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Reconstruction of sediment provenance and transport processes from the surface textures of quartz grains from Late Pleistocene sandurs and an ice-marginal valley in NW Poland

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Abstract

During the Pomeranian phase of the Weichselian glaciation (~17–16 ka), the Toruń-Eberswalde ice-marginal valley (NW Poland and easternmost Germany) drained water from the Pomeranian ice sheet, while intensive aeolian processes took place across Europe in the foreland of the Scandinavian ice sheet ('European Sand Belt'). The micromorphology of the quartz grains in the Toruń-Eberswalde ice-marginal valley shows no traces of these aeolian processes, or only vague signs of aeolian abrasion. This is unique among the aeolian sediments in other Pleistocene ice-marginal valleys in this part of Europe. The study of the surfaces of the quartz grains shows that the supply of grains by streams from the south was minimal, which must be ascribed to the climate deterioration during the Last Glacial Maximum, which resulted in a decrease of the discharge of these extraglacial rivers to the ice-marginal valley.

Keywords: quartz-grain micromorphology, ice-marginal valley, sandur, Weichselian glaciation, Poland

1. Introduction

Extensive sandur/ice-marginal-valley systems developed in the Polish-German Lowlands during the Pleistocene glaciations. In the foreland of each ice sheet, sandurs built up; proglacial rivers from these sandurs supplied sediment to an ice-marginal valley, which was also fed by extraglacial rivers from the south. Ice-marginal valleys (indicated in the following as IMVs) developed in front of the stagnating ice sheets; these were the Wrocław-Magdeburg IMV, the Głogów-Baruth IMV, the Warsaw-Berlin IMV and the Toruń-Eberswalde IMV (Marks, 2012; see Fig. 1A).

Sediments accumulated on the largest sandurs of NW Poland and in the Toruń-Eberswalde IMV in the Polish-German northern plains during the Pomeranian phase of the Weichselian glaciation were analysed. The N-S oriented Drawa and Gwda sandurs, 80 and 110 km long, respectively, built up south of the Pomeranian ice front; they supplied material to the E-W (= parallel to the ice front) running Toruń-Eberswalde ice-marginal valley. When the Toruń-Eberswalde drained the meltwater from the north and the streams from the south and east during the Pomeranian phase, the periglacial zone extended further southwards. Aeolian activity then was common in this zone in abandoned channels, particularly in the older Głogów-Baruth and Berlin-Warsaw IMVs (Fig. 1A) (e.g. Zeeberg, 1998; Mol et al., 2000; Zieliński et al., in press). In the Toruń-Eberswalde IMV, the braided river system was affected by solifluction, thermal erosion and short fluvial reworking of the glacigenic sediments (Galon, 1961; Mojski, 2005; Pisarska-Jamroży & Zieliński, 2011; Weckwerth, 2013; Weckwerth & Pisarska-Jamroży, 2015). The aeolian activity under periglacial conditions also affected the sandurs that

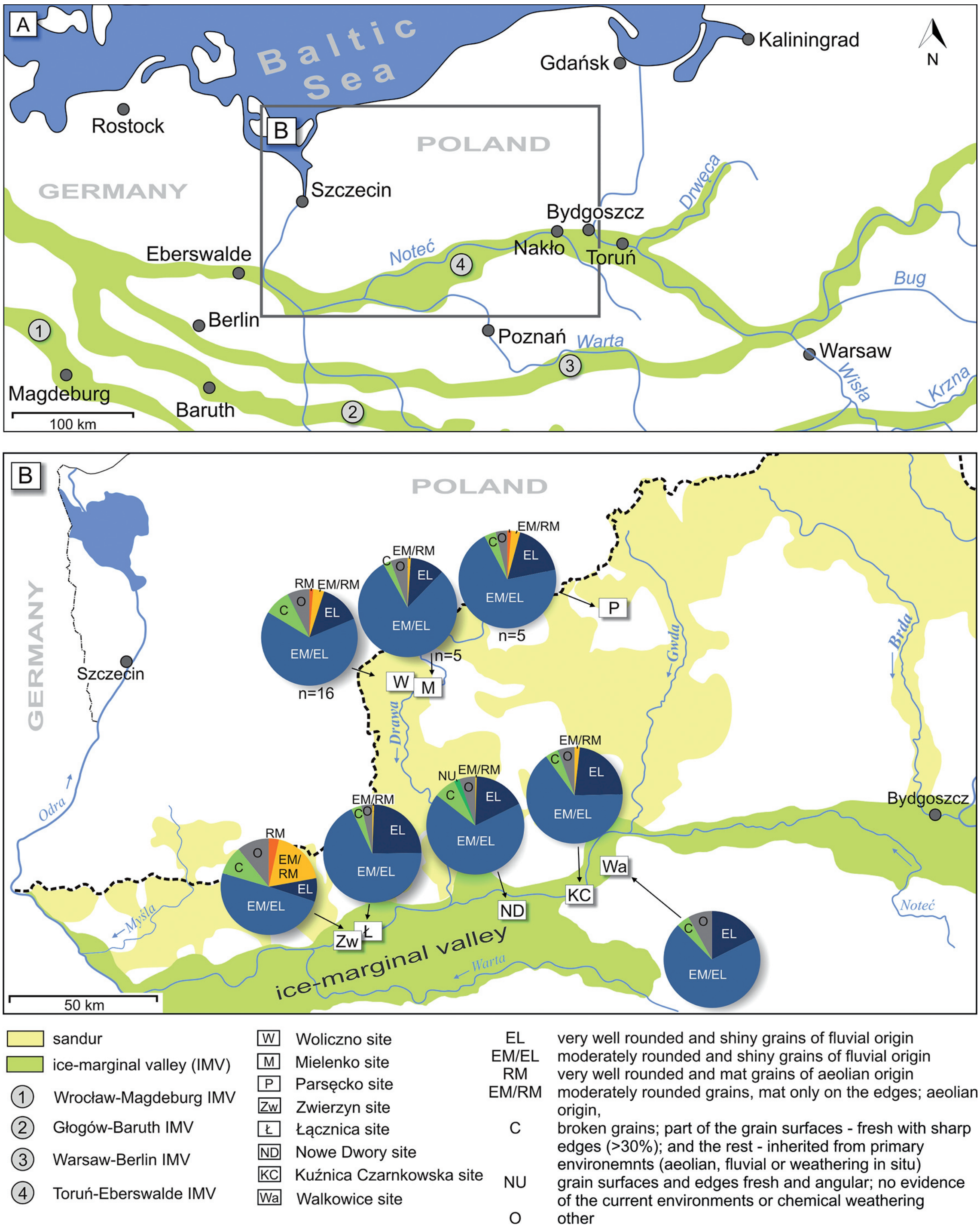

Fig. 1. Location of the study area in NW Poland.
A – Schematic positions of the main ice-marginal valleys; **B –** Positions of the Pomeranian sandurs and the part of the Toruń-Eberswalde ice-marginal valley under study, with the distribution of quartz-grain classes in the sites under study.

had built up north of the Toruń-Eberswalde IMV during the Pomeranian phase.

One of the possible sources of information about processes operating in depositional environments, for instance concerning their duration, postdepositional changes as well as the provenance of the deposits, is the micromorphology (surface texture) of quartz grains (Mahaney, 2002; Mycielska-Dowgiałło & Woronko, 2004; Woronko, 2012; Woronko & Pisarska-Jamroży, in press). A micromorphological analysis of sand grains can provide indications about the transport and weathering processes. This holds also for sandur and IMV sediments. The present contribution reports the result of such a micromorphological study of sand-sized quartz grains deposited during the Pomeranian phase on a terrace of the Toruń-Eberswalde IMV and on two sandurs north of it.

This study was carried out in order (1) to trace the source(s) of the sandur deposits and IMV deposits, (2) to evaluate the role of the proglacial (sandur) and extraglacial (non-glacial) streams feeding the IMV, (3) to specify the reworking and weathering processes that affected the quartz grains during transport, and (4) to consider the influence of the fast aggradation of the sandurs and in the IMV on the development of aeolian traces on the quartz grains.

2. Geological setting

The Drawa and Gwda sandurs and the Toruń-Eberswalde IMV terrace were formed during the Pomeranian phase of the Weichselian glaciation (see Galon, 1961; Kozarski, 1986; Pisarska-Jamroży 2015; Pisarska-Jamroży et al., 2015a). The samples for micromorphological analysis were collected from two gravel pits on the Drawa sandur (the Woliczno and Mielenko sites), one gravel pit on the Gwda sandur (Parsęcko) and from five gravel pits on the IMV terrace spread over a 150 km distance (Zwierzyn, Łącznica, Nowe Dwory, Kuźnica Czarnkowska and Walkowice; Fig. 1B).

The Toruń-Eberswalde IMV in the study area drained the water from proglacial streams of the Drawa and Gwda sandurs. The surface of the Drawa sandur reaches 110–120 m a.s.l. in the gravel pits under study, and is inclined towards the southeast. The surface of the Gwda sandur reaches 145 m a.s.l. in the gravel pit under study and is inclined towards the south. In the Toruń-Eberswalde IMV all five gravel pits are located on the same terrace at 14–16 m above river level (Galon, 1961, 1968; Kozarski, 1986); the terrace slopes from 50 m a.s.l. in the most eastern pit (Walkowice) to 40 m a.s.l. in the most western pit (Zwierzyn).

3. Methods

The rounding of the quartz grains was investigated following Cailleux (1942), as modified by Mycielska-Dowgiałło & Woronko (1998). Over 150 quartz grains of the sand fraction (0.8–1 mm) were counted from each of the 48 samples that were collected from the eight gravel pits. The lithofacies are described and coded (Fig. 2) following Miall (1978), and Zieliński & Pisarska-Jamroży (2012). The micromorphology of the quartz grains from the proximal part of the Drawa and Gwda sandurs and from the terrace sediments of the Toruń-Eberswalde IMV (Fig. 1B) was also investigated.

Seven classes of quartz grains were distinguished on the basis of the rounding and surficial frosting traces: (1) very well rounded and mat grains of aeolian origin (RM), (2) moderately rounded grains of aeolian origin that are mat only on their corners (EM/RM), (3) very well rounded and shiny grains of aquatic (fluvial or beach) origin (EL), (4) moderately rounded and shiny grains of aquatic (fluvial or beach) origin (EM/EL), (5) broken grains under glacial and/or periglacial conditions (C), (6) fresh, angular grains with edges that are all sharp of glacial and/or *in situ* weathered (e.g. periglacial) origin (NU), and (7) other grains (O). The above codes of the seven classes of quartz grains are based on common use (e.g. Mycielska-Dowgiałło & Woronko, 1998; Woronko et al., 2013; Zieliński et al., in press).

Correspondences between the various quartz-grain classes were established with Statistica 10 software through cluster analysis, using the Euclidean distance of the Ward method for the percentage data set (Ward, 1963; Pisarska-Jamroży et al., 2015a, b). This method reconciles two different approaches toward the investigation of spatial relationships between the points: the agglomerative method and the divisive method. A dendrite graph is constructed on a nearest neighbour (in this case a specific class of quartz) basis and then divided into statistical clusters. This procedure ensures an effective reduction of the number of possible splits.

4. Characteristics of the quartz grains

The similarities and differences in rounding and frosting of the quartz grains from the sandurs and IMV show graphically a dendrite-like shape (Fig. 3). Three clusters of quartz grains can be distinguished:

(1) cluster *a* contains only the very well rounded aquatic (fluvial and beach) grains (EL); cluster *b* contains the largest number of grain classes, and indicates the largest similarity between the glacial and *in situ* weathered (probably periglacial) angular grains (NU), the well rounded aeolian grains (RM), the broken grains (C), and other grains (O), with for the sandurs also the moderately rounded aquatic (fluvial and beach) grains (EM/EL) and for the IMV the moderately rounded aeolian grains (EM/RM); cluster *c* contains the moderately rounded aeolian grains (EM/RM) for the grains from the sandurs, and the moderately rounded fluvial grains (EM/EL) for the grains from the IMV.

The quartz grains from both sandurs (Fig. 1B, 2; Table 1) are mostly very well to moderately round-

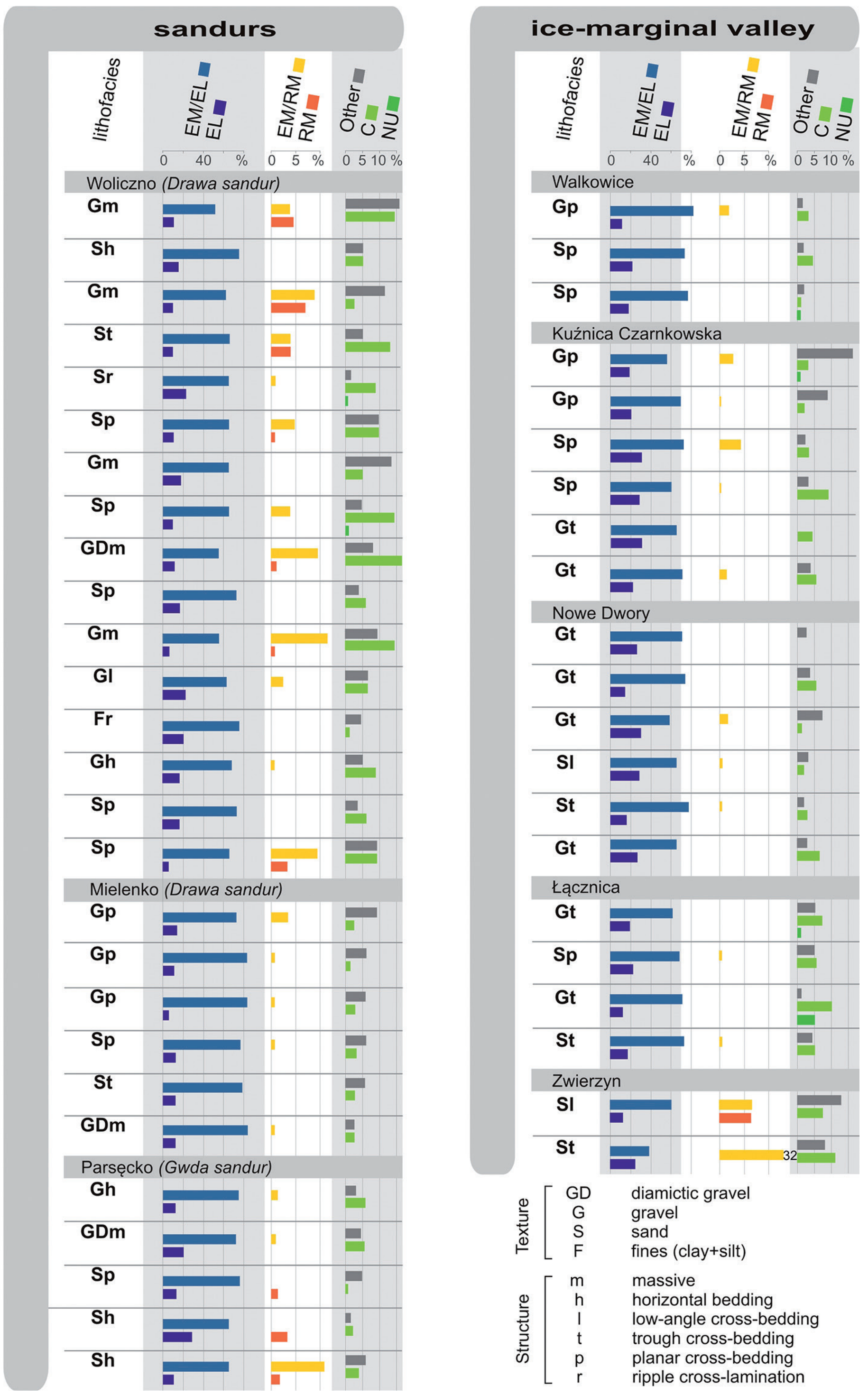

Fig. 2. Classes of quartz-grain rounding and frosting from vertical profiles in the sandurs and in the ice-marginal valley.

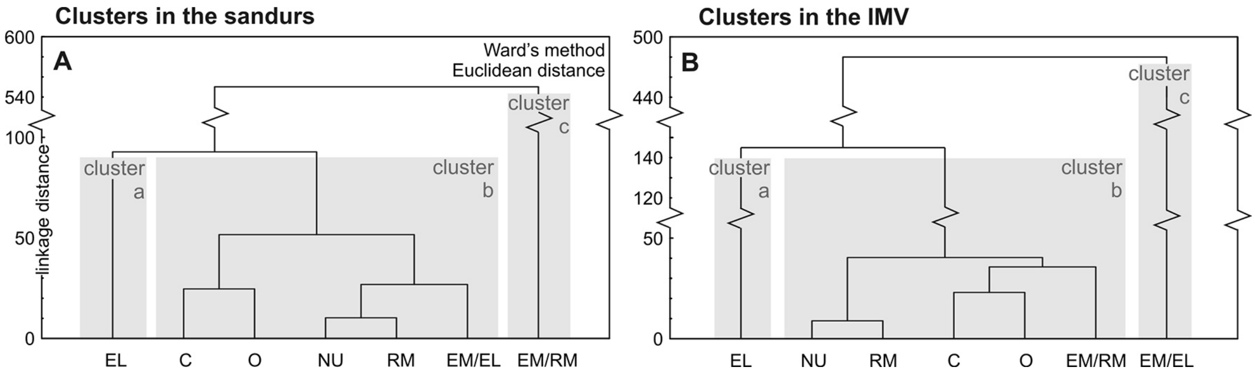

Fig. 3. Cluster analyses of the sediments based on their rounding and frosting classes of quartz grains. The smaller the vertical distances, the more the assemblages are similar.
A – Clusters for both sandurs; **B –** Clusters for the five sites in the ice-marginal valley.

ed, and their surfaces are shiny, indicating derivation from aquatic environments (EM/EL and EL). The very well rounded aquatic grains (EL) in the sandurs make up 13.3%, while moderately rounded grains (EM/EL) make up 69.3%. The quartz grains from the sandurs are abraded on their convex sides, and their surfaces show evidence of etching in the form of solution pits, crevasses and dulled surfaces (Fig. 4A, B). Abrasion marks with small conchoidal fractures, V-shaped percussion cracks and crescentic gouges occur on the edges of some grains from the sandurs (Fig. 4C, D, E). Many grains show breakage blocks (microstructures typical of long-distance transport in a fluvial environment (Fig. 4F) (Woronko et al., 2013). The proportion of aeolian quartz grains (EM/RM+RM) from the sandurs is small and does on average not exceed 4%. Broken quartz grains (C) from glacial and *in situ* weathered (probably periglacial) processes in the Drawa sandur constitute 2.5–8.8%, and other grains (O) 5.6–7.4%, while the proportions of both classes are only half as large for grains from the Gwda sandur.

Percentages of quartz-grain classes					
Sandur sediments			Ice-marginal valley sediments		
EM/EL EL	69.3 13.9	83.2	EM/EL EL	67.0 19.8	86.8
EM/RM RM	3.0 1.0	4.0	EM/RM RM	2.4 0.3	2.7
NU	0.1		NU	0.4	
C	6.5		C	4.9	
O	6.3		O	5.2	

Table 1. Average percentages of quartz-grain classes in the sandurs and the ice-marginal valley.

Quartz grains rounded in streams prevail in the IMV (EM/EL = 67%; EL = 19.8%). The EM/EL and EL grains are commonly abraded on their convex parts, which show V-shaped percussion cracks and crescentic gouges (Fig. 4B; Table 1, 2).

All IMV sediments are characterised by fairly similar quartz grains regarding their rounding and frosting classes; only the most western pit in Zwierzyn (Fig. 1B) is an exception (Table 2). The proportion of moderately rounded aeolian grains (EM/RM) in the IMV does not exceed 5%, but in Zwierzyn it reaches 18.8%. Very well rounded aeolian grains (RM) occur almost exclusively in the Zwierzyn pit, where their percentage is, however, not significant either (3.4%). The remaining classes of quartz grains are all present in low percentages only (Table 2).

5. Origin of the quartz grains – discussion

5.1. Fluvial and beach provenance

Both the sandur sediments and the IMV sediments contain significant percentages of rounded aquatic EM/EL and EL quartz grains (Fig. 2; Table 1, 2), but the IMV quartz grains show a slightly better rounding. The transport of the quartz grains from the distal part of sandurs to the IMV was very short: it did not exceed 1–5 km, which is insufficient to explain the change in rounding of the quartz grains. It must therefore be deduced that the well (EM/EL) and very well rounded (EL) quartz grains with shiny surfaces in the sandur sediments probably obtained these characteristics during earlier residence in a fluvial or beach environment. In these environments, the grains were abraded, rounded and etched (recognised on the basis of dulled surfaces). The high proportion of such grains with a fluvi-

Percentages of quartz-grain classes in the study sites of the ice marginal valley										
grain class \ site	Zwierzyn		Kuźnica Czarnkowska		Nowe Dwory		Łącznica		Walkowice	
EM/EL EL	49.5 7.9	57.4	65.3 22.9	88.2	68.2 24.2	92.4	67.9 17.2	85.1	70.0 17.6	87.6
EM/RM RM	18.8 3.4	22.2	1.8 0	1.8	0.6 0	0.6	0.5 0	0.5	0 0	0
NU	0		0		0		1.8		0	
C	9.6		4.4		3.4		7.3		4.4	
O	10.8		5.6		3.6		5.3		8.0	

Table 2. Average percentages of quartz-grain classes in each of the five sites in the ice-marginal valley.

al provenance suggests that they were derived from Neogene or Palaeogene sediments; these sediments crop out in the southern part of the Baltic Sea and in cliffs along the sea coast (Kaulbarsz et al., 2008). Moreover, petrographic analyses of Weichselian tills in an outcrop near the mouth of the Gwda river in the Toruń-Eberswalde IMV show that these tills contain gravel-sized clasts of which the source has been identified as the eastern Baltic (Kozarski & Nowaczyk, 1985; Kozarski, 1991; Böse & Górska, 1995). This indicates that sediments were eroded from the Baltic basement, which may explain the rounding of the quartz grains collected from the sandurs. It may also be, however, that some of the quartz grains were eroded from glaciotectonically elevated Pliocene or Miocene sediments that are present below the sandurs (see e.g. the Brda sandur; Mojski, 2005).

Experiments concerning the influence of fluvial transport on quartz-grain surfaces show that changes in the micromorphology and roundness develop only slowly (Lindé & Mycielska-Dowgiałło, 1980; Lindé, 1984; Woronko et al., 2013). After thousand hours of simulated fluvial transport, corresponding to fluvial transport over 300 km, initially sharp edges of quartz grains are still only slightly dulled, but V-shaped percussion cracks have developed (Lindé, 1984). Woronko et al. (2013) claim that quartz-grain surfaces become shiny after 750 h of simulated fluvial transport, but even then the roundness has not yet changed significantly. Another factor of importance is the high sedimentation rate of sandur sediments (Pisarska-Jamroży & Zieliński, 2014), which implies that grains have hardly any chance to become more rounded by exposure to running water.

The proportion of shiny and well-rounded quartz grains (EL) in the IMV tends to decrease westwards (downstream), from 17.6% at Walkowice to 7.9% at Zwierzyn (Table 2). During westward transport, part of these well-rounded grains will be left behind (grains with an irregular shape are more easily transported), so that their relative proportion diminishes. These well-rounded grains in the eastern part of the IMV were possibly eroded from the Eemian (see Weckwerth & Chabowski, 2013) or from Pliocene and Miocene sediments which also crop out in the IMV (Galon, 1961).

5.2. Aeolian provenance

Quartz grains belonging to the EM/RM and RM classes are rare in the sandurs; jointly these classes make up only 4%. The micromorphology points at an aeolian origin, and wind activity is common, indeed, in front of an ice sheet. Tylman et al. (2013) reported that each successive Weichselian ice sheet covered an area affected by permafrost processes with sand wedges, frost segregation structures and ventifacts; it is therefore remarkable that aeolian quartz grains are so scarce in the sandur sediments under study.

The proportion of aeolian grains is also extremely low in the IMV, except in the pit at Zwierzyn (Fig. 1B, Table 2). Weckwerth (2013) recorded similar low values of aeolian grains in the eastern part of the Toruń-Eberswalde IMV. The aeolian grains in the IMV can: (1) have been supplied by streams coming from the sandurs, (2) be derived from eroded older Toruń-Eberswalde IMV terraces, and (3) have developed their surface texture during aeolian processes in the foreland of the ice sheet. The very small proportion of aeolian grains in the IMV (Fig. 1B; Table 2) indicates, however, that the last-mentioned option (3) can at most have played a minor role and that aeolian activity in the foreland of the Pomeranian ice sheet must have been short-lived.

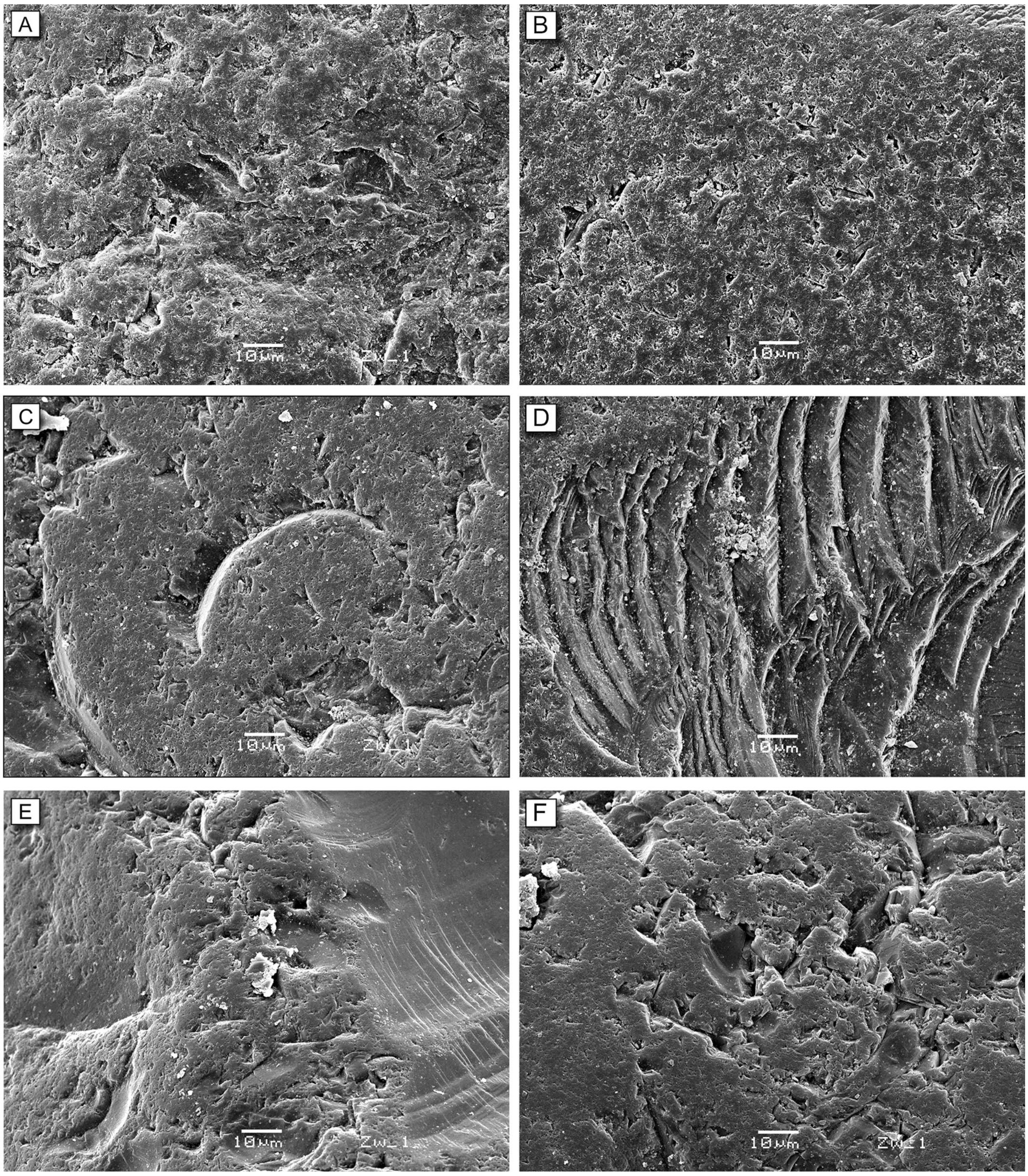

Fig. 4. Micromorphology of some quartz grains.
A, B – Fragment of a quartz grain with traces of etching, represented by solution pits and crevasses; **C –** Fragment of a quartz grain with crescentic gouges; **D –** Arc-shaped steps resulting from crushing; **E –** Convex fragment of a quartz grain with dulled surface varieties by V-shaped percussion cracks, and with small and large conchoidal fractures; **F –** Fragment of a quartz grain with dulled surface varieties by breakage blocks microstructures.

However, Kozarski (1965) described sand wedges from the terrace of the Toruń-Eberswalde IMV under study, implying that periglacial conditions were present. Antczak-Górka (2005), on the other hand, found only a small number of ventifacts, Mycielska-Dowgiałło (1993, 2001) stresses that if the duration of the aeolian processes is relatively short (several hundreds of years), the quartz grains are dominated by specimens that show abrasion only at the grains' edges. Tricart (1965) also points out that the effects of abrasion are visible on the surface of quartz grains only when the aeolian activity is well advanced, and according to Mycielska-Dowgiałło (2001) very well rounded aeolian quartz grains (RM) appear only after several thousands of years of aeolian activity. Most probably the aeolian quartz grains in the sandur sediments were derived from erosion of previous deposits from which they inherited surface characteristics, because the high aggradation rate on the sandurs did not allow the development of a distinctly aeolian micromorphology.

Another explanation for the almost absence of aeolian grains in the Toruń-Eberswalde IMV sediments is the E-W extent of older IMVs (the Głogów-Baruth and the Warsaw-Berlin IMV's), which can have captured the grains transported by rivers from the south. In the Głogów-Baruth IMV (Fig. 1A), for instance, huge amounts of aeolian quartz grains are present in fluvial and aeolian deposits. These deposits were much longer exposed to aeolian processes under permafrost conditions in the central part of the 'European Sand Belt' during the Pleniglacial and Late Glacial (Koster, 1988; Kasse et al., 2003; Goździk, 2007; Zieliński et al., in press).

5.3. Sources of the remaining quartz-grain classes

Broken quartz grains (C) in both the sandurs and the IMV (Fig. 1B; Table 1, 2) originated probably from the crushing of fluvial and aeolian grains. The crushing must have occurred in the subglacial environment (e.g. Iverson et al., 1996; Hart, 2006; Rose & Hart, 2008; Mahaney, 1995, 2002; Traczyk & Woronko, 2010). Angular quartz grains can, however, also have been derived from an eroded active layer in the foreland of the ice sheet (Van Vliet-Lanoë, 2010; Woronko & Hoch, 2011; Woronko, 2012).

Intensively coated and abraded other grains (O) can have originated in the same way as those of the C class. Repeated freeze/thaw cycles led both to silica precipitation on the grains' surfaces (Dietzel, 2005; Woronko, 2007, 2012) and to quartz-grain crushing.

6. Periglacial conditions during the development of the Toruń-Eberswalde IMV

Intensive aeolian activity affected northern Europe during the Pomeranian phase of the Weichselian glaciation (e.g. Manikowska, 1991; Kasse, 1997; Zieliński et al., in press). During this phase, the streams on the sandurs supplied huge amounts of sediment-laden meltwater to the Toruń-Eberswalde IMV. The influx into the IMV from southern extraglacial rivers, which drained the periglacial zones (e.g. the pre-Wisła river system), was most probably minimal (see Pisarska-Jamroży et al., 2015a). Lithofacies analysis of the IMV deposits suggests that the IMV developed under permafrost conditions (Pisarska-Jamroży & Zieliński, 2011; Weckwerth, 2013; Weckwerth & Pisarska-Jamroży, 2015). It is possible that this almost negligible contribution from the south was due to climatic deterioration, which resulted in a decrease of the discharge of rivers running northwards from the extraglacial zone. During the Pomeranian phase, aeolian processes dominated in the abandoned parts of rivers all over Europe (Kamińska et al., 1986; Mol et al., 2000; Van Huissteden et al., 2001; Kasse et al., 2003; Zieliński et al., in press) and in many valleys (Woronko et al., 2011).

7. Conclusions

The following conclusions can be drawn from the present study.

- The rounding and frosting of quartz grains from the Pomeranian sandurs and the Toruń-Eberswalde IMV sediments are the same.
- In both the sandurs and the IMV, very well to moderately rounded and shiny quartz grains prevail; they have a fluvial origin, but the rounding is slightly better in the ice-marginal valley. The fluvial quartz grains in the sandur sediments were probably eroded from sediments in the East Central Baltic, whereas the fluvial quartz grains in the IMV were supplied by streams running over the sandurs, or they were eroded from older terrace sediments.
- The sediments of the Pomeranian sandurs and the Toruń-Eberswalde IMV terrace under study contain a small amount of aeolian quartz grains. This must be ascribed to the short duration of the aeolian activity in the front of the Pomeranian ice sheet, which left insufficient time for changing the micromorphology of the quartz grains; an alternative explanation is that transport of particles by rivers from the south (from the extraglacial zone) to the IMV was restricted by pre-Pomeranian IMVs. These older IMVs were situated parallel to the Toruń-Eberswalde IMV, and could capture the sedimentary particles transported by rivers from the south. Moreover the climate deterioration during the Last Glacial Maximum led to a decrease in the discharge of extraglacial rivers to the Toruń-Eberswalde IMV.

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References

Antczak-Górka, B., 2005. *Głazy rzeźbione przez wiatr jako wskaźniki różnowiekowych stref peryglacjalnych ostatniego zlodowacenia w Polsce Zachodniej* [*Wind-polished stones as indicators of last-glaciation periglacial zones of various ages in western Poland*]. UAM Press (Poznań), 209 pp.

Böse, M. & Górska, M., 1995. Lithostratigraphical studies in the outcrop at Ujscie, Toruń-Eberswalde Pradolina, western Poland. *Eiszeitalter und Gegenwart* 45, 1–14.

Cailleux, A., 1942. Les actionnes éoliennes périglaciaires en Europe. *Mémoires de la Société Géologique de France* 41, 176 pp.

Dietzel, M., 2005. Impact of cyclic freezing on precipitation of silica in Me-SiO_2-H_2O systems and geochemical implications for cryosoils and sediments. *Chemical Geology* 216, 79–88.

Galon, R., 1961. Morphology of the Noteć-Warta (or Toruń-Eberswalde) ice marginal streamway. *Prace Geograficzne* 29, 7–115.

Galon, R., 1968. New facts and problems pertaining to the origin of the Notec-Warta Pradolina and the valleys linked with it. *Przegląd Geograficzny* 40, 307–315.

Goździk, J., 2007. The Vistulian aeolian succession in central Poland. *Sedimentary Geology* 193, 211–220.

Hart, J.K., 2006. An investigation of subglacial processes at the microscale from Briksdalsbreen, Norway. *Sedimentology* 53, 125–146.

Iverson, N.R., Hooyer, T.S. & Hooke, R.L., 1996. A laboratory study of sediment deformation: stress heterogeneity and grain-size evolution. *Annals of Glaciology* 22, 167–175.

Kamińska, R., Konecka-Betley, K. & Mycielska-Dowgiałło, E., 1986. The Liszyno dune in the Vistula Valley (east of Płock). *Biuletyn Peryglacjalny* 31, 141–162.

Kasse, C., 1997. Cold-climate aeolian sand-sheet formation in North-Western Europe (c. 14–12.4 ka); a response to permafrost degradation and increased aridity. *Permafrost and Periglacial Processes* 8, 295–311.

Kasse, C., Vandenberghe, J., van Huissteden, J., Bohncke, S.J.P. & Bos, J.A.A., 2003. Sensitivity of Weichselian fluvial systems to climate change (Nochten mine, eastern Germany). *Quaternary Science Reviews* 22, 2141–2156.

Kaulbarsz, D., Jurys, L., Kramarska, R. & Słodkowska, B., 2008. Orłowo cliff – geology, glaciotectonics and palynological study of Neogene deposits. [In:] S. Lisicki (Ed.): *Quaternary of the Gulf of Gdańsk and Lower Vistula regions in Northern Poland: sedimentary environments, stratigraphy and palaeogeography*. PIG Press, Warsaw, 91–92.

Koster, E.A., 1988. Ancient and modern cold-climate aeolian sand deposition: a review. *Journal of Quaternary Science* 3, 69–83.

Kozarski, S., 1965. Zagadnienie drogi odpływu wód pradolinnych z zachodniej części Pradoliny Noteci-Warty [The problem of the outflow from the western part of Noteć-Warta ice-marginal valley]. *Prace Komisji Geograficzno-Geologicznej* 5, 87 pp.

Kozarski, S., 1986. Skale czasu a rytm zdarzeń zdarzeń geomorfologicznych vistulianu na Niżu Polskim [Time scales and rhythm of geomorphological events during the Vistulian in the Polish Lowlands]. *Czasopismo Geograficzne* 57, 247–270.

Kozarski, S., 1991. Litostratygrafia górnego plenivistulianu Niziny Wielkopolskiej w granicach ostatniego zlodowacenia: nowe dane i interpretacje [Lithostratigraphy of the upper Plenivistulian in the Wielkopolska Lowland during the last glaciation: new data and interpretations]. [In:] A. Kostrzewski (Ed.): Geneza, litologia i stratygrafia utworów czwartorzędowych [Genesis, lithology and stratigraphy of Quaternary sediments]. *Geografia* 50, 471–496.

Kozarski, S. & Nowaczyk, B., 1985. Stratygrafia osadów plejstoceńskich w profilu Ujście nad Notecią [Stratigraphy of the Pleistocene sediments at Ujście]. *Sprawozdanie Poznańskiego Towarzystwa Przyjaciół Nauk* 101, 49–51.

Lindé, K., 1984. Scanning electron microscope studies of different sands and silts. *Acta Universitatis Upsaliensis* 748, 1–10.

Lindé, K. & Mycielska-Dowgiałło, E., 1980. Some experimentally produced microtextures on grain surfaces of quartz sand. *Geografiska Annaler* 62A, 171–184.

Mahaney, W.C., 1995. Pleistocene and Holocene glacier thicknesses and/or transport histories inferred from microtextures and quartz particles. *Boreas* 24, 293–304.

Mahaney, W.C., 2002. *Atlas of sand grain surface textures and applications*. Oxford University Press, Oxford, 237 pp.

Manikowska, B., 1991. Vistulian and Holocene aeolian activity, pedostratigraphy and relief evolution in central Poland. *Zeitschrift für Geomorphologie* 90, 131–141.

Marks, L., 2012. Timing of the Late Vistulian (Weichselian) glacial phases in Poland. *Quaternary Science Reviews* 44, 81–88.

Miall, A.D., 1978. Lithofacies types and vertical profile models in braided river deposits: a summary. [In:] A.D. Miall (Ed.): Fluvial sedimentology. *Canadian Society of Petroleum Geologists* 5, 597–604.

Mojski, J.E., 2005. *Ziemie polskie w czwartorzędzie. Zarys morfogenezy* [Poland in the Quaternary. Morphogenesis]. PIG Press, Warsaw, 404 pp.

Mol, J., Vandenberghe, J. & Kasse, C., 2000. River response to variations of periglacial climate in mid-latitude Europe. *Geomorphology* 33, 131–148.

Mycielska-Dowgiałło, E., 1993. Estimates of Late Glacial and Holocene aeolian activity in Belgium, Poland and Sweden. *Boreas* 22, 165–170.

Mycielska-Dowgiałło, E., 2001. Wpływ warunków klimatycznych na cechy strukturalne i tekstualne osadów mineralnych [The influence of climatic conditions on structural and textual features of mineral deposits]. [In:] A. Karczewski & Z. Zwoliński (Eds): *Funkcjonowanie geosystemów w zróżnicowanych warunk-*

ach morfoklimatycznych – monitoring, ochrona, edukacja [*The functioning of geosystems under different morphoclimatic conditions – monitoring, protection, education*]. Wydawnictwo Naukowe UAM, Poznań, 377–394.

Mycielska-Dowgiałło, E. & Woronko, B., 1998. Analiza obtoczenia i zmatowienia powierzchni ziarn kwarcowych frakcji piaszczystej i jej wartość interpretacyjna [Rounding and frosting analysis of quartz sand-grain surfaces and their significance for interpretations]. *Przegląd Geologiczny* 46, 1275–1281.

Mycielska-Dowgiałło, E. & Woronko, B., 2004. The degree of aeolization of Quaternary deposits in Poland as a tool for stratigraphic interpretation. *Sedimentary Geology* 168, 149–163.

Pisarska-Jamroży, M., 2015. Factors controlling sedimentation in the Toruń-Eberswalde ice-marginal valley during the Pomeranian phase of the Weichselian glaciation: an overview. *Geologos* 21, 1–29.

Pisarska-Jamroży, M. & Zieliński, T., 2011. Genesis of a till/sand breccia (Pleistocene, Noteć Valley near Atanazyn, central Poland). *Sedimentary Geology* 236, 109–116.

Pisarska-Jamroży, M. & Zieliński, T., 2014. Pleistocene sandur rhythms, cycles and megacycles: Interpretation of depositional scenarios and palaeoenvironmental conditions. *Boreas* 43, 330–348.

Pisarska-Jamroży, M., van Loon, A.J., Woronko, B. & Sternal, B., 2015a. Heavy-mineral analysis as a tool to trace the source areas of sediments in an ice-marginal valley, with an example from the Pleistocene in NW Poland. *Netherlands Journal of Geosciences* 94, 185–200.

Pisarska-Jamroży, M., van Loon, A.J. & Woronko, B., 2015b. Sorting of heavy minerals in sediments deposited at a high accumulation rate, with examples from sandurs and an ice-marginal valley in NW Poland. *GFF*, 137, 126–140

Rose, K.C. & Hart, J.K., 2008. Subglacial comminution in the deforming bed: inferences from SEM analysis. *Sedimentary Geology* 203, 87–97.

Traczyk, A. & Woronko, B., 2010. Historia zlodowacenia doliny Łomnicy w Karkonoszach w zapisie mikromorfologii powierzchni ziarn kwarcowych [The history of glaciation of the Łomnica Valley at Karkonosze as shown by the records of the quartz-grain surface micromorphology]. *Przegląd Geologiczny* 58, 1182–1191.

Tricart, J., 1965. *Principes et méthodes de géomorphologie*. Masson, Paris, 496 pp.

Tylman, K., Wysota, W., Adamiec, G., Molewski, P. & Chabowski, M., 2013. Relict sand wedges in glacial till sequences: indicators of late Pleistocene periglacial environment in north-central Poland. [In:] *Palaeolandscapes from Saalian to Weichselian. South Eastern Lithuania*. Abstracts of International Field Symposium, 2013, Vilnius–Trakai–Lithuania, 95.

van Huissteden, J., Schwan, J.C.G. & Bateman, M.D., 2001. Environmental conditions and paleowind directions at the end of the Weichselian Late Pleniglacial recorded in aeolian sediments and geomorphology (Twente, Eastern Netherlands). *Netherlands Journal of Geosciences* 80, 1–18.

van Vliet-Lanoë, B., 2010. Frost action. [In:] G. Stoops, V. Marcellino & F. Mees (Eds): *Interpretation of micromorphological features of soils and regoliths*. Elsevier, London, 81–108.

Ward, J.H., 1963. Hierarchical grouping to optimize an objective function. *Journal of the American Statistical Association* 58, 236–244.

Weckwerth, P., 2013. *Procesy fluwialne toruńskiego basenu sedymentacyjnego podczas zlodowacenia wisły* [*Fluvial processes of the Toruń Basin during the Weichselian glaciation*]. Nicolaus Copernicus University Press, Toruń, 205 pp.

Weckwerth, P. & Chabowski, M., 2013. Heavy minerals as a tool to reconstruct river activity during the Weichselian glaciation (Toruń Basin, Poland). *Geologos* 19, 25–46.

Weckwerth, P. & Pisarska-Jamroży, M., 2015. Periglacial and fluvial factors controlling the sedimentation of Pleistocene breccia, NW Poland. *Geografiska Annaler*, 97A, 415–430.

Woronko, B., 2007. Typy mikromorfologii powierzchni ziarn kwarcowych frakcji pylastej i ich wartość interpretacyjna [Micromorphology types of quartz grains surface of silt fraction of their interpretative meaning]. [In:] E. Mycielska-Dowgiałło & J. Rutkowski (Eds): *Badania cech teksturalnych osadów czwartorzędowych i wybrane metody oznaczania ich wieku* [*Textural features of Quaternary sediments and some methods to determine their age*]. SWPR Press, Warsaw, 181–204.

Woronko, B., 2012. Micromorphology of quartz grains as a tool in the reconstruction of periglacial environment. [In:]: P. Churski (Ed): *Contemporary issues in Polish geography*, Wydawnictwo Naukowe UAM, Poznań, 111–131.

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, 214–227.

Woronko, B., Szwarczewski, P. & Bujak, P., 2011. Zapis zmian środowiska przyrodniczego w dolinie rzeki Mlecznej w rejonie wczesnośredniowiecznego grodziska Piotrówka w Radomiu na podstawie charakteru powierzchni ziarn kwarcowych frakcji piaszczystej [The record of environmental changes in the Mleczna river valley in the region of the early medieval Piotrówka settlement at Radom, based on the nature of the surface of sand-sized quartz grains]. [In:] A. Buko, D. Główka & M. Trzeciecki (Eds): *Radom: korzenie miasta i regionu. Radomski zespół osadniczy w dolinie rzeki Mlecznej. Wyniki badań interdyscyplinarnych* [*Radom: the roots of the city and the region. The Radom settlement in the valley of the Mleczna river. Results of interdisciplinary investigations*]. Instytut Archeologii i Etnologii PAN 2, Warsaw, 149–167.

Woronko, B., Rychel, J., Karasiewicz, M.K., 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, 47–66.

Woronko, B. & Pisarska-Jamroży, M. in press. Micro-scale frost weathering of sand-sized quartz grains. *Permafrost and Periglacial Processes*. DOI: 10.1002/ppp.1855.

Zeeberg, J.J., 1998. The European sand belt in eastern Europe – and comparison of Late Glacial dune orientation with GCM simulation results. *Boreas* 27, 127–139.

Zieliński, P., Sokołowski, R.J., Woronko, B., Jankowski, M., Fedorowicz, S., Zaleski, I., Molodkov, A. & Weckwerth, P., in press. The depositional conditions of the fluvio-aeolian succession during the last climate minimum based on the examples from Poland and NW Ukraine. *Quaternary International,* doi.org/10.1016/j.quaint.2014.08.013.

Zieliński, T. & Pisarska-Jamroży, M., 2012. Jakie cechy litologiczne warto kodować, a jakie nie? [Which features of deposits should be included in a code and which not?]. *Przegląd Geologiczny* 60, 387–397.

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