

# Climate evolution during the Pleniglacial and Late Glacial as recorded in quartz grain morphoscopy of fluvial to aeolian successions of the European Sand Belt

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## Abstract

We present results of research into fluvial to aeolian successions at four sites in the foreland of the Last Glacial Maximum, i.e., the central part of the “European Sand Belt”. These sites include dune fields on higher-lying river terraces and alluvial fans. Sediments were subjected to detailed lithofacies analyses and sampling for morphoscopic assessment of quartz grains. Based on these results, three units were identified in the sedimentary succession: fluvial, fluvio-aeolian and aeolian. Material with traces of aeolian origin predominate in these sediments and this enabled conclusions on the activity of aeolian processes during the Pleniglacial and Late Glacial, and the source of sediment supply to be drawn. Aeolian processes played a major role in the deposition of the lower portions of the fluvial and fluvio-aeolian units. Aeolian material in the fluvial unit stems from aeolian accumulation of fluvial sediments within the valley as well as particles transported by wind from beyond the valley. The fluvio-aeolian unit is composed mainly of fluvial sediments that were subject to multiple redeposition, and long-term, intensive processing in an aeolian environment. In spite of the asynchronous onset of deposition of the fluvio-aeolian unit, it is characterised by the greatest homogeneity of structural and textural characteristics. Although the aeolian unit was laid down simultaneously, it is typified by the widest range of variation in quartz morphoscopic traits. It reflects local factors, mainly the origin of the source material, rather than climate. The duration of dune-formation processes was too short to be reflected in the morphoscopy of quartz grains.

**Keywords:** fluvial to aeolian succession, aeolization of quartz sand grains, periglacial conditions, extraglacial zone

## 1. Introduction

The Late Pleniglacial and Late Glacial were periods of intensive climate changes generated by advances and retreats of the ice sheet, observed in all sedimentary environments. River valleys, particularly prone to such fluctuations, often bear a record of successive fluvial to aeolian settings (Kolstrup, 1980; Kasse, 1997; Van Huissteden et al., 2000;

Mol et al., 2000; Van Huissteden & Kasse, 2001; Van Huissteden & Pollard, 2003; Kasse et al., 2007; Zieliński et al., 2009, 2011, 2014a, b). Fluvio-aeolian sequences described from Pleistocene deposits are frequently accompanied by large-scale cryoturbations, abundant large ice-wedge casts (including syngenetic casts), frost cracks and aeolian deflation lags, found in the top or median parts of units (Vandenbergh, 1988; Kasse & Vandenbergh, 1998; Mol

et al., 2000; Van Huissteden et al., 2000; Zieliński et al., 2014a, b). Identification of such successions that yield only sparse botanical remains is based mainly on sediment texture and structure (Van Huissteden et al., 2000; Mol et al., 2000; Van Huissteden & Kasse, 2001; Kasse, 2002), with grain size as a feature of particular interest. Other characteristics, e.g., mineral composition (including heavy minerals), as well as type of quartz grain surface in the sand fraction, are rarely considered, although such features have been examined by geomorphologists and geologists in stratigraphic, palaeogeographic and genetic studies (Goździk, 1980; Mycielska-Dowgiałło & Woronko, 2004; Woronko, 2012; Woronko et al., 2013).

The objectives of the present paper are to analyse and discuss: (1) the type of quartz grain surfaces characteristic of fluvio-aeolian sedimentary successions, (2) the type of quartz grain surface as indicator of intensity of aeolian processes, (3) the importance of sandy material supplied from outside the accumulation area in relation to multiple sediment redeposition *in situ*, and (4) changes in climatic conditions and sedimentary settings in the extraglacial zone during the Last Glaciation.

## 2. Study area

The key sites are situated in the central part of the European Sand Belt (ESB; Koster, 1988) in Poland and western Ukraine, within an approximately 1,000 km long, E-W oriented area (Fig. 1A). Deposits from four sites, Postolin, Niwiska, Józefów and Berezno, were considered to be representative of the ESB and subjected to detailed textural analyses (Fig. 1B-E). The above-mentioned sites were selected on the basis of their location in the Last Glacial Maximum (LGM) foreland and on account of their varied geomorphological setting, including higher-lying river terraces and accumulated alluvial fans (Fig. 1). All sites are situated in the extraglacial zone outside the range of meltwater clastic material supply from the last continental ice sheet (Marks, 2002). Additionally, sediments at each site were assumed to provide a record of complete fluvial to aeolian succession.

The age of the sediments examined ranges from Middle Pleniglacial to Early Holocene (Figs 2-5). Fluvial deposits generally accumulated during the Late Weichselian and their oldest portions at Józefów were dated as Middle Pleniglacial. The transient fluvio-aeolian unit was deposited at the end of the Late Pleniglacial and the beginning of the Late Weichselian. The age of aeolian

sediments is Late Weichselian to Holocene (Zieliński et al., 2014b).

### 2.1. Postolin

This locality is in the eastern part of the Milicz Basin (part of the Głogów-Baruth ice-marginal valley, western Poland; Fig. 1B), within the northern dune, i.e. one of the two parallel, longitudinal, WNW-ESE oriented dunes. These dunes are c. 300 m apart and reach a maximum length of 2 km and a relative altitude of up to 7 m, and are surrounded by aeolian sand cover with depressions and deflation remnants. In a northwesterly direction, they overlie a very gently inclined surface consisting of fluvial sands, while towards the east, the dune encroaches on glacial upland (Winnicka, 2007, 2008).

### 2.2. Niwiska

The site is situated on a high sandy terrace of the Wisłoka River valley (Sandomierz Basin, southern Poland; Fig. 1C; Mądry, 1994), within a crescent-shaped dune in a large dune complex adjacent to the eastern valley slope. This WNW-ESE oriented landform, with a c. 600 m long ridge and 10 m high front, includes a small blowout in its peripheral part (Fig. 1C).

### 2.3. Józefów

This locality is in the southeastern part of the Józefów Vale (Tomaszów Roztocze Region, south-east Poland; Fig. 1D), within a small parabolic dune (3 m high at its front and 450 m long along the ridge). This dune is the outermost, southwesterly component of a WNW-ESE-oriented compound dune. The dune closes off the exit of a small, erosional valley entering the vale from the south (Fig. 1D; Kurkowski, 1997).

### 2.4. Berezno

This site is situated in the Słucz River valley, northeast of the town of Berezno (Volhynian Polesie Region, western Ukraine; Fig. 1E). This part of the valley includes an eroded fragment of a Weichselian terrace, located below the gentle slope of the Odranian (=Dnieper) valley outwash. The terrace is covered with various dunes. The wavy surface of the terrace has an altitude slightly exceeding 168 m

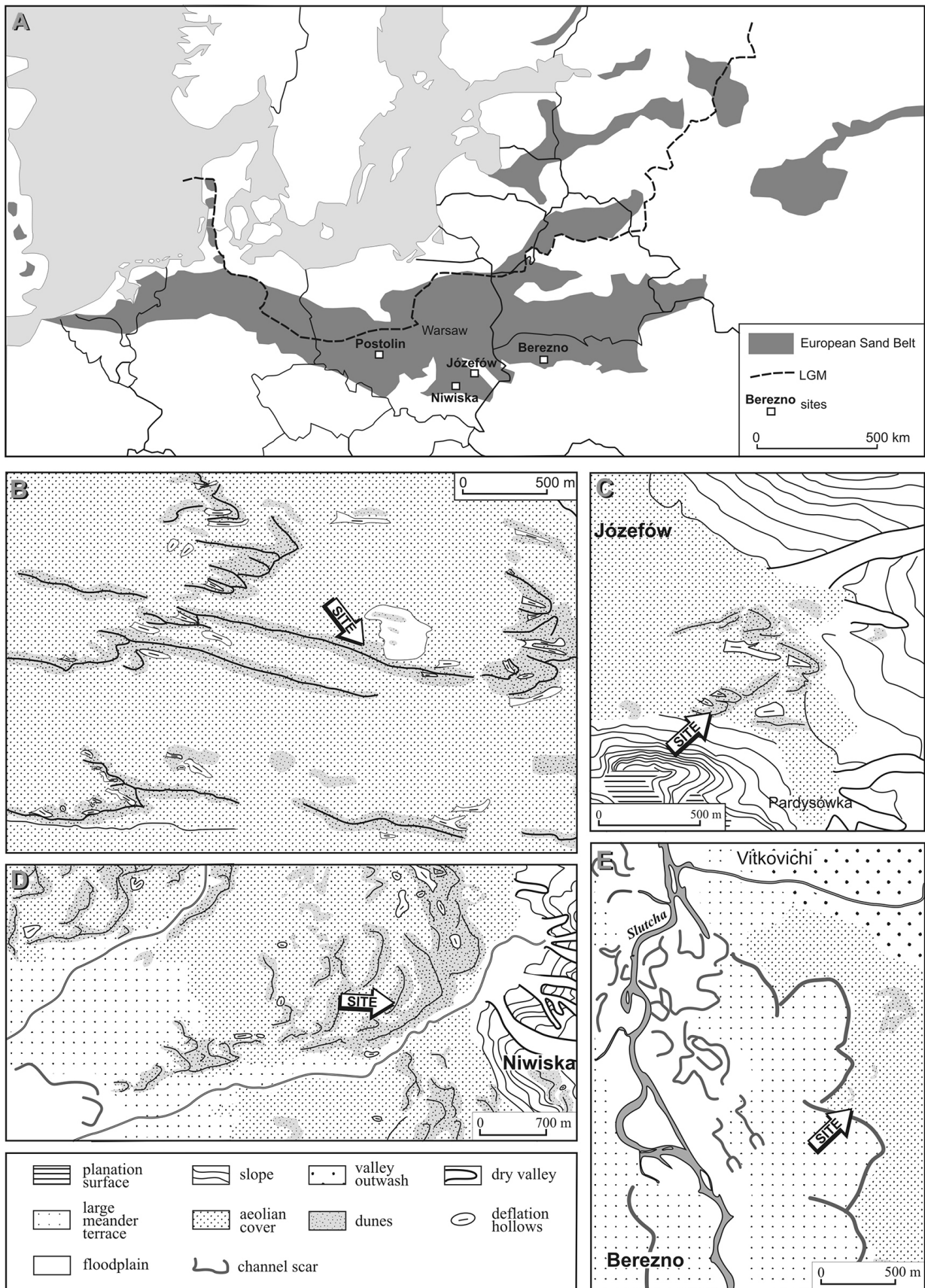


Fig. 1. A - Location of the sites studied in the European Sand Belt; B - Postolin; C - Niwiska; D - Józefów; E - Berezno.

a.s.l. Easily recognised dune crests rise to a height of 176 m a.s.l.

### 3. Methods

Deposits from the localities studied were subjected to detailed lithofacies analysis with coding following Zieliński & Pisarska-Jamroży (2012). Characteristics of periglacial structures and pedogenic levels were noted as well. Additionally, quartz grains of the sand fraction (0.8–1.0 mm) were examined in order to determine roundness according to the 9-degree classification by Krumbein (1941), and surface type, following the method of Cailleux (1942) as modified by Goździk (1980) and Mycielska-Dowgiało & Woronko (1998). In each sample, 100–150 grains from the 710–1000 μm size category were analysed and assigned to one of seven types (Table 1).

The TL age of the deposits analysed was determined at the University of Gdańsk (Fedorowicz, 2006) and the IR-OSL dating was done at the Research Laboratory for Quaternary Geochronology (RLQG) at the Tallinn University of Technology (Molodkov & Bitinas, 2006).

### 4. Results

At each of the sites presented here, three facies types were distinguished: fluvial (lower unit), flu-

vio-aeolian (middle unit) and aeolian (upper unit, developed as cover and/or dune sands) (Figs 2–5).

#### 4.1. Postolin

##### 4.1.1. Fluvial unit

The fluvial unit comprises a rhythmite of horizontally stratified sands (Sh) and horizontally laminated sandy silts (FSh) in the basal part (Fig. 2). Sands with trough cross-stratification (St), grading into sands with ripple cross-lamination (Sr) and silty sands of deformed structure (Sd) in the top part. The unit is marked by two generations of synsedimentary pseudomorphs, developed after ice-wedge casts, and small-scale, finger-shaped load-cast structures. The lower and upper layers of wedges correspond to the top of the sandy-silty rhythmite and the top of the unit, respectively. The lower and middle units are separated by an aeolian pavement which represents a record of long-term deflation preceding the deposition of the fluvio-aeolian unit (Fig. 6A).

The unit shows a strong predominance of moderately rounded grains, frosted only in their most convex parts (EM/RM; 72–81%). The frequency of RM grains generally does not exceed 10%, but gradually decreases upwards (Fig. 2). The content of moderately rounded and shiny grains (EM/EL) amounts to *c.* 10% in the entire unit, and the content of grains classified as ‘other’ ranges between 2.3 and 6.7% (Fig. 2).

Table 1. Type of roundness and frosting of quartz sand grains according to Cailleux (1942) as modified by Goździk (1980) and Mycielska-Dowgiało & Woronko (1998).

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 <i>environments</i> 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

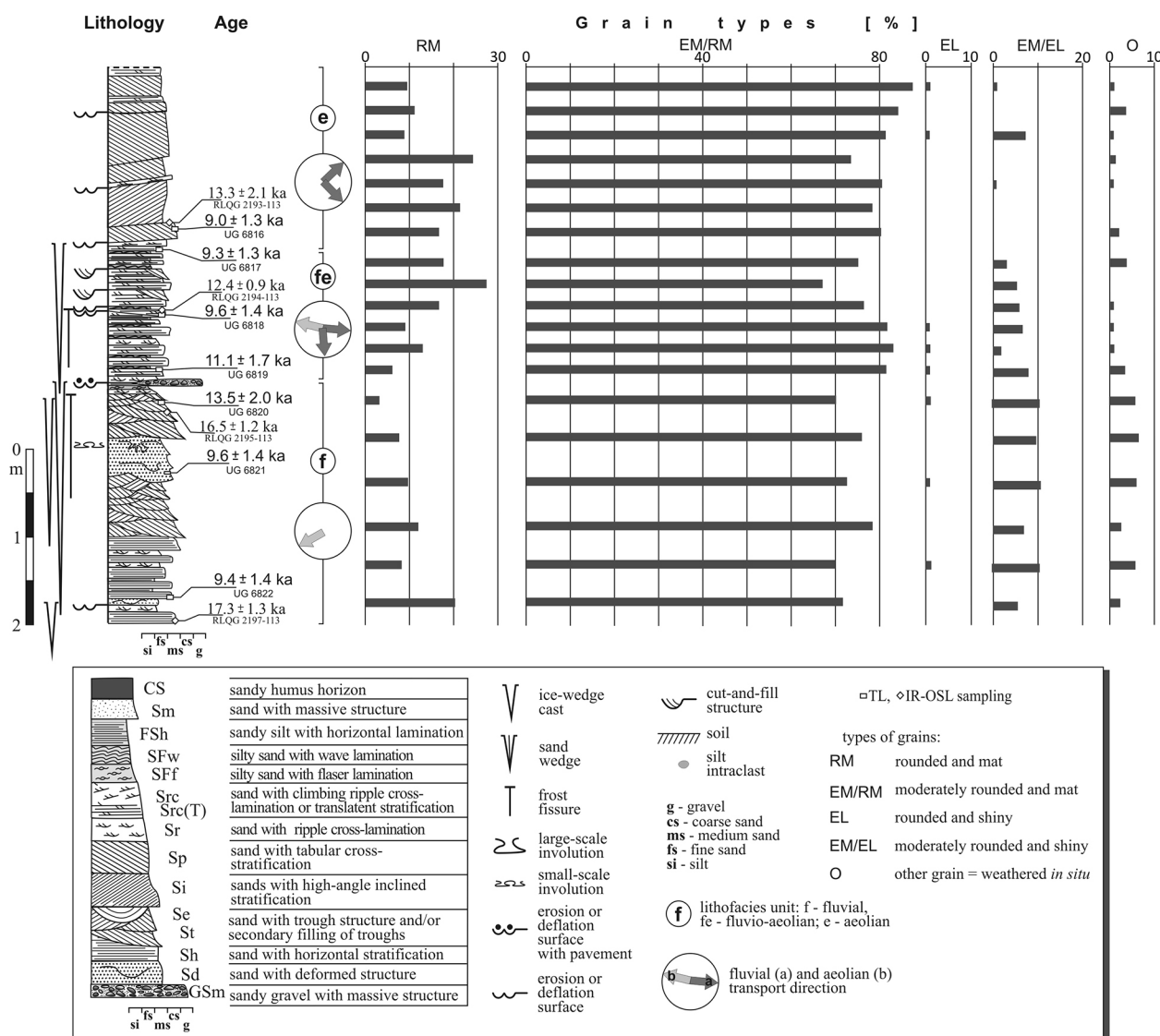


Fig. 2. Postolin: rounding and frosting of quartz grains.

NU = fresh, angular; RM = rounded and mat; EL = rounded and shiny; EM/RM = moderately rounded and mat; EM/EL = moderately rounded and shiny; C = broken; O = other, coated by silica or partly dissolved.

Fluvial deposits accumulated in channels functioning on an alluvial fan with continuous permafrost (Fig. 2). Roundness and frosting analyses of quartz grain surfaces demonstrate their low diversity within the section.

#### 4.1.2. Fluvio-aeolian unit

This consists of sands showing a translantent stratification (Src(T)), interbedded with sands of ripple cross-lamination (Sr) or silty sands of wavy lamination (SFw). The unit includes occasional cut-and-fill structures and numerous symsedimentary pseudomorphs, developed after ice-wedge casts (Fig. 6A).

The deposits still include mainly EM/RM grains, but are accompanied by a higher propor-

tion of well-rounded and mat (RM) grains, in comparison to the fluvial unit. RM values increase upwards reaching a maximum value of 27.4% at the top of this unit. The frequency of moderately rounded and shiny grains (EM/EL) reaches values below 10% and decreases to zero at the top of the series (Fig. 2).

These deposits formed in an aeolian environment and were redeposited in periods of intensive nival melt.

#### 4.1.3. Aeolian unit

This unit comprises sands with large-, medium- and small-scale planar cross-stratification (Sp) and occasional translantent stratification (Fig. 6B). These deposits provide a record of the functioning of

a longitudinal (seif) dune (Tsoar, 1982; Pye & Tsoar, 1990; Figs. 2, 6B).

The unit shows a distinct change in quartz grain morphoscopy (Fig. 2). Nearly the entire base of the unit is formed of mat and mostly moderately rounded grains (EM/RM; up to 88%), accompanied by well-rounded grains (RM; up to > 20%). In the top part, the content of RM grains drops below 10%, while amounts of shiny (EM/EL) and 'other' grains increase (Fig. 2).

## 4.2. Niwiska

### 4.2.1. Fluvial unit

The fluvial unit includes sands with large- (base) and medium-scale (top) trough cross-stratification (St), turning laterally into sands with horizontal stratification (Sh) and ripple cross-lamination (Sr; Fig. 6C).

The results of our analysis of quartz grain morphoscopy show that the lower part of the deposit contains mainly mat grains, both moderately and very well rounded (Fig. 3). The frequency of RM grains gradually increases towards the top, with large-scale trough cross-stratification (St), and finally reaches a constant level of *c.* 10%. RM and EM/RM grains, increasing in number, replace the disappearing EL and EM/EL grains, the content of which decreases from *c.* 15% at the base to zero EL

grains at the top of the series. The frequency of EM/EL grains increases again at the top of the unit, in sediments with medium-scale trough cross-stratification (St) (Fig. 3).

The sediments illustrate the functioning of a braided river, marked by intensive aggradation. The river existed under periglacial conditions, as evidenced by syngenetic ice-wedge casts, found in the uppermost and middle parts of the unit, mainly in abandoned valley segments.

### 4.2.2. Fluvio-aeolian unit

Deposits of this unit are approximately 2 m thick and are dominated by the Src(T) lithofacies and cut-and-fill structures (Fig. 6D). Similar to the fluvial unit, EM/RM and RM grains predominate. However, the proportion of RM grains gradually increases upwards and reaches the maximum value at the top of the section (Fig. 3). The sediment properties indicate a record of aeolian accumulation and re-deposition resulting from concentrated subcritical ephemeral flow.

### 4.2.3. Aeolian unit

This upper unit comprises mainly sands with translent stratification (Src(T)), laterally accompanied by sands with inclined stratification (Si). Sediments formed within a stationary crescent-shaped dune (Zieliński et al., 2014a). Compared to the fluvio-aeolian unit, the aeolian unit shows a noticeable

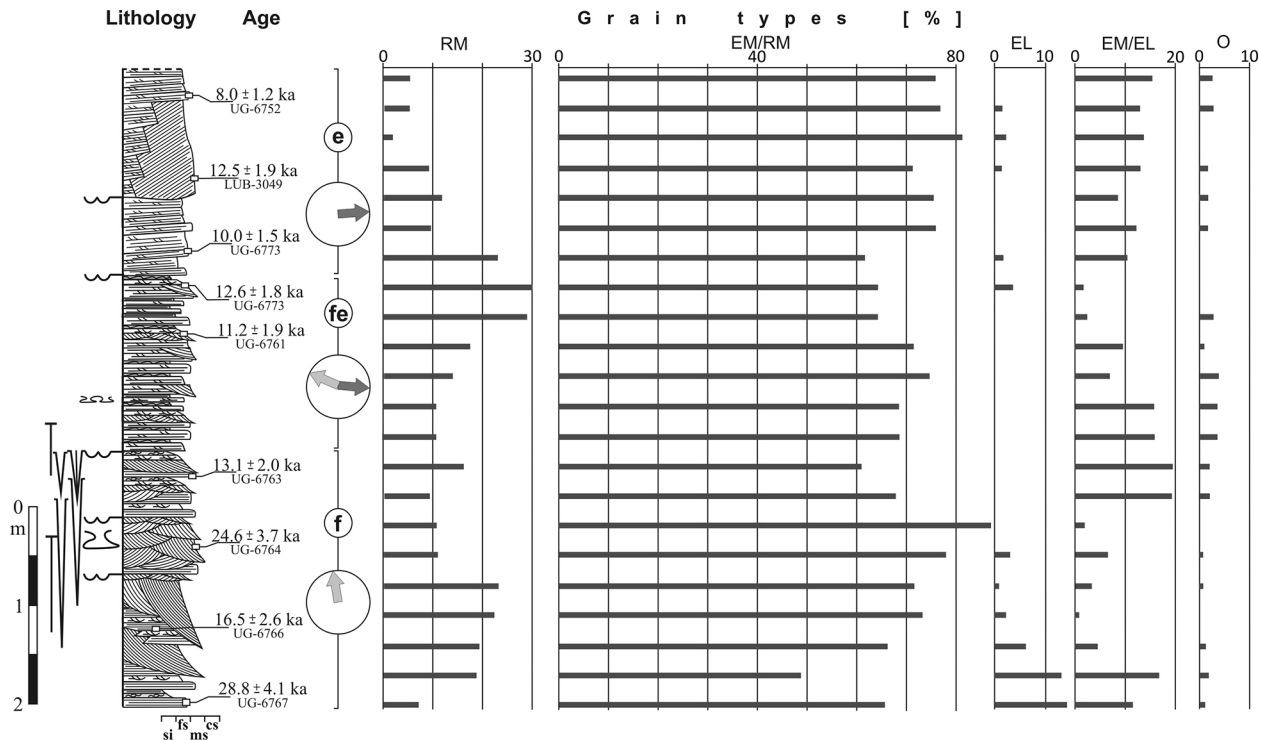


Fig. 3. Niwiska: rounding and frosting of quartz grains (see Fig. 2).

decrease in the content of RM grains, replaced by EM/RM and moderately rounded and shiny EM/EL grains (Fig. 3).

### 4.3. Józefów

#### 4.3.1. Fluvial unit

The fluvial unit, identified at the base of the deposits, includes two sedimentary cycles: sands with trough cross-stratification (St) and with a scale decreasing up the cycle, and horizontally stratified sands (Sh) marked by erosion and deformation at the contact zone (Fig. 6E).

Mat grains of the EM/RM and RM types predominate in these deposits. In the lower part of the unit, the proportion of very well-rounded RM grains is high (max. 40%) but varies, while in the horizontally stratified sands (Sh), it shows a decrease to a constant level of *c.* 10%, accompanied by a slight increase in EM/RM grains and large numbers of EM/EL, EL and 'other' types of grains (Fig. 4).

These sediments, comprising syngenetic ice-wedge casts as well as frequent fine cracks and load casts, provide evidence of the presence of a shallow braided river under periglacial conditions (Figs. 4, 6E).

#### 4.3.2. Fluvio-aeolian unit

This unit comprises a rhythmite of fine- and medium-grained horizontally stratified sands (Sh), silty sands with wavy lamination (SFw) and sands with climbing ripple cross-lamination (Src(T)). They include sands with trough cross-stratification (St) or cut-and-fill structures (Figs. 4, 6E, F). Three generations of small-scale involutions were also recorded in this set.

In the fluvio-aeolian unit, EM/RM and RM grains have a total frequency varying between 70 and 90%. The RM content slowly, but constantly, increases upwards and reaches maximum values at the top. At the same time, grains of all other types disappear (Fig. 4). These sediments illustrate aeolian deposition on humid (SFw) or dry (Src(T)) surfaces, and subsequent redeposition in incidental supercritical (Sh) or subcritical (St) flows (Figs. 4, 6F).

#### 4.3.3. Aeolian unit

The upper unit, comprising mainly mixed-grained sands of inclined stratification (Si) with reactivation surfaces, provides a record of deflation and subsequent accumulation at the lee side of a migrating dune (Figs. 4, 6F). Similar to the underlying deposits, the unit is composed mainly of EM/RM and RM grains, reaching values as high as 90%. However, it should be noted that EM/RM grains clearly predominate, while the RM content does not exceed 12% and varies strongly (Fig. 4).

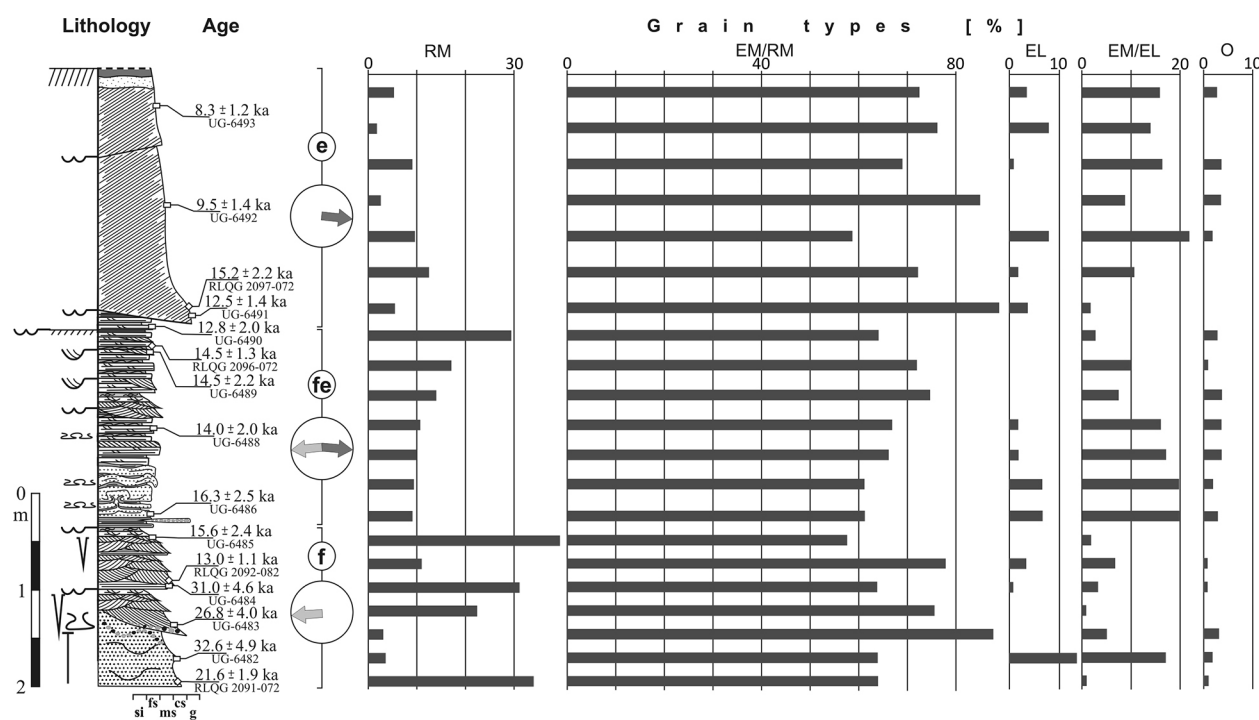


Fig. 4. Józefów: rounding and frosting of quartz grains (see Fig. 2).

#### 4.4. Berezno

##### 4.4.1. Fluvial unit

The fluvial unit documents sedimentary successions with alternating sand and silt layers (Fig. 5, 6G). The sandy interval consists mainly of sands with trough cross-stratification (St) and planar cross-stratification (Sp), while the silt-sand interval includes lithofacies with ripple cross-lamination and flaser lamination (SFr, Ff). This unit contains also pseudomorphs of ice wedges overlain by sandy wedges, as well as large-scale involutions at the top (Fig. 6G). Periglacial structures indicate deposition by a braided and anastomosing river system, under harsh climatic conditions with continuous permafrost (Zieliński et al., 2009, 2014a) (Fig. 5).

##### 4.4.2. Fluvio-aeolian unit

The middle unit is represented by a rhythmite of horizontally stratified sands (Sh) and sandy silts with wavy lamination (FSv). The basal part includes an erosional cut filled with sands of trough cross-stratification (St; Figs. 5, 6H).

##### 4.4.3. Aeolian unit

The upper unit comprises a rhythmite of sands with translantent stratification (Src(T)) or planar cross-stratification (Sp) and sandy silts with horizontal lamination (FSh) or massive structure (FSm; Fig. 5).

All three units are dominated by mat grains (EM/RM and RM). However, the amounts of specific grain types do not display clear increasing or decreasing trends, as observed in the three other

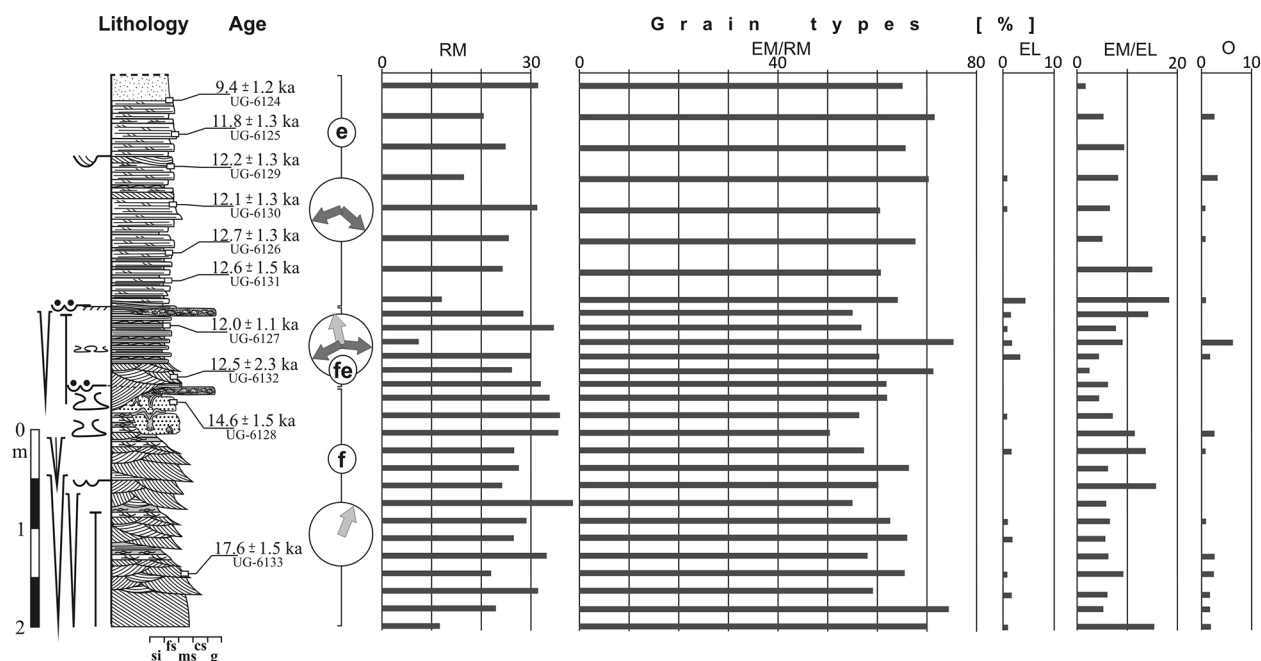


Fig. 5. Berezno: rounding and frosting of quartz grains (see Fig. 2).

Fig. 6. Examples of depositional and cryogenic structures documented.

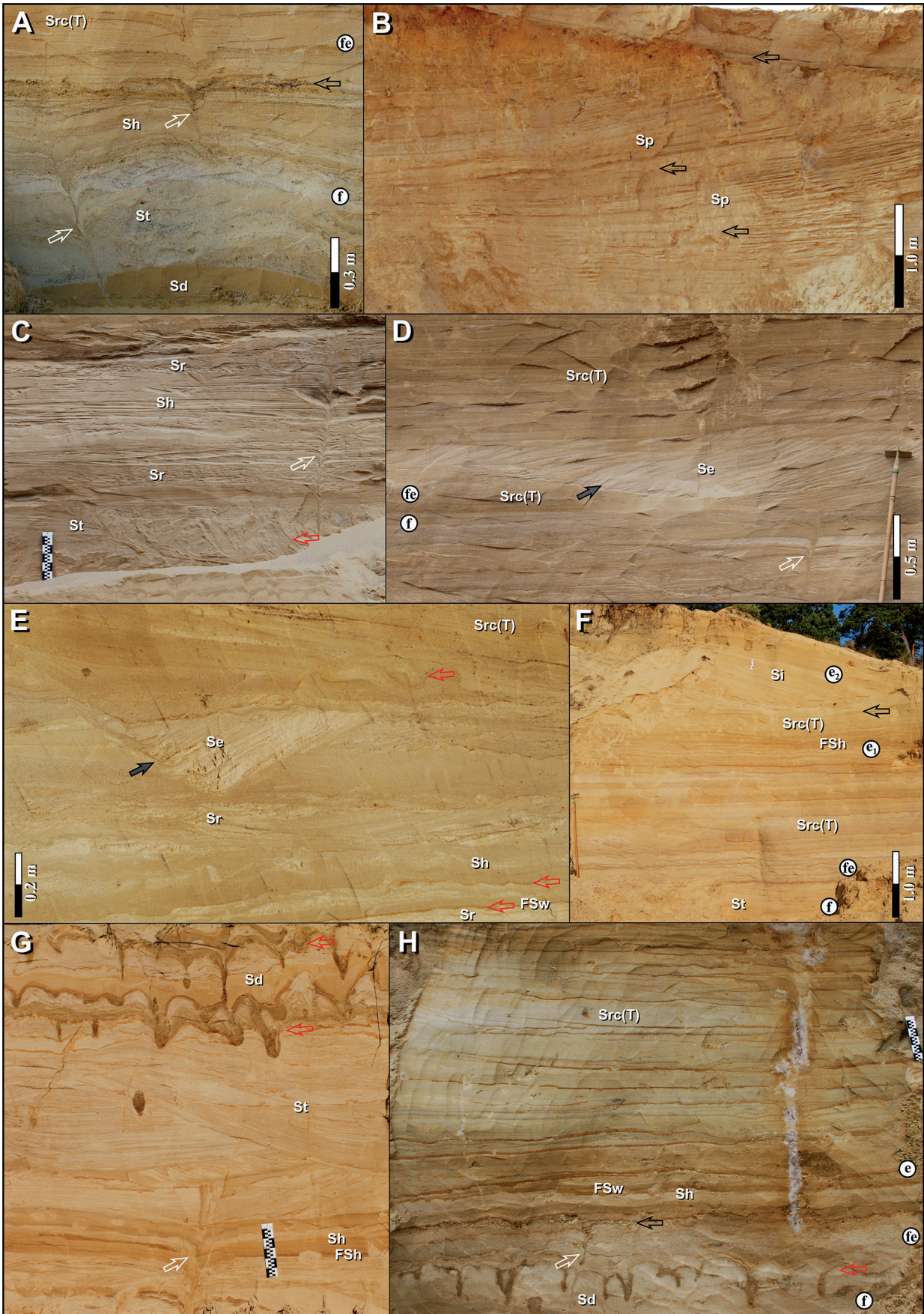
Postolin: **A** – contact zone of fluvial (f) and fluvio-aeolian (fe) units, marked by deflation (aeolian) pavement (black arrow), pseudomorphs after ice wedges present in both units (white arrow); **B** – aeolian unit, many deflation surfaces (black arrow).

Niwiska: **C** – fluvial unit with pseudomorph after ice wedge (white arrow) and cryoturbations (red arrow); **D** – uppermost part of fluvial unit (f) with pseudomorph after ice wedge (white arrow), corresponding to top of unit and floor of fluvio-aeolian unit (fe) with cut-and-fill structure (grey arrow).

Józefów: **E** – fluvio-aeolian unit with small-scale involutions (red arrow) and cut-and-fill structure (grey arrow); **F** – complete fluvial-aeolian sedimentary succession; fluvial unit (f), fluvio-aeolian unit (fe) and aeolian unit developed in the form of aeolian sediments (e1) and dune sediments (e2) separated by deflation surface (black arrow).

Berezno: **G** – fluvial unit with two generations of large-scale involutions (red arrow) in top and unit wedges (white arrow); **H** – sedimentary succession at site, top of fluvial unit (f) deformed by large-scale involutions (red arrow), aeolian unit (e) separated from fluvio-aeolian unit (fe) by deflation surface with pavement (black arrow); pseudomorph after ice wedge (white arrow) corresponding to deflation surface. Other explanations in Figure 2.





sections, particularly where RM grains are concerned. Moderately rounded and shiny EM/EL grains were recorded at levels of *c.*10–15% throughout the section (Fig. 5).

## 5. Palaeoclimatic and palaeoenvironmental interpretation

All sites discussed in the present study were formerly situated in the LGM (Last Glacial Maximum) foreland (Fig. 1), which explains why they could be expected to provide evidence of changes in climate, sedimentary settings and source of deposits during the entire MIS 2 and older periods. The Late Pleniglacial (MIS 2) generally is divided into two stages. The older stage was the phase of maximum cold, resulting from the formation and maximum extent of the ice sheet (28–18 ka), which supported the development of various periglacial phenomena and continuous permafrost. The younger period (18–13 ka) was marked by a temperature rise and progressive disappearance of permafrost conditions (Huijzer & Vandenberghe, 1998; Mol et al., 2000).

### 5.1. Sources of deposits

Sources of deposits, particularly of those of the fluvial units, remain an open issue. In the LGM foreland, aeolian processes were already under way at the end of the Saalian glaciation (Goździk, 2007), while south of the Saalian maximum, they were active also during older periods (Schokker et al., 2005; Woronko, 2012). However, they were also recorded from older phases of the Weichselian. A very high content of aeolian grains, including RM, was reported for deposits dated as the younger part of stage 3 (younger than ~45 ka) and as ~60 ka (Van Huissteden & Pollard, 2003; Dzierżek & Stańczuk, 2006; Kalińska, 2010; Marks et al., 2014). Already Dylík (1969) suggested that the origin of 25.2 kyr old sediments from Bełchatów might have resulted from aeolian processing occurring not only during the Late Pleniglacial, but also shortly after the Brørup. On the other hand, Goździk (1980) assumed that the intensive aeolian processes during the Weichselian begun much later than the Brørup. The potential source of sandy material, which could be incorporated into aeolian transport, has a different genesis at each site, as a result of differences in local geological structure. In the case of the Postolin site, the material was of glacialic/fluvioglacial

origin, derived mainly from erosion of end moraines of the Saalian glaciation (Winnicka, 2007). At Berezno and Niwiska, material of the fluvial unit was of allochthonous origin. It came mostly from long-term transportation from recharge areas situated to the south of the above-mentioned sites. The Carpathians were a source of sediments at Niwiska, and the Volhynian (Ukrainian) shield at Berezno (Mądry, 1994). In the case of Józefów, these were primarily Miocene sands, glacial till and deluvial deposits from the direct vicinity (Kurkowski, 1997).

The material forming the dunes and cover sands came from other sources, including former aeolian series and fluvio-glacial sediments. A large diversification of the degree and nature of quartz grains processing at the individual sites (key sites) reflect changes in seasonal and long-term directions of transportation, which is best seen at Postolin (Fig. 2) and a gradual increase in the range of the deflation process, which reaches sediments at increasingly greater depths. Contrary to the dune fields in large river valleys, there was no material available from river terraces with similar textural characteristics at the sites studied (Ruegg, 1983; Klatkova, 1996).

### 5.2. Fluvial unit

The age of the fluvial unit examined in the area of the European Sand Belt has been dated as Middle and Late Pleniglacial at Józefów (32.6±4.9 - 15.6±2.4 ka; Fig. 4) and as Late Pleniglacial and Oldest Dryas at Postolin, Niwiska and Berezno (28.8±4.1–13.1±2.0 ka; Figs 3, 5) (Zieliński et al., 2014b). The sand fraction of the alluvial deposits was obviously dominated by mat, well- and very well-rounded RM and EM/RM grains (Figs 2–5). However, such a surface type resulted from abrasion occurring in the previous aeolian environment (Mycielska-Dowgiałło & Woronko, 1998; Woronko, 2001). The frequency of these grains did not noticeably change in a west-east gradient, except for the easternmost site (Berezno) with a slightly higher and more stable content of completely mat and very well rounded RM grains in the vertical section. Grains representing different, e.g. aquatic (EL and EM/EL grains) or weathering ('other' grains) sedimentary environments were recorded only in small amounts. The sediment characteristics described clearly show that fluvial alluvia were supplied mainly by wind-transported grains. Uplands surrounding the valleys were subjected to intensive deflation and all dry, exposed and unconsolidated sandy deposits may have been included in aeolian transport (Fig. 7). These sediments accumulated on the floodplain and aeolian

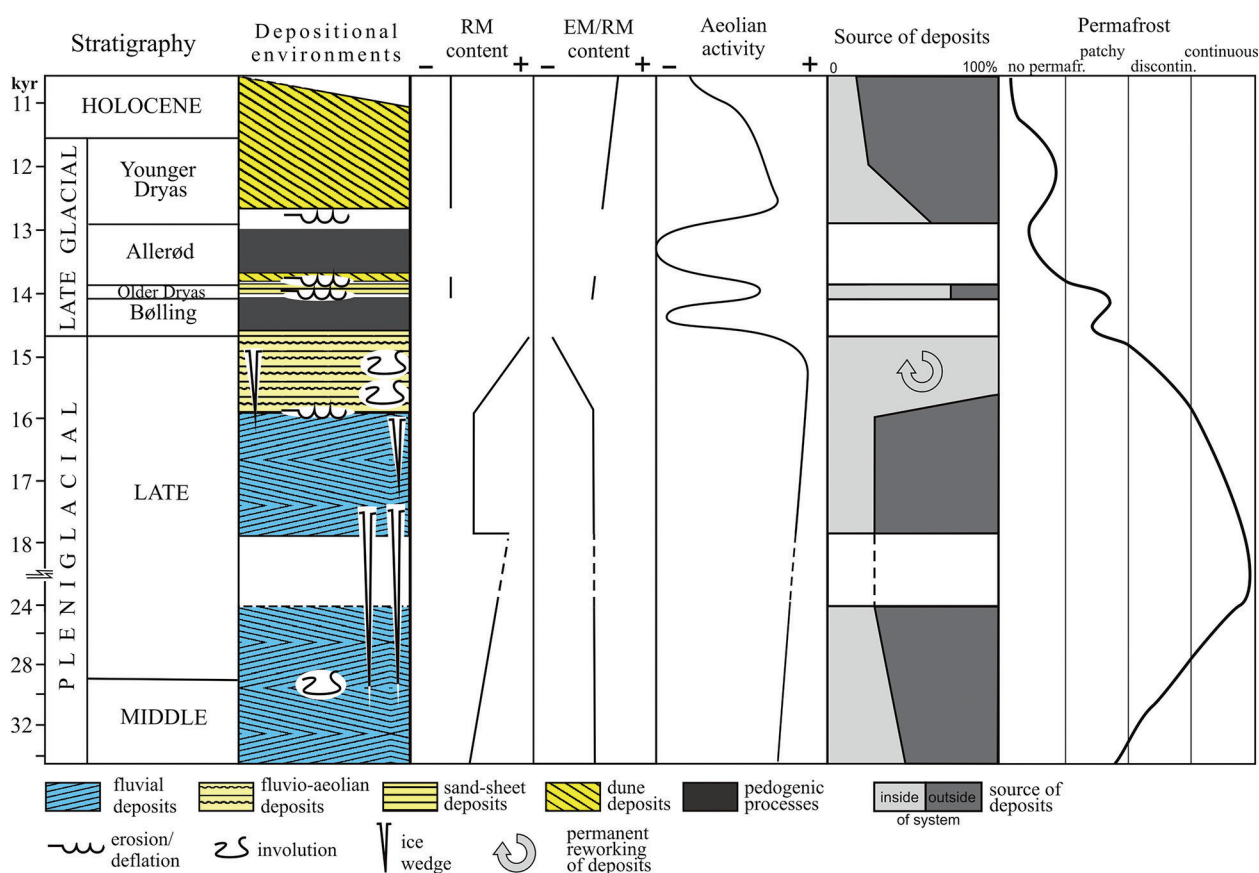


Fig. 7. The model of fluvio-aeolian deposition: morphology of sand grains and interpretation of palaeoenvironmental conditions.

materials eroded from valley slopes (Kasse, 2002) were also redeposited. The large supply of aeolian material into the valley accounted for a high aggradation ratio (Zieliński, 2007). Similar depositional environments have been recorded from numerous river valleys in the Netherlands, Germany and Poland (Koster, 1988, 2009; Turkowska, 1994; Mol et al., 2000; Van Huissteden et al., 2000; Kasse et al., 2003; Mycielska-Dowgiałło & Woronko, 2004; Goździk, 2007; Zieliński, 2007; Woronko, 2012). The predominance of aeolian grains in the alluvia could indicate cold climatic conditions in the valleys and immediate surroundings, as well as active aeolian processes, while the occurrence of syngenetic ice-wedge casts in the sediments provides evidence of permafrost conditions (Kasse et al., 2007; Fig. 7).

The lower part of the fluvial unit documents the role of aeolian processes, intensified in the area as the climate became colder and drier. The processes were activated most likely during winter (Koster, 1995). Sand was released from the frozen soil by sublimation (McKenna Neuman, 1990, 1993, 2004; Kasse et al., 2007), and repeatedly redeposited before final supply to the alluvia. The analysis of quartz grain morphoscopy indicated that aeolian

processes were strong and synchronous with accumulation in fluvial environments, but the preservation of aeolian sediments was low (Kasse, 1997; Sidorchuk et al., 2001).

The upper part of the fluvial unit, in which the disappearing RM grains are accompanied by still very frequent EM/RM grains, provides evidence of the continuation of very active aeolian processes (Fig. 7). The material could have become more easily accessible for aeolian transport than during accumulation of the lower part of the unit. Consequently, the deposition was extensive and burial rapid, which prevented repeated redeposition and led to a higher degree of rounding and frosting of grains. This observation may be supported by the fact that in the Niwiska and Berezno sections, the top parts of the fluvial unit are marked by large-scale involutions (Figs. 3, 5). Their record, combined with the presence of ice-wedge casts, indicates degradation of the ice-rich permafrost as a result of climate ameliorations (Kolstrup, 1980; Vandenberghe, 1988; Van Huissteden et al., 2000; Kasse et al., 2007). Lowering of the permafrost top and drying of the surface sediment layer led to more material being accessible for aeolian transport (Kasse, 1997).

In the Postolin section, the fluvial unit, which includes limited, upward-decreasing amounts of RM grains (Fig. 2), may be represented only by its upper part. An upward decrease in RM grains was not recorded at Berezno, presumably due to: (1) much longer persistence of conditions favourable to aeolian processes accompanying deposit accumulation, or (2) erosion of the uppermost sediments of the fluvial unit.

Accumulation of the fluvial unit was accompanied by intensive aeolian processes (Fig. 7). Results obtained indicate the increasing importance of such processes in the supply of sand material to the regions of deposition. Their maxima presumably occurred in the 24–18 ka interval. However, there are no sediments from this period to substantiate this.

### 5.3. Fluvio-aeolian unit

Similar to the fluvial unit, deposits of the fluvio-aeolian series, dated as  $16.3 \pm 2.5$ – $12.0 \pm 1.1$  ka (Zieliński et al. 2014b), were clearly dominated by EM/RM and RM grains representing the aeolian environment at each examined site (Figs 2, 4 and 6). At all localities, except for Berezno (Fig. 5), the content of RM grains gradually increased upsection. Such features show that the deposits were simultaneously affected by aeolian processing and fluvial accumulation, and afterwards repeatedly re-deposited in an aeolian environment (Good & Bryant, 1985; Goździk, 1995; Woronko, 2012; see Fig. 6). The relatively limited thickness of fluvio-aeolian sediments (i.e. from several tens of centimetres to 2.5 m), compared to similar series from the Netherlands (Ruegg, 1983; Kasse, 2002) and Germany (Mol et al., 2000), indicates a small supply of material from elsewhere. This may result from low availability of sand material around the locations analysed. The processes were accompanied by progressive degradation of permafrost, as concluded from the absence or infrequent presence (exclusively at the base of the unit) of loading structures. However, the occurrence of small-scale involutions and lack of ice wedges in this unit indicate cool climatic conditions and deep seasonal frost with Mean Annual Air Temperature (MAAT)  $< -1^\circ\text{C}$  (Kasse et al., 2003). Such conditions intensified infiltration and drying of the surface sediment layer, making it prone to incorporation into aeolian transport and intensive deflation, producing pavement gravels (Figs. 2–5; Van Huissteden et al., 2000). Results obtained indicate that aeolian processes during the Late Pleniglacial were most intensive and efficient during accumulation of the fluvio-aeolian unit. This finding was

confirmed by studies carried out in other parts of Europe where the maximum aridity was dated as between 18.6 and 16.9 ka and the most intensive activity of aeolian processes as Late Pleniglacial (Ruegg, 1983; Van Huissteden & Kasse, 2001; Kasse et al., 2007).

### 5.4. Aeolian unit

The luminescence age of this unit (15.2–8 ka) indicates accumulation during cold weather conditions of the Late Glacial and Early Holocene (Zieliński et al. 2014b; see Fig. 7). This is consistent with generally accepted (in the literature) aeolian accumulation/dune-formation phases (compare Kozarski & Nowaczyk, 1991; Kasse, 2002; Goździk, 2007; Kasse et al., 2007; Zieliński et al., 2014b). Nevertheless, most of the material was deposited during short spells in the Older and Younger Dryas. This fact is clearly reflected in the morphoscopic characteristics of quartz grains from the aeolian unit, because the period was too short for aeolian transport to result in increased roundness of quartz grains (Mycielska-Dowgiałło, 1993, 2001; Goździk, 2007). In the sections examined, the aeolian transport is reflected in the predominance of EM/RM grains, with a relatively minor increase in their content throughout the section at the expense of EM/EL grains (Postolin and Berezno; Figs. 2, 5). At other sites, such a trend is indiscernible and the content of EM/EL grains increases. This fact, as well as much smaller content of RM grains in relation to the underlying units, indicate that sediments of units 1 and 2 were not the sole source of these deposits. This means that dune material was supplied mostly from outside the systems studied (Zeeberg, 1998). Postolin seems to be an exception – initially the content of RM is similar to that in unit 2, but it drops rapidly in the uppermost part and becomes similar to that in unit 1. This can be explained by extraction of the local material for the construction of a dune. Initially, erosion affected the fluvio-aeolian sediments; however, supply from the underlying fluvial sediments proceeded with increasing depth of a wind-blown hollow. The groundwater level, which at that time was significantly lowered, was the sole determining factor (Kasse, 1997).

A clear decrease in the RM content may also be explained by a change in the recharge area where morphoscopic characteristics of sediments differed significantly. This option may be corroborated by two different directions of dune-forming wind reflected in characteristics of lithofacies units (Fig. 2) and a similar distribution of these properties at

Niwiska (Fig. 3), and, to a lesser extent, at Józefów (Fig. 4). The content of RM grains at these localities drops below the level observed in the underlying units, which clearly implies a different source of the material; likely, this was due to the reconstruction of the general atmospheric circulation during the Late Glacial period (Isarin et al., 1997; Zeeberg, 1998).

## 6. Conclusions

Analysis of quartz grain morphoscopy showed that surface type and rounding degree are good tools for the reconstruction of the intensity and duration of aeolian processes in fluvial to aeolian depositional successions.

- The fluvial unit at sites in eastern Poland and western Ukraine is characterised by dichotomy. The borderline between both subunits is emphasised by a stratigraphic gap comprising the climatic pessimum (22–18 ka) and a clear erosional boundary. In the lower part, an increase in the content of quartz grains with signs of aeolian transport is observed. This indicates deteriorating climatic conditions during the Last Glacial Maximum (MIS 2). Furthermore, aeolian transport was increasingly important in the supply of sandy material to river valleys. The smaller content of grains with aeolian origin and numerous traces of permafrost degradation in the upper part of the fluvial unit indicates milder climatic conditions during the Late Pleniglacial.
- The increasing number of very well-rounded aeolian (RM) and moderately rounded aeolian (EM/RM) grains in the fluvio-aeolian unit is a result of successive redeposition of sediments by aeolian processes within the valleys and washing away by episodic flows. Material from outside the valley was of minor significance. The beginning of deposition of this unit was diachronic and dependent of local hydrological conditions and lithology of the substratum, or the size of a drainage basin.
- The disappearance of permafrost contributed to a rapid increase in the permeability of the substratum, the disappearance of regular flows and the release of a large amount of sandy material. The rate of permafrost degradation was determined by local factors, mainly by exposure of slopes. This resulted in the rapid disappearance of permafrost at Józefów and, in part, at Niwiska. In contrast, permafrost at Postolin and Berezno lasted until the early Bölling warming phase.
- Despite the diachroneity of the fluvio-aeolian unit and a varying rate of permafrost degradation, there is a marked homogeneity of structural and textural characteristics of deposits. In this case, local factors were of minor importance.
- The aeolian unit was laid down in periods of climatic cooling in the Older and Younger Dryas. These relatively short intervals (several hundred years) resulted in a higher content of EM/RM grains. However, the period was too short to result in stronger processing of quartz grains and an increase in the number of RM grains in relation to the underlying units. The material comes mainly from outside the depositional areas. The lower units were at least partially protected by soil horizons that developed during the Bölling interphase (Józefów and Berezno).
- Compared to other units, the aeolian unit is characterised by the highest heterogeneity of lithofacies and morphoscopic properties of quartz grains. This reflects a stronger impact of local factors (sediment sources, terrain morphology, presence of vegetation cover) on the processing of quartz grains in comparison to climatic, in particular aerodynamic, conditions.

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