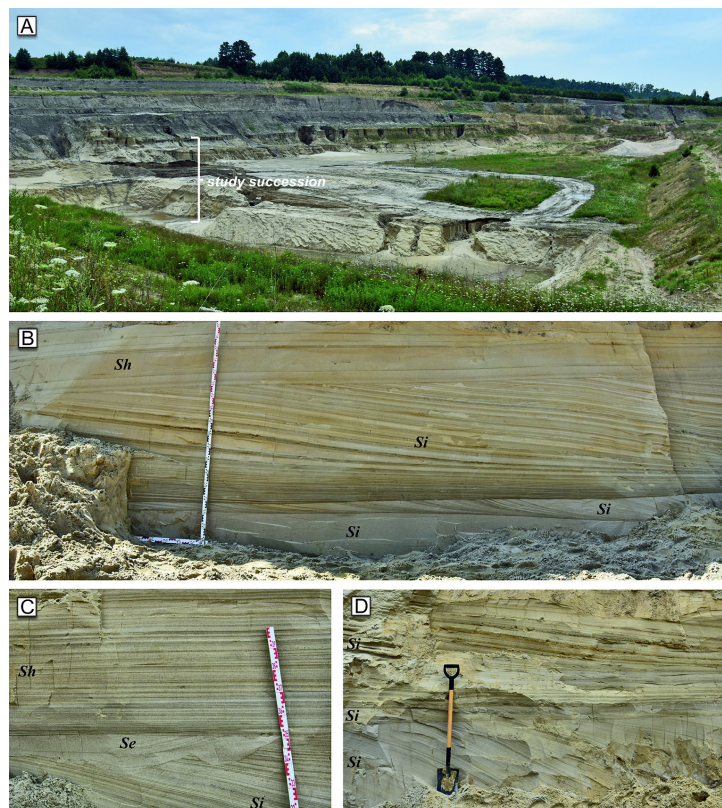


Fig. 3. Sedimentary succession at Ujście: **A** – Vertical and lateral continuity of sediments; **B** – Three clinoforms of subaqueous fans (lithofacies *Si*) and lower part of the alluvial fan (lithofacies *Sh*); **C** – Distributary channels (lithofacies *Se*) occurring in the uppermost set of lithofacies *Si*; **D** – More distal part of three clinoforms of subaqueous fans (presented in photograph C)

diamictons, following Krüger and Kjær (1999). The term 'fines' used in the present paper, refers to clay and silt together. Grain size indication follows the Udden-Wentworth scale (Udden, 1914; Wentworth, 1922), while grain size parameters such as median grain size, sorting and skewness, were calculated using the Folk and Ward method (Folk & Ward, 1957). The results obtained from grain size analyses are presented in a Passega C-M diagram, where the values of the first percentile (C) are plotted against the median grain diameter (M).

Nineteen samples for grain size and five samples for quartz grain rounding and frosting (following Cailleux, 1942; Mycielska-Dowgiałło & Woronko, 1998; Woronko et al., 2015) and heavy mineral composition (following Marcinkowski & Mycielska-Dowgiałło, 2013) were analysed. The samples were taken from the entire extent of the outcrop.

Furthermore, five samples were dated by optically stimulated luminescence (OSL) – two from the lower and three from the upper part of sandy

succession analysed (Fig. 2). The OSL measurements were performed at the GADAM Gliwice Luminescence Laboratory using the standard multi-grain aliquots method. Equivalent doses of samples were determined using the single-aliquot regenerative-dose (SAR) protocol (e.g., Thrasher et al., 2009).

4. Sedimentary succession

At Ujście, the 14-m-thick sandy sequence forms the lower portion of a 35-m-thick sedimentary succession (Figs 2, 3A). The uppermost part of the Saalian and Weichselian-aged sediments have previously been described and interpreted in detail (see references below), but the subject of the present study is the lowermost sandy succession, which comprises three lithofacies: *Si* – sands with inclined stratification, *Sh* – horizontally stratified sands and *Se* – sands with scour fills (Figs 2, 3B–D, 4A).

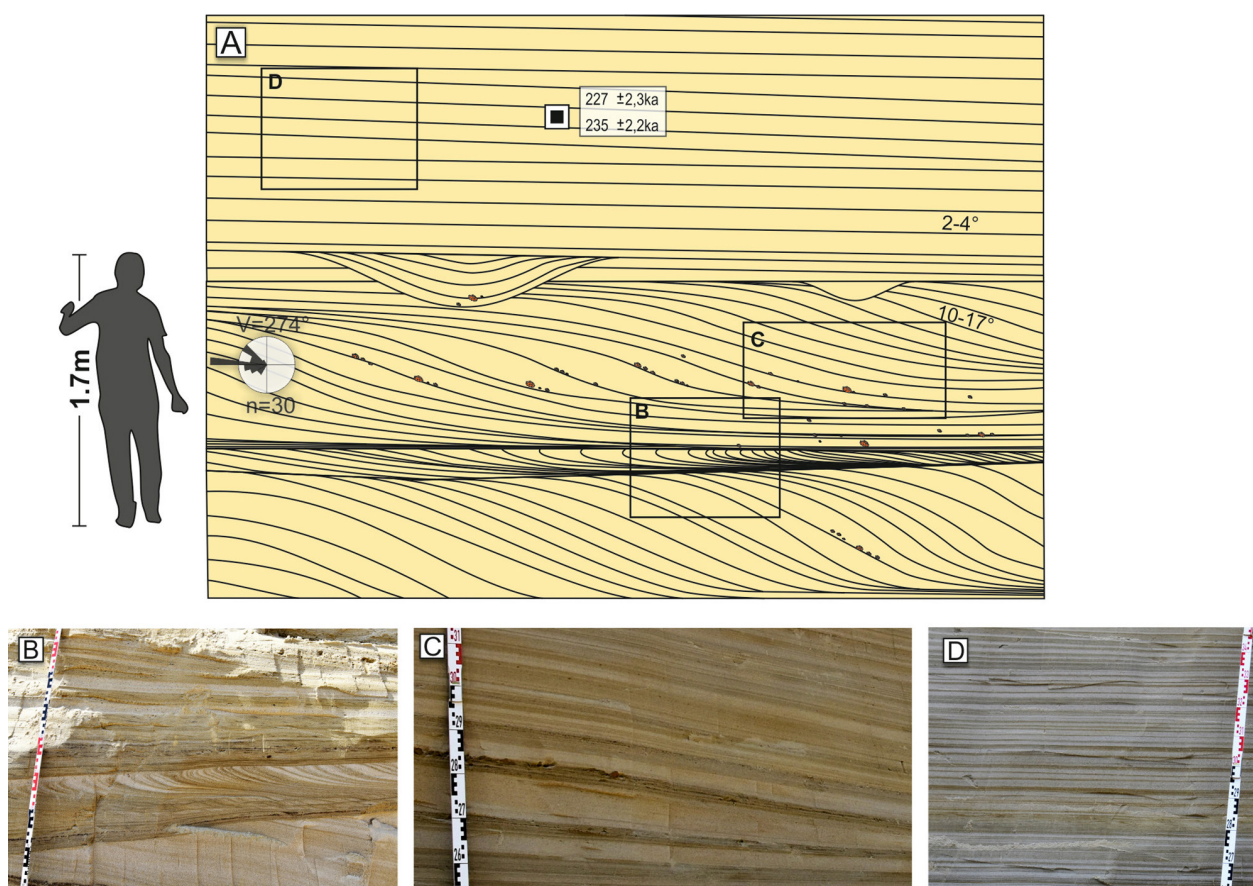


Fig. 4. Sandy sediments occurring in the lowermost part at Ujście: **A** – Schematic vertical and lateral distribution of sediments in the sandy succession; **B** – Middle sandy set with inclined tangential stratification and bent beds in the upper part (see centre of photograph); **C** – Upper set of sands with inclined sigmoidal stratification; **D** – (Sub)horizontally-stratified sands of alluvial fan. For details see Table 1

4.1. Description

4.1.1. Textural features of lithofacies

The three lithofacies distinguished here are characterised by almost identical textural features (Fig. 5): grain size distribution indicates well-sorted, mainly fine-grained, sandy sediment, with identical heavy mineral spectra. Grains have mainly mat surfaces and are rounded. However, subtle differences are described below.

Lithofacies *Si* comprises between 95 and 100% well-sorted, fine-grained sand. Individual beds of this lithofacies are delineated by colour (Figs 4C, 5). The lighter beds consist of mostly fine (53–65%) and medium sand (32–42%), with an admixture of very fine sand and fines (1–2%), as well as coarse sand (up to 1%). Statistical parameters of grain size distribution in the lighter-coloured beds are as follows: mean grain size 0.189 mm, moderately well sorted (0.508) and very coarse skewed (−0.473). In contrast, the darker-coloured beds contain mainly fine (60–61%), very fine (12–25%) and medium sand (7–16%), with an admixture of fines (2.5–5.5%) and coarse sand (1.5–9%). These beds are characterised by a mean grain size of 0.152 mm, moderately good sorting (0.677) and are fine to very coarse skewed (from 0.165 to −0.373). The Passega diagram shows that grains from the lighter-coloured beds are grouped in section Q, while those from the darker-coloured beds are distributed over two sections, Q and P (see Fig. 6).

In its lower portion, lithofacies *Sh* consists of 97–100% of sand, mainly fine and very fine grained (64–84%), with an admixture of medium-grained

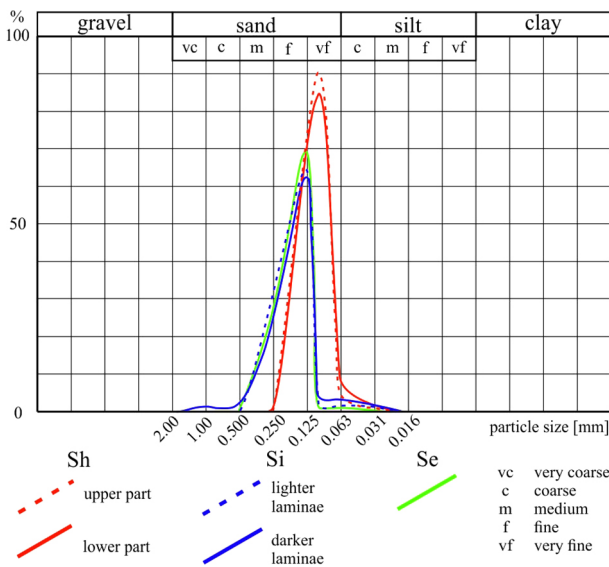


Fig. 5. Mean grain size composition of sandy lithofacies *Sh*, *Si* and *Se* at Ujście

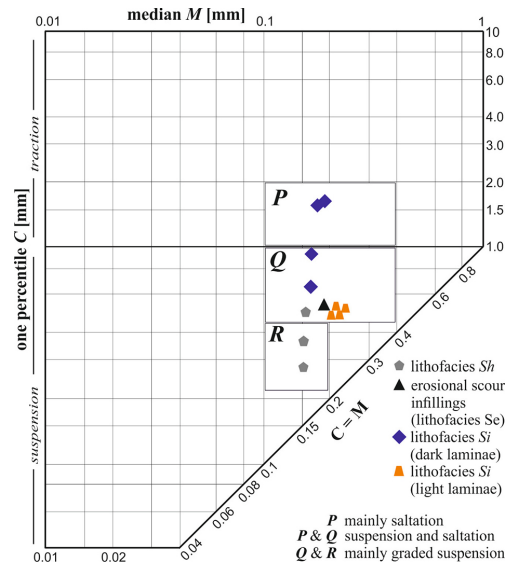


Fig. 6. Types of grain transport in sandy lithofacies at Ujście according to the Passega diagram (based on Passega, 1964; Zieliński, 2014)

sand (14–32%) and silt (up to 3%). These deposits is characterised by a mean grain size of 0.135 mm, moderately good sorting (0.528) and a symmetrical skewness (−0.06). The upper part of lithofacies *Sh* contains 98–99% fine and very fine sand and a small amount of silt (1–2%). Statistical parameters of grain size distribution in this part are as follows: mean grain size of 0.132 mm, very good sorting (0.322) and a fine skewness (0.163). The grains are distributed over two sections, R and Q, in the Passega diagram (Fig. 6).

Lithofacies *Se* comprises 99–100% sand, mainly fine grained (about 70%), with an admixture of medium-grained sand (about 28%) and very fine

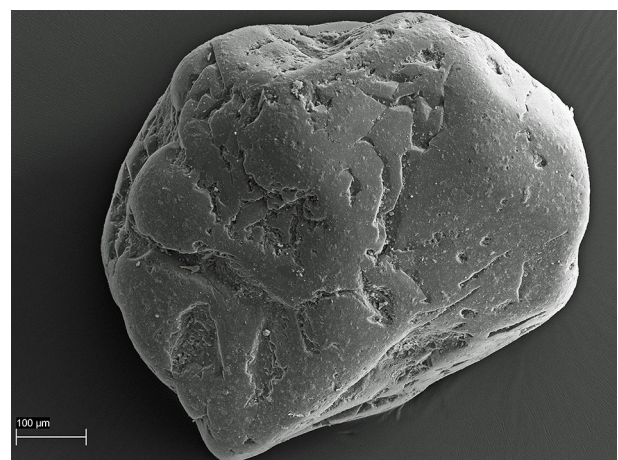


Fig. 7. SEM micrograph of the surface of a sand-sized quartz grain (from lithofacies *Sh* at Ujście) derived from a beach environment

sand and fines (up to 4%). Statistical parameters of grain size distribution within this lithofacies are as follows: mean grain size of 0.183 mm, good sorting (0.492) and a very coarse skewness (-0.523). The grains of lithofacies *Se* occur in section Q of the Passega diagram (Fig. 6).

The majority of sand-sized quartz grains in lithofacies *Si* and *Sh* are mat (83% and 61–77%, respectively; see Fig. 7). In lithofacies *Si*, quartz grains are mainly moderately subrounded and moderately angular (35% and 31%, respectively) and rounded (25%), while in lithofacies *Sh* the majority are moderately angular (33%) and moderately subrounded (27%) and rounded (26%).

Heavy mineral spectra in the sandy succession indicate a predominance of epidote (19%), tourmaline (17%), garnets (13%), staurolite (10%), amphibole (9.5%) and kyanite (5%).

4.1.2. Structural features of lithofacies

Lithofacies *Si* has three sets: lower, middle and upper (Figs 3D, 4A, B). The lower one is at least 1 m thick; the lower was not reached in the excavation. The middle set has a maximum thickness of 0.7 m, which decreases northwards (Fig. 3D). The upper *Si* set is up to 1.6 m thick (Fig. 4B). Boundaries between sets are well marked and erosional (Fig. 4A, B). The laminae of all sets have a sigmoidal shape and dip between 14 and 27° westwards in the lower sets and between 10 and 17° westwards in the upper. However, the angle of inclination decreases in the lower and

upper parts of sets (Fig. 8A). A tangential shape of laminae occurs only locally in the middle set where they are deformed; see Figure 4B that shows laminae bending in the upper part of the set. Furthermore, numerous mud balls, 1 to 7 cm in diameter, armoured by sand and fine gravel grains (Figs 4A, 8C) are clustered mainly in the lower, less-inclined part of sets. Organic detritus occurs also in some beds.

Lithofacies *Sh* is 9 metres thick (Figs 2, 4A, D). The lower and upper boundaries are well marked. However, the lower is erosional, the upper depositional. The parallel-stratified sands are inclined under a small angle (2–4°) towards the south, southwest and west, and are referred to as (sub) horizontally stratified. In the upper part of lithofacies *Sh* occur ice-wedge casts which reach up to 1.2 m in height (Fig. 8B). The width of these casts increases from a few millimetres at the base to 15–20 cm in the uppermost part (Fig. 8B). Close to the ice-wedge casts, in the upper part of the succession, normal faults, offsets and flexures of several centimetres occur (Fig. 8B). Furthermore, organic detritus is visible in the top part of the sands.

The trough cross-stratified lithofacies *Se* is cut in the upper part of lithofacies *Si* and in the lower part of lithofacies *Sh* (Figs 3C and 4A). The lower and upper boundaries of troughs are sharp and erosional. The internal structure of troughs is massive or cross stratified. Furthermore, armoured mud balls (up to 12 cm in diameter; Fig. 8D) were also observed within lithofacies *Se*.

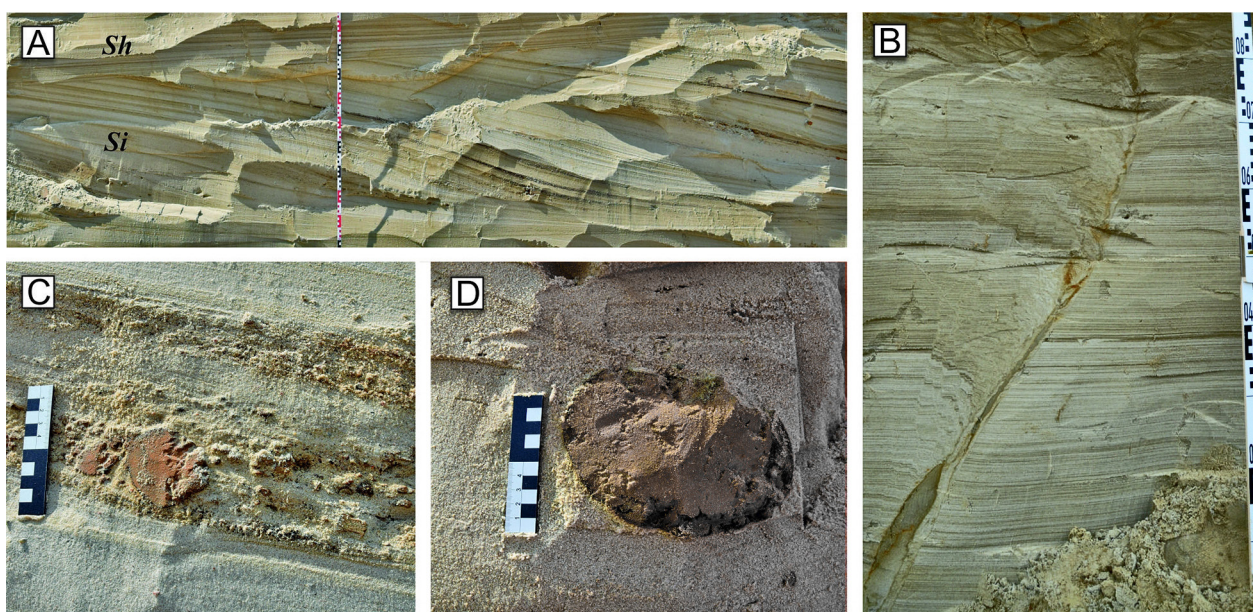


Fig. 8. Some structures within the sandy succession at Ujście: **A** – Sigmoidal-shaped beds in upper lithofacies *Si*, in the upper part of the photograph – lithofacies *Sh* of alluvial fan; **B** – Ice-wedge cast in upper part of alluvial fan (lithofacies *Sh*) with accompanying small-scale faults and flexures; **C** – Armoured mud balls in the upper set of lithofacies *Si*; **D** – The largest armoured mud balls in the massive infill of a distributary channel (lithofacies *Se*)

4.2. Interpretation

The sands in three clinoform lithofacies were deposited under similar, yet slightly changing depositional conditions (for details, see below). The grains in the lighter-coloured laminae of lithofacies *Si* were transported by graded suspension, those in the darker-coloured laminae by a combination of saltation and graded suspension. This may indicate a cyclic change in flow dynamics. Grains in lithofacies *Sh* were deposited mostly from graded suspension. The good sorting of sandy sediments in the entire succession and mat surface of grains may suggest beach reworking (see Fig. 7). The heavy mineral spectra show the same source of sediments by evidence of resistant heavy minerals, such as epidote, tourmaline, garnets and staurolite that are similar to a known source.

The sets of lithofacies *Si* represent three clinoform bodies laid down as a subaqueous lacustrine fan. The sigmoidal shape of the lamination of lithofacies *Si* is similar to the foreset subfacies of a delta. However, delta forms can only be identified if at least two (of three) parts of delta (i.e., bottomset, foreset and topset) occur. Moreover, the low angle of inclination of the depositional slope (10–17°) in the upper set, in comparison with the grain size of sediment (Kirkby, 1987; Zieliński, 2014) and types of grain transport, does not allow interpretation of the clinoforms as a typical delta foresets. For sandy foresets of a typical delta the dip angle should reach 20–30° (compare Kirkby, 1987; Zieliński, 2014), whereas in the succession studied this angle is 10–17°, and only occasionally exceeds 20°. Grain size

analyses show that the sediments were distributed over subaqueous slopes by suspension and traction currents. This type of transport probably is a record of low-density turbidite currents that formed at river mouths by significant supply of fine-grained sediments. Increased flow energy on the fan slope caused an increase in proportion of suspension over bedload transport (Reineck & Singh, 1980), which resulted in long-distance deposition recorded in the low-angle dip of laminae and the tangential shape of clinoforms.

The sets of *Si* clinoforms should not be treated as a bars of rivers because they do not meet the following criteria: (1) point-bar lithofacies should show a fining-up granulometry with muddy or even peat lithofacies of floodplain deposits at the top (e.g. Toonen et al., 2012; Moskalewicz et al., 2016), (2) point-bar *Si* lithofacies should pass into trough cross-stratified lithofacies of dunes or megaripples, deposited on the slope of a point bar or in the thalweg zone (e.g., Allen, 1964; Singh, 1977; Zieliński, 1998; Zieliński, 2014; Moskalewicz et al., 2016), (3) point-bar succession usually begins with channel-lag sheets or coarse-grained bedforms developed in the deepest part of a channel (e.g., McGowen & Garner, 1970; Zieliński, 2014; Moskalewicz et al., 2016), (4) on point bars should occur ripple- or climbing ripple cross-laminated lithofacies with an orientation that is opposite to that of the direction of dip of the *Si* lithofacies (e.g., Zieliński, 2014; Sokołowski et al., 2019), (5) transverse bars with inclined foresets often formed in braided rivers usually coexist with trough cross-stratified lithofacies derived from megaripples (e.g., Ziel-

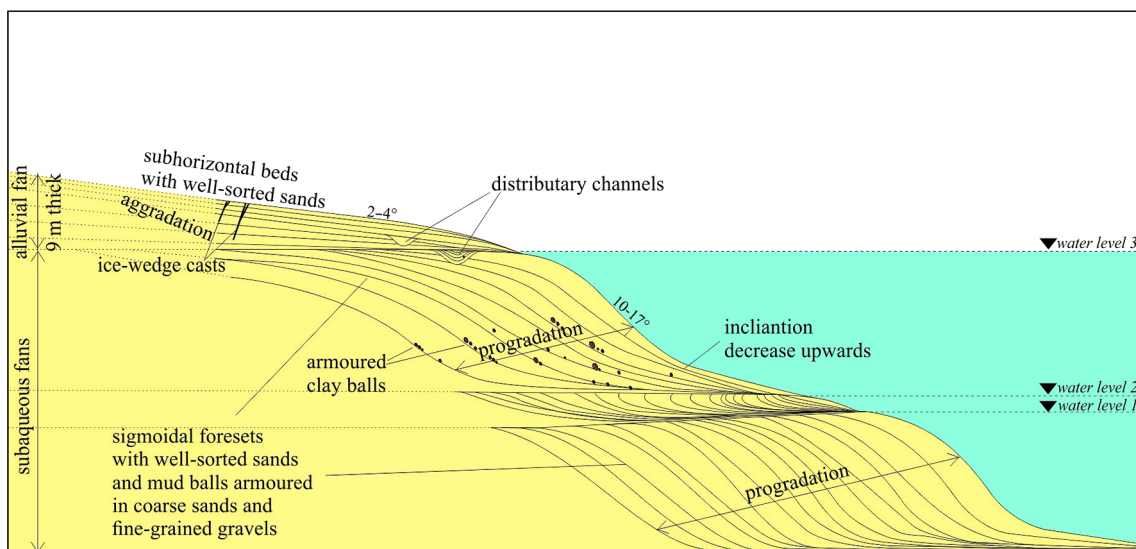


Fig. 9. Model and definition of subaqueous and alluvial fans of Miocene-aged sands at Ujście during the Odranian stadial of the Saalian glaciation

iński, 1993; Pisarska-Jamroży, 2015), (6) at the top of transverse bars, ripple- or trough cross-stratified deposits of small bedforms (ripples or small-scale megaripples) migrating on the top of bars occur (e.g., Zieliński, 2014), (7) compound transverse bars characterised by several overlapping *Si* sets require the co-existence of trough cross-stratified lithofacies (Sambrook Smith et al., 2006).

The sigmoidal shape of the clinofolds also indicates that progradation and aggradation processes were slow. The occurrence of three clinofold sets, separated by sharp and erosional surfaces, is linked to changes in the water level of the lake. The clinofolds were deposited on the low-angle slope of the sandy subaqueous fan in a quite shallow lake (Fig. 9). Afterwards, the thick (sub)horizontally-stratified lithofacies *Sh* – deposited by sheetfloods – formed. Lithofacies *Sh* is characterised by the same grain size as the underlying lithofacies *Si*, which may indicate the same sediment source. However, the depositional conditions had slightly changed. The thickness of 9 metres of these (sub)horizontal sands and their uniform granulometric composition indicate a period of stable depositional conditions. The thick lithofacies *Sh* probably is a record of river sheetfloods in the distal part of an alluvial fan.

We speculate that three clinofolds (i.e., bodies with clinofold structure) of fans were deposited subaqueously, and the water level of the lake suddenly rose at least twice (up to water level 2 and 3 in Fig. 9), which was probably caused by lake outflow damming by e.g. blocks of ice. The lake was relatively shallow (up to a few metres in depth) and not extensive. The single distributary channels occurred only in the transition zone between uppermost subaqueous fan (upper set of lithofacies *Si*) and the lower part of the alluvial fan (lithofacies *Sh*), which likely indicates that this part was at least partially emerged and eroded by streams.

On the exposed part of the fan, ice-wedge casts evolved. They were formed in a thermal-contraction crack, and infilled by massive silty clay, probably from the overlying active layer. Afterwards the crack was rejuvenated and grew upwards in response to aggradation of the alluvial fan. The general narrowness of the wedge indicates that the sedimentation rate was relatively high (see French, 2017). The presence of ice-wedge casts that directly cut the upper part of the 9-m-thick alluvial fan suggests that the study area was subjected to periglacial processes. The small-scale faulting and flexures close to the ice-wedge casts formed as a result of consolidation and/or dewatering of previously water-laid sediments (see Pisarska-Jamroży et al., 2019b).

5. Discussion

Both lithostratigraphy and OSL ages suggest that the 14-m-thick sandy succession at Ujście was deposited during the Saalian glaciation. However, the mono-mineral, fine-grained spectrum of sandy sediments and their good sorting suggest an atypical source of sediments during glaciation.

5.1. Possible sources of sandy sediments

There are two possible sources of the sandy deposits at Ujście: glaciofluvial strata of Saalian age or eroded and redeposited older strata.

A characteristic feature of Pleistocene glacial deposits across Europe is the significant contribution of Scandinavian erratic rocks (e.g., Czubla et al., 2006; Górska-Zabielska, 2008; Czubla, 2015). In addition, sediments with high textural and architectural variability, resulting from unstable conditions of transport and deposition, are observed (e.g., Pisarska-Jamroży, 2006, 2008; Pisarska-Jamroży & Zieliński, 2014). In contrast, in the case of Ujście, the 14-m-thick sandy succession is characterised by very well-sorted, mono-mineral, fine-grained sediment without Scandinavian erratic boulders and cobbles.

Very good sorting and the mono-mineral character of sediments are features that typically occur in Miocene-aged deposits that have previously been documented from the research area (Piwocki & Ziemińska-Tworzydło, 1997; Bartczak, 2006). In the Ujście area, quartz sands of four Miocene formations are known: the Lower Miocene Gorzów Formation and the Middle Miocene Krajeńska, Adamów and Pawłowice formations (see Bartczak, 2006). These units comprise mostly grey, fine-grained quartz sands with intercalations of brown fines (Bartczak, 2006) and have almost the same grain size distribution as sands at Ujście (e.g., fine-grained sands account for 75–95% in the Gorzów Formation; see Fig. 10). Moreover, the heavy mineral spectra of the sandy succession at Ujście and in the Gorzów Formation are similar (see Romanek, 2010; Fig. 10). Quartz sands of Miocene age have also been described from Mecklenburg-Vorpommern in northeast Germany as the Mölliner Schichten (formerly Quarzsand Gruppe or Quarzsand Horizont; see Piwocki & Ziemińska-Tworzydło, 1997; Bartholomäus & Granitzki, 2004; Schwietzer & Niedermeyer, 2005). These are characterised by light grey-coloured fine-grained sands that contain 93–95% of quartz grains (Zwahr, 2001).

The Miocene sands were deposited in a limno-fluvial environment on widely distributed allu-

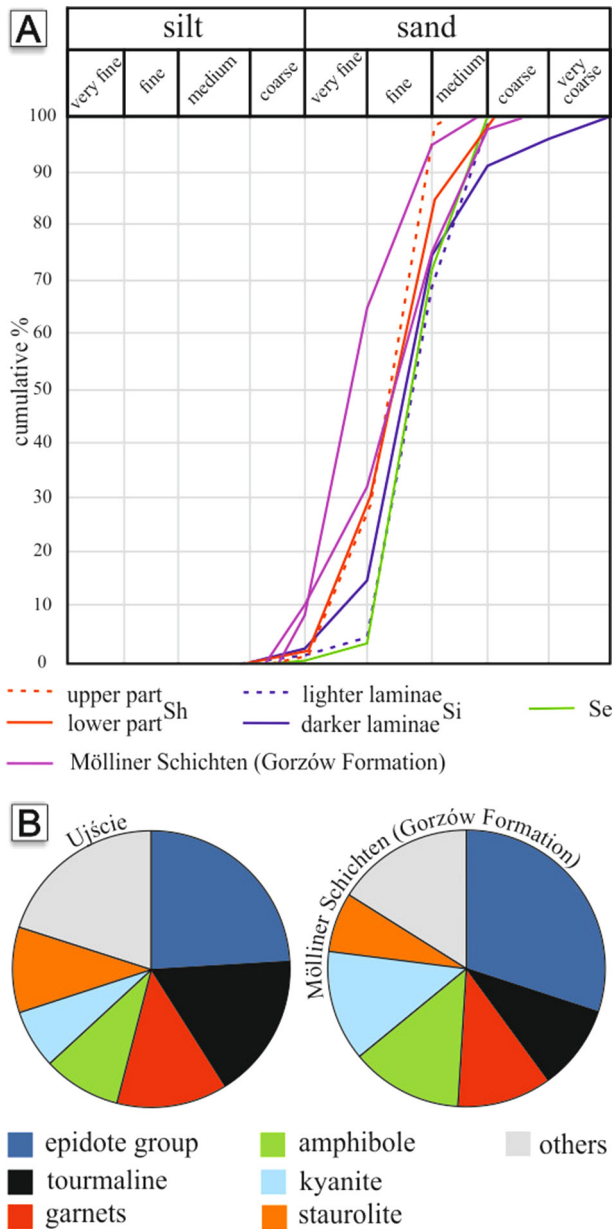


Fig. 10. Comparison of textural and mineralogical features of sandy sediments at Ujście and strata assigned to the Gorzów Formation (based on Schwietzer & Niedermeyer, 2005; Romanek, 2010): **A** - Grain-size composition; **B** - Heavy mineral spectra

vial plains that came into being following the marine regression (Piwocki, 1978; Ciuk & Pożaryska, 1982). The sediments were originally deposited as alluvial fans and deltas, most probably in a brackish environment. Such sediments were probably transported to the fluvial system and laid down on Miocene alluvial fans and deltas. Features of quartz grains from sandy sediments at Ujście seem to confirm this interpretation.

The Miocene formations in the vicinity of Ujście reach up to 51 m a.s.l. (Bartczak, 2006), whereas

the sandy succession at Ujście analysed attains 77 m a.s.l. (Fig. 2), so we speculate, that Miocene sediments were eroded *en block* and transported as a raft by the Saalian ice-sheet. Afterwards, these sediments were washed out and redeposited by meltwaters on a subaqueous fan in a relatively shallow lake and on a subaerial fan.

5.2. Timespan of deposition of the sandy succession

The results of OSL dating for the lower part of the succession analysed indicate 227 ± 2.2 and 235 ± 2.2 ka BP (GdTL-2679 and GdTL-2680, respectively), i.e., the sandy succession studied must have formed prior to the Odranian stadial of the Saalian glaciation (MIS 8; 210–180 ka; see Marks et al., 2016). However, the upper part of the succession is dated as 173 ± 1.6 BP (GdTL-2681), which may suggest deposition between the Odranian and Warthanian stadials, that is, during the Lublinian interglacial (MIS 7). However, the palynological content comprises *Pinus*, *Corylus*, *Alnus* and *Ulmus* and Miocene-aged *Liquidambar*, *Nyssa* and *Ostrya* (Woźniak, 2001, unpubl.). Taken together, these data suggest that the entire succession studied was laid down during the Odranian stadial of the Saalian glaciation.

6. Conclusions

The following conclusions can be drawn from this study:

1. The 14-m-thick sandy succession at Ujście consists of almost unimodal, fine-grained sandy deposits that formed during the Odranian stadial of the Saalian glaciation (MIS 8),
2. The very good sorting of sediment and lack of Scandinavian erratic rocks within the sandy succession at Ujście are indicative of their Miocene age. The sand grains derived from the Lower Miocene Gorzów Formation (widely distributed in the vicinity of Ujście), which is characterised by a similar grain size composition and heavy mineral spectra,
3. The lower part of the sandy succession (lithofacies Si) was deposited probably on subaqueous fans. A sequence of three stacked clinothems is separated by angular discordances and record two pulses of water level rise. The water rose in a relatively shallow proglacial lake, which was caused probably by lake outflow damming. Subsequently, the 9-m-thick alluvial fan was deposited. The presence of a few distributary channels

in the uppermost part of the subaqueous fan and in the lower part of the subaerial fan may indicate that depositional bodies formed during the final phase of lake development. Moreover, the upper part of the alluvial fan was subjected to periglacial processes, as indicated by the presence of ice-wedge casts.

Acknowledgments

We thank Leszek Grochal, Janusz Hegyi and Paulina Frankiewicz (Ardagh Glass S.A., Ujście) for their kindness and permission to conduct geological investigations, Piotr Paweł Woźniak for discussion and Szymon Belzyt and Małgorzata Roman for field assistance. Basia Woronko took a SEM photograph of grains. Suggestions by anonymous reviewers and by Tomasz Zieliński have greatly helped to improve the manuscript, for which we are most grateful. This study has been financially supported by grants No. 2015/19/B/ST10/00661 and No. 2017/25/N/ST10/00322 from the National Science Centre Poland.

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Manuscript received: 18 April 2019

Revision accepted: 10 July 2019