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Sediment sources and transport pathways of dune sands, western Sandomierz Basin (Southern Poland)

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Abstract

Aeolian dune fields of the European Sand Belt extend across Poland, yet their southern limit coincides with the Sandomierz Basin, where potential sand sources from the Małopolska Upland and the Carpathians converge. This study uses quartz-grain morphology to constrain the provenance of dune sands in the western Sandomierz Basin and to assess Late Pleniglacial (MIS 2) aeolian–fluvial interactions. Sediments were sampled from aeolian dunes, fluvial terraces and outwash plains across c. 2,500 km², including the Vistula and its tributaries (Dunajec, Raba, Rudawa and Przemsza) and adjacent uplands. Stratigraphic ages were assigned using the Detailed Geological Map series (1:50,000). Grain roundness was measured on the 0.8–1.0 mm fraction using Krumbein's scale, and grain-surface textures were classified with the Cailleux morphoscopic approach (NU, EL, RM, EM).

Carpathian-river alluvia (Raba, Dunajec) show predominantly subangular to subrounded grains in Early Pleniglacial deposits, indicating limited aeolian abrasion despite long fluvial transport. In Late Pleniglacial alluvia, RM proportions increase markedly and roundness distributions become bimodal, reflecting enhanced aeolian reworking during the coldest MIS 2 phases. In contrast, Vistula and upland-tributary alluvia contain higher RM contents and more rounded grains, consistent with recycling of sands previously modified by long-distance aeolian transport on the Małopolska Upland. Dune deposits display strong spatial variability: the northern dune zone adjacent to the Vistula is dominated by Vistula-like, well-rounded RM grains, whereas southern dune clusters (Raba Fan, Raba–Dunajec interfluve, Tarnów Plateau) record mixed contributions, locally modulated by river corridors and topographic barriers that constrained aeolian pathways.

Quartz-grain morphology thus provides an effective, low-cost proxy for distinguishing upland versus Carpathian sand sources and for reconstructing short-range transport pathways and sediment mixing within coupled aeolian–fluvial systems during the Late Pleniglacial.

Keywords: European Sand Belt, sand abrasion, Pleniglacial, provenance of dune sand

1. Introduction

Poland is traversed by the so-called *European Sand Belt* (Koster, 1988; Zeeberg, 1998; Kasse, 2002), where extensive dune fields and sheets of aeolian cover sands are developed. The origin of these sediments and landforms is primarily associated with aeolian processes that operated under cold-climate conditions during the Pleistocene. Questions concerning the lithology, genesis, and chronology of these deposits have been addressed in numerous studies conducted in the countries traversed by the sand belt. Earlier research focused mainly on the internal structure and age of individual dune forms, emphasising their stabilisation during the Late Glacial and considering nearby sediments as their

most probable source. In contrast, investigations of dune fields in contemporary deserts go beyond the description of their present morphology and seek to reconstruct the conditions that enabled dune-field development. Such studies aim to identify the sources of sand, the pathways of its transport, and the conditions that led to its accumulation in specific areas at given times (Garzanti, 2016, 2017; Cui et al., 2024). Considerable attention is also devoted to interactions between aeolian and fluvial systems. More recent research on Pleistocene dune fields in Poland has begun to address these aspects (Buraczyński, 1994; Goździk, 1991, 2007a; Łopuch et al., 2023; Moska et al., 2022; Sokołowski et al., 2022).

The Sandomierz Basin, coincides with the southern limit of the European Sand Belt. North of this boundary, numerous dune fields and extensive sheets of aeolian cover sands are present. In the Carpathians, however, only silty aeolian sediments occur, while sandy deposits are absent (analyses of the Geological Maps of Poland 1:50,000). One manifestation of the contrasting intensity of aeolian processes between the Carpathians and the adjacent sand-belt areas is the difference in the proportion of rounded and matted sand grains formed by aeolian abrasion. As early as 1942, Cailleux reported a high content of such grains in Quaternary sediments of central Poland, whereas in the Carpathians he found only trace amounts.

Various sediment characteristics are currently employed to reconstruct sand sources, transport pathways, and fluvial–aeolian interactions. Analyses of mineral composition and geochemical signatures are often applied (Muhs et al., 2003; Garzanti et al., 2013, 2015; Du et al., 2018; Ninard et al., 2023). However, in certain contexts, textural attributes – particularly grain shape – may serve as useful indicators. This approach is applicable where areas favourable and unfavourable to intensive aeolian abrasion are located in close proximity.

Our study concerns the morphology of sand-sized quartz grains in dune and fluvial deposits accumulated during the Pleniglacial (i.e. the Last Glacial Maximum, and in the Polish stratigraphic division the so-called Plenivistulian) (Pillans, 2013; Marks, 2013). Recent morphometric studies, for example on the Bory Stobrawskie Dune Field in SW Poland, show evidence for multi-phase Lateglacial aeolian activity, with variation in dune type (transverse, parabolic) controlled by sand supply, wind direction, and vegetation cover (Łopuch et al., 2023). Likewise, radiocarbon and OSL chronostratigraphy from Niemodlin Plateau (SW Poland) indicates phases of fluvio-aeolian succession during Late Pleniglacial and Late Glacial intervals (Moska et al., 2020, 2022). Reinterpretation of fluvio-aeolian successions in central Poland using high-resolution radiocarbon data further confirms the importance of spatial variability in sediment supply (Sokołowski et al., 2022).

Upon entering the Sandomierz Basin, Carpathian rivers form terraces and extensive alluvial fans, which represent potential sources of dune sand. These deposits, however, contain only very small proportions of grains with clear aeolian imprints. Consequently, it is relatively straightforward to assess the contribution of sands supplied by Carpathian rivers relative to that derived from adjacent areas of the European Sand Belt. It is equally important to account for the spatial variability of this proportion in relation to dune position and to reconstruct potential aeolian transport pathways within the Basin (= Sandomierz Basin).

This paper investigates the provenance of dune sands in the western Sandomierz Basin, focusing on differences in quartz grain morphology between upland and Carpathian sources, and the interactions of aeolian and fluvial processes during the Late Pleniglacial.

2. Study area

The Sandomierz Basin is triangular in form, bounded to the south by the Carpathian Foothills and to the north by the Małopolska Upland. (Fig. 1). Dunes within the Basin are unevenly distributed, with the highest concentrations occurring in the north-east. In the western part of the Sandomierz Basin, dunes form smaller, more dispersed fields, the largest of which is situated on the Raba River Fan. South of the Vistula valley, the Basin floor is crossed by two major Carpathian rivers – the Raba and the Dunajec – together with their tributaries (Fig. 1). Only a few minor rivers originate within the Basin itself. As a consequence, the river network and associated sand-transport pathways in the western sector are relatively simple. To the east, the Tarnów Plateau forms the boundary of the study area (Fig. 1).

To complement existing knowledge on the morphology of sand grains transported by rivers into the Sandomierz Basin, the sampling area was extended to include the Carpathian Foothills. The Cracow Gate, a pronounced depression between the Małopolska Upland and the Carpathian Foothills, is occupied by the Vistula River and acted as a major corridor for the delivery of sandy material into the Sandomierz Basin. The entire study area is illustrated in Figures 1 and 2.

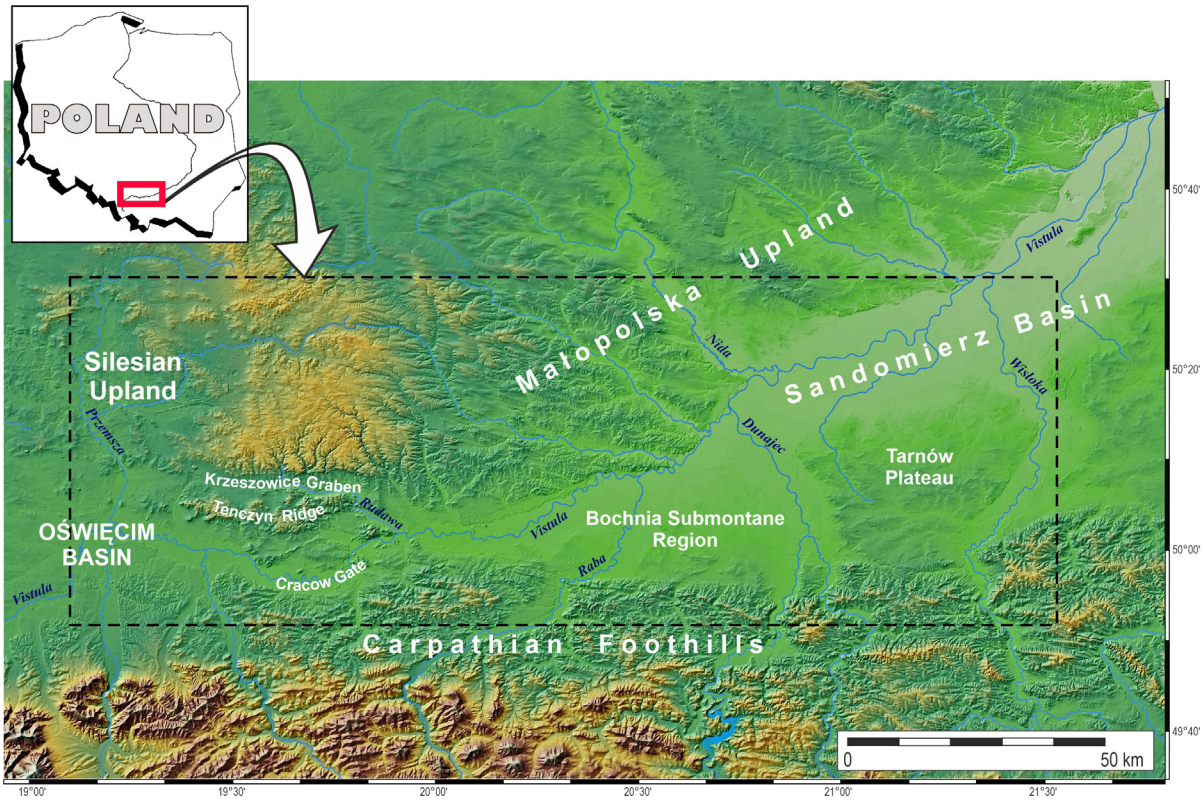

Fig. 1. Location of the study area (geographical units after Solon et al., 2018). DEM image downloaded from geoportal.gov.pl.

Approximately three-quarters of the western Sandomierz Basin is occupied by the floors of the Vistula River and its Carpathian tributaries. These floors are covered by alluvial formations comprising several terrace levels and alluvial fans. Older Pleistocene terraces are preserved only locally, whereas Weichselian terraces and alluvial fans occupy extensive areas (Fig. 2). Two principal terrace levels occur at elevations of 15–20 m and 10–15 m above the present river beds. Of these, the 10–15 m terraces are the most widespread Pleistocene accumulative level. Within the Cracow Gate (Fig. 1) they form narrow strips along the Vistula valley and its tributaries, while in the Sandomierz Basin they are represented by right-bank Vistula terraces as well as terraces and fans of Carpathian tributaries. This level also extends into the foothill reaches of the Raba and Dunajec valleys. The sandy alluvium of the braided rivers forming this terrace has been dated to 24–17 ka BP (Gębica, 2004; Moska et al., 2022).

During the Upper Pleniglacial, when cold-desert conditions prevailed, dune fields developed. Most dunes in the study area are located in the Sandomierz Basin; their latitudinal arrangement reflects the direction of prevailing dune-forming winds. The extensive flat sand-gravel surfaces favoured aeolian processes (Łopuch et al., 2023).

At the transition from the Pleniglacial to the Late Weichselian, between approximately 16–15 ka BP, climatic amelioration likely reduced the intensity of aeolian processes across many parts of Central Europe. The stabilisation of dunes became more pronounced during the Bølling–Allerød interstadial (14.7–12.9 ka BP), whereas both the Older and Younger Dryas were associated with renewed phases of aeolian activity, as previously reported in studies from Poland (Izmaiłow, 1975; Wojtanowicz, 2003). Fluvial systems were also subject to substantial changes. Phases of erosion occurred between c. 17 and 15 ka BP, but the widespread transition from braided to meandering channels is generally better documented after 15 ka BP, although the timing varied regionally. This transformation was largely driven by increasing vegetation cover and reduced sediment supply, which altered channel stability. Stratigraphic investigations in southwestern Poland document a complex, multi-phase fluvio-aeolian succession spanning approximately 24–13.5 ka BP, with aeolian activity occurring not only before but also after 15 ka BP (Moska et al., 2022). According to Słowik (2023), the shift from braided to meandering and anabranching rivers in postglacial and loess landscapes of Europe was a gradual rather than a single, abrupt transformation. In this mod-

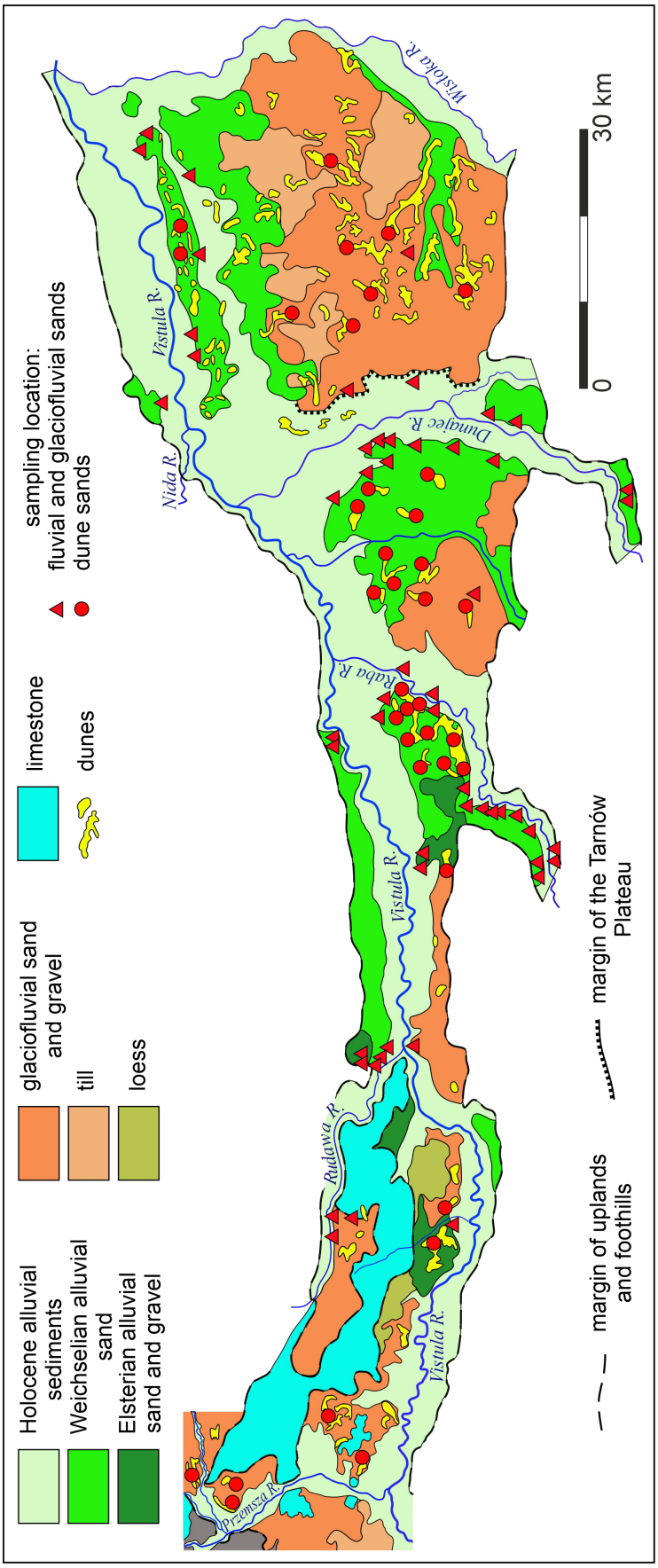

Fig. 2. Sample collection locations against the background of the geological-geomorphological sketch.

el, landforms inherited from braided-river activity were progressively reshaped into more sinuous and, subsequently, anabranching channels during the Late Weichselian and early Holocene. Successive phases of erosion and accumulation during this period produced sequences of lower terrace levels, reflecting the long-term geomorphic adjustment of river systems.

3. Methods

The study was conducted on sediments collected from aeolian dunes, fluvial terraces and outwash plains. The origin of the forms was determined on the basis of n field observations and analyses of geological maps at a scale 1:50,000. The samples came from an area of approximately 2,500 km^2, which included valleys of the Vistula, Dunajec, Raba, Rudawa and Przemsza rivers as well as the uplands: Tarnów Plateau, Bochnia Submontane Region and Silesian Upland (Fig. 1). The sediments collected were sands in a wide range of grain sizes: from fine-grained and medium-grained sand to gravelly coarse-grained sand (Fig. 3). Eighty-eight sand samples weighing 500 grams each were studied. The samples were collected from mining pits, hand-dug trenches, and hand drillings at depths of 100–150 cm below the ground surface.

The age of the sediments was determined based on the stratigraphy derived from the Detailed Geological Map series at a scale of 1:50,000. The age designations contained therein appear to be entirely sufficient for this study.

Grain roundness and grain surface textures were determined under laboratory conditions. For these analyses, grains within the 0.8–1.0 mm size fraction were selected. Prior to examination, the grains were treated with hydrochloric acid to remove iron oxides and subsequently rinsed with water and a peptising agent to eliminate clay coatings. Grain roundness was assessed using Krumbein's (1941) scale, which distinguishes nine classes ranging from angular (0.1) to very well rounded (0.9).

At the end of the last century, the dune sands of the Sandomierz Basin were a popular research topic (e.g. Galon, 1969; Schirmer, 1999; and the papers therein). Roundness analyses were also based on the graniformametric method proposed by Krygowski (1964). This technique quantifies the proportion of grains that roll down an inclined plate of the graniformameter set at increasing angles. Grains that roll down at inclinations between 20° and 80° are classified as γ-type, i.e. very well to well rounded. Notably, only 30–50% of grains with roundness values between 0.9 and 0.7, together with a small proportion of grains in the 0.6–0.5 range, meet the criteria for γ-type classification, whereas grains with lower roundness values are entirely excluded. As demonstrated by Goździk (2001), this discrepancy indicates that the actual proportion of well-rounded grains (>0.6) is nearly twice that suggested by the γ-type

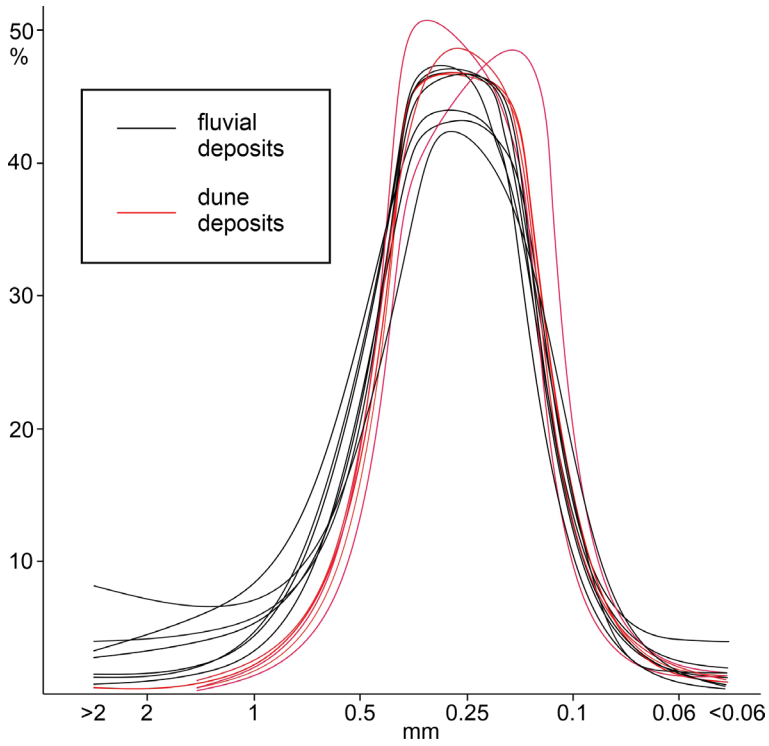

Fig. 3. Examples of grain size distributions of fluvial and dune deposits.

category. Consequently, the γ-type classification provides only a rough estimate of the abundance of well-rounded grains and may underestimate the degree of aeolian abrasion. For this reason, results obtained using Krygowski's mechanical roundness analysis are not directly comparable with those derived from the optical Krumbein method.

In the analysis of aeolian sediments, the morphoscopic method developed by Cailleux (1942) has been widely applied in Central Europe. This method differentiates three principal grain types, each indicative of distinct depositional environments: unworn grains (non-usés, NU), blunt-shiny grains (émoussés-luisants, EL), typically formed by aquatic processes, and round-matt grains (ronds-mats, RM), produced predominantly by aeolian abrasion. Later, Cailleux (1973) also recognised transitional forms between NU and RM, which he classified as blunt-matt grains (émoussés-mats – EM).

According to Goździk (1980), RM grains include only those with a roundness ≥0.7 on Krumbein's scale. This criterion has proven effective in Quaternary sediment analyses from central Poland, where RM grains are commonly found. However, as research extended into areas with less intensive aeolian modification (Goździk, 1986, 2007a), it became necessary to include matt grains with roundness values below 0.7. Consequently, a distinct class of less rounded grains with roundness values between 0.6 and 0.4 was defined and designated as EM (blunt matt).The lower boundary of 0.4 was adopted because grains with roundness ≤0.3 typically display only slightly blunted edges, and their surface dullness is challenging to detect under binocular magnification. In this study, the main focus was on grains shaped by aeolian processes. Based on morphoscopic analysis, the following grain types were distinguished: EL and NU (non-aeolian), and within the aeolian group, RM (≥0.7) and EM (0.6–0.4 roundness). Grains with roundness ≤0.3, as well as those showing transitional features (e.g., partly matt and partly shiny) or altered by non-aeolian processes (e.g., chemical weathering), were grouped into a general 'remaining' (R) category.

This method is rapid and inexpensive, allowing for the examination of large numbers of samples. In our opinion, this simple method is entirely sufficient for distinguishing sand grains that have undergone glacial/fluvioglacial, fluvial, and aeolian transport, without the need for more sophisticated, modern methods such as scanning electron microscopy (SEM).

4. Results

4.1. Morphology of quartz grains in alluvia of the Sandomierz Basin

The alluvia of the Carpathian rivers (Raba and Dunajec) display following features. Early Pleniglacial alluvia comprise sands with abundant gravels. In their sandy fractions, grains with transitional morphoscopic features (R-type) constitute 49.6% in the Dunajec and 59.5% in the Raba (Table 1, Fig. 4).

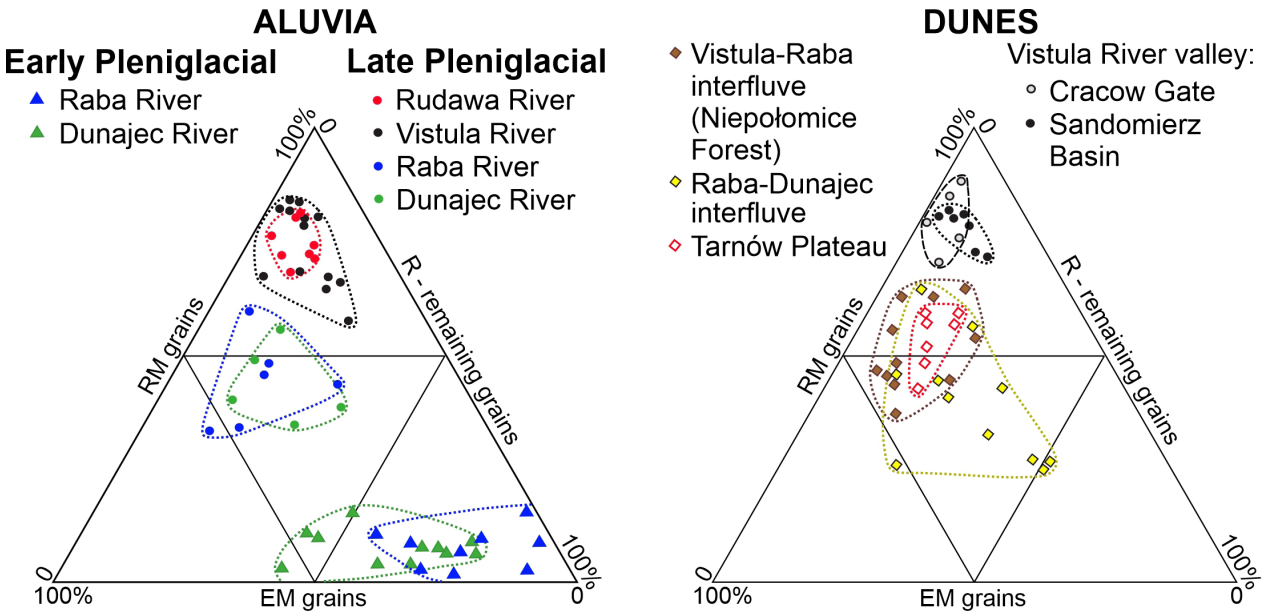

Fig. 4. Triangular diagrams showing the proportions of RM (round-matt) grains, EM (blunt-matt) grains, and R (remaining) grains.

Table 1. Origin of deposits versus their grain shapes.

Origin, location and age of sediments			Number of samples	Grain types according to A. Cailleux				
				RM %	EM %	EL %	NU %	R %
Alluvia	Dunajec River valley	Late Pleniglacial (MIS 2)	5	47.2	37.0	0.7	0.4	14.7
		Early Pleniglacial (MIS 4)	11	7.7	36.4	0.7	5.6	49.6
	Raba River valley	Late Pleniglacial	6	45.7	31.5	0.3	2.3	20.2
		Early Pleniglacial	9	8.3	20.2	1.9	10.1	59.5
	Vistula River valley	Late Pleniglacial	13	66.3	18.9	1.7	0.9	12.2
	Rudawa River valley	Late Pleniglacial	8	74.2	18.2	0.0	0.0	7.6
Glaciofluvial sands		Elsterian (MIS 12) and Saalian (MIS 6)	12	18.7	16.9	13.4	4.7	46.3
Dune sands (Late Pleniglacial – Late Glacial)	Przemsza River catchment		6	86.5	12.6	0.4	0.4	0.1
	Vistula River valley in Cracow Gate		7	79.3	17.6	0.1	0.1	2.9
	Vistula River valley in Sandomierz Basin		6	74.2	17.6	0.3	0.0	7.9
	Raba River alluvial fan		11	52.3	33.3	0.9	0.2	13.3
	Interfluve of Raba and Dunajec rivers		11	45.2	31.2	0.5	0.4	22.7
	Tarnów Plateau		7	53.0	35.2	1.7	0.0	10.1

Most are poorly rounded. These characteristics reflect supply during the Pleistocene from weathered Mesozoic and Palaeogene sedimentary rocks, and in the Dunajec also from plutonic and metamorphic sources. Even over a fluvial distance of c. 275 km, grains in the Dunajec alluvia remained largely angular and unpolished, confirming that long-distance river transport does not significantly enhance grain roundness. The great prevalence of sub-rounded and moderately rounded grains resulted in a unimodal distribution with a modal value at the border between poorly rounded and moderately rounded (Fig. 5). Comparable low degrees of roundness were observed in Cracow-sector fluvial deposits of the Vistula valley, where mixed aeolian–fluvial inputs still yielded low rounded grains content (Rychel et al., 2018).

Middle Pleniglacial sediments locally overlie Early Pleniglacial gravels, and Late Pleniglacial deposits form a more continuous cover. Quartz grain morphology in the Late Pleniglacial sands differs markedly from Early Pleniglacial assemblages (Table 1, Fig. 4). The proportion of RM grains increases severalfold, reaching 45.7% in Raba alluvia and 47.2% in Dunajec alluvia. Grain roundness distributions are bimodal, with modes at 0.4–0.5 and 0.7–0.8 (Fig. 5). The emergence of bimodality and higher RM proportions accords with regional observations that aeolian abrasion increasingly modified quartz-grain surfaces during the coldest phases of MIS 2 (Woronko & Bujak, 2018).

In Vistula alluvia, only Late Pleniglacial deposits were analysed. RM grains predominate (66.3%), exceeding the values in the Raba and Dunajec valleys. EM grains form a secondary admixture (18.9%) (Table 1). The grain-roundness distribution is left-skewed, with a modal value of 0.8 (Fig. 5). In the adjacent Krzeszowice Graben, the Rudawa River (a Vistula tributary) yields the highest RM content recorded (74.2%), with a distribution similar to the Vistula (Figs. 2, 4). This contrast highlights the strong influence of aeolian reworking on the Upland and Vistula system, echoing conclusions drawn from morphoscopic and luminescence-based reconstructions of Late Pleniglacial dune activity elsewhere in southern Poland (cf. Łopuch et al., 2023).

Samples from Early Pleniglacial alluvia of the Vistula and Rudawa were not available for this study. However, Mycielska-Dowgiałło (1978) analysed a complete Pleniglacial sequence in the northern Sandomierz Basin. Using Krygowski's method, she distinguished lower gravelly Early Pleniglacial layers and overlying sandy Late Pleniglacial layers. The proportion of γ-type grains in gravels was estimated at 15–30%, suggesting about twice as many well-rounded grains (0.7–0.9 on Krumbein scale). In the sandy upper part, γ-type proportions increased upward from 20–35% to 20–50%. Mycielska-Dowgiałło (op. cit) attributed the abundance of well-rounded grains to erosion of aeolian sand covers from the adjacent Upland.

Comparable results were obtained in other sites of Sandomierz Basin. Early Pleniglacial alluvia contain 15–30% γ-type grains (Mycielska-Dowgiałło, 1978). Further east, Buraczyński & Butrym (1989) recorded ~30% this type of grains. In the Cracow Gate, Sokołowski et al. (2014) documented Early Pleniglacial alluvia of the Vistula with >90% RM and EM grains, mostly less rounded. These are the alluvia lying in the Vistula River valley slightly be-

low the mouth of the Rudawa River. The alluvia could develop from the mixing of material transported by these rivers. These results corroborate Mycielska-Dowgiałło's (1978) conclusion that Early Pleniglacial alluvia of the Vistula were less rounded than Late Pleniglacial sediments, and confirm the role of earlier aeolian abrasion in shaping quartz surfaces.

Marked differences in grain morphology are evident between Early Pleniglacial alluvia of the Vistula and its northern tributaries versus those of the Carpathian rivers. Carpathian alluvia contain mostly subrounded grains derived from weathering mantles, with little evidence of aeolian abrasion. By contrast, Vistula and upland tributary alluvia contain few grains lacking aeolian features, reflecting sources that had undergone prolonged aeolian transport. Moreover, substrate Cretaceous and Neogene sands already displayed moderate roundness, and their shiny surfaces indicate fluvial shaping.

By the Late Pleniglacial, differences between Vistula and Carpathian alluvia are less pronounced. Carpathian alluvia display bimodal distributions: one mode resembles their Early Pleniglacial assemblages, while the other approaches values observed in the Vistula, though with fewer well-rounded grains. This reduction in contrast reflects intensive aeolian processes during the Upper Pleniglacial. The similarity in grain size between Late Pleniglacial alluvia (dominated by medium sand) and dune sands also indicates aeolian input. The scarcity of EL grains in all alluvia studied (Table 1) – although abundant in glaciofluvial deposits – demonstrates their limited role as direct sand sources. This was mainly due to the development of coarse pavements in these sediments, inhibiting further erosion.

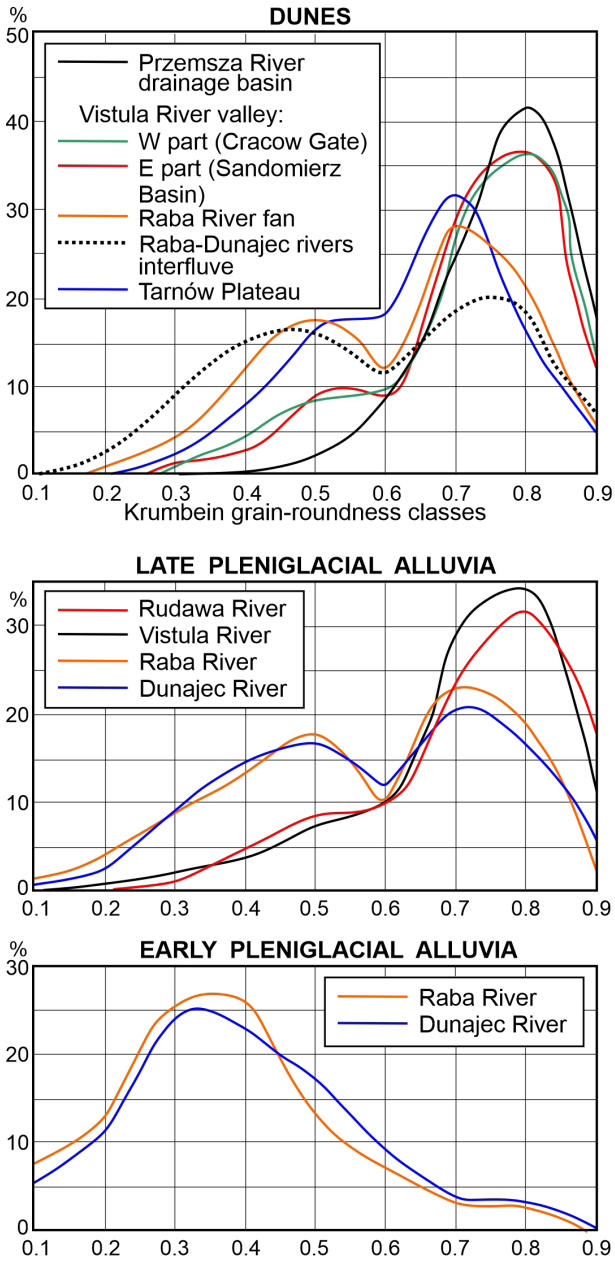

Fig. 5. Grain roundness distribution of the fluvial and aeolian sediments.

4.2. Morphology of quartz grains in dune deposits of the Sandomierz Basin

To facilitate a spatial analysis of sand-grain morphology within dune clusters of the western Sandomierz Basin, the study area was subdivided into smaller parts. The subdivision was based on the orientation of rivers relative to the prevailing directions of aeolian transport, as well as on differences in the composition of alluvia. Two principal zones can be distinguished: a northern and a southern zone. The northern zone is relatively homogeneous and associated with the Vistula River valley, whereas the southern zone is more diverse, comprising three distinct dune clusters: (1) the Raba River Fan (i.e. western Bochnia Submontane Region, also called Niepołomice Forest), (2) the interfluve between the Raba and Dunajec rivers, and (3) the Tarnów Plateau east of the Dunajec tiver (Fig. 1).

In the northern zone, the only dune cluster developed east of the confluences of the Dunajec and Nida rivers (Fig. 2). Here, dune sands show a high proportion of RM grains (74.2%) accompanied by 17.6% EM grains. Their morphoscopic characteristics are similar to those of dune sands in the Vistula valley at the Cracow Gate, near the boundary with the Oświęcim Basin (Table 1; Figs. 1, 6). Comparisons with dunes from the Przemsza catchment in

the Małopolska Upland reveal both similarities and differences: roundness distributions are left-skewed with modes close to 0.8 on Krumbein's scale, yet the degree of skewness is greater in the Sandomierz Basin. The proportion of RM grains is also lower by ~10%. Moreover, the roundness curve of Vistula valley dune sands displays a marked inflection at 0.6, with values above the bend resembling the Przemsza dunes, and values below resembling Carpathian-derived sediments. Similar left-skewed distributions in aeolian systems of southern Poland were also reported by Łopuch et al. (2023).

No direct data are available for the Late Pleniglacial alluvia of the Nida River. However, studies from the Małopolska Upland suggest that RM grains predominate there, accompanied by a significant share of EM grains (Goździk, 2007a; Woronko et al., 2015). Krygowski's graniformametric analyses consistently yield high proportions of γ-type grains, comparable to those in Vistula alluvia. It is therefore reasonable to assume that similar features were present in Nida alluvial deposits.

When comparing dune sands of the Vistula valley with Late Pleniglacial alluvia of the Vistula, a high degree of similarity is observed (Figs. 4–5; Table 1). In contrast, no distinct morphological traits diagnostic of Dunajec alluvia are evident.

The southern zone extends between the Vistula valley and the Carpathian Foothills. Dunes in this zone consistently display lower RM contents and less rounded grains than those in the northern zone (Table 1; Fig. 6), though variability exists between the three dune clusters.

1. On the Raba River Fan, ~150 dunes have been identified (Izmaiłow, 1975). A minor portion overlies Vistula terraces, but the majority, including the largest forms, occur on the alluvial fan itself (Fig. 2). Rivers on the fan flow almost in straight lines towards the main river. This evident deflection of the Raba River has most probably been caused by an intensive aeolian supply of sand from the west which, filling the river bed, shifted it towards the east.
   The highest RM contents (>60%) are observed near the Vistula valley, whereas average values are 20% lower than in the northern zone (Table 1). The highest content of such grains, exceeding 60%, is observed only in the immediate neighbourhood of the Vistula River valley. Similar proportions were recorded in aeolian cover sands at the northern margin of the Raba River Fan (Gębica & Woronko, 1998; Gębica, 2004). Grain-roundness distributions of the Niepołomice Forest (Vistula-Raba interfluve) dunes resemble those of Late Pleniglacial Raba alluvia, though with higher RM proportions and a distinct bimodality partly attributable to aeolian input from the Vistula valley. This bimodality, linking aeolian reworking with fluvial sources, is consistent with broader observations of Pleniglacial sedimentary systems in southern Poland (Sokołowski et al., 2014).

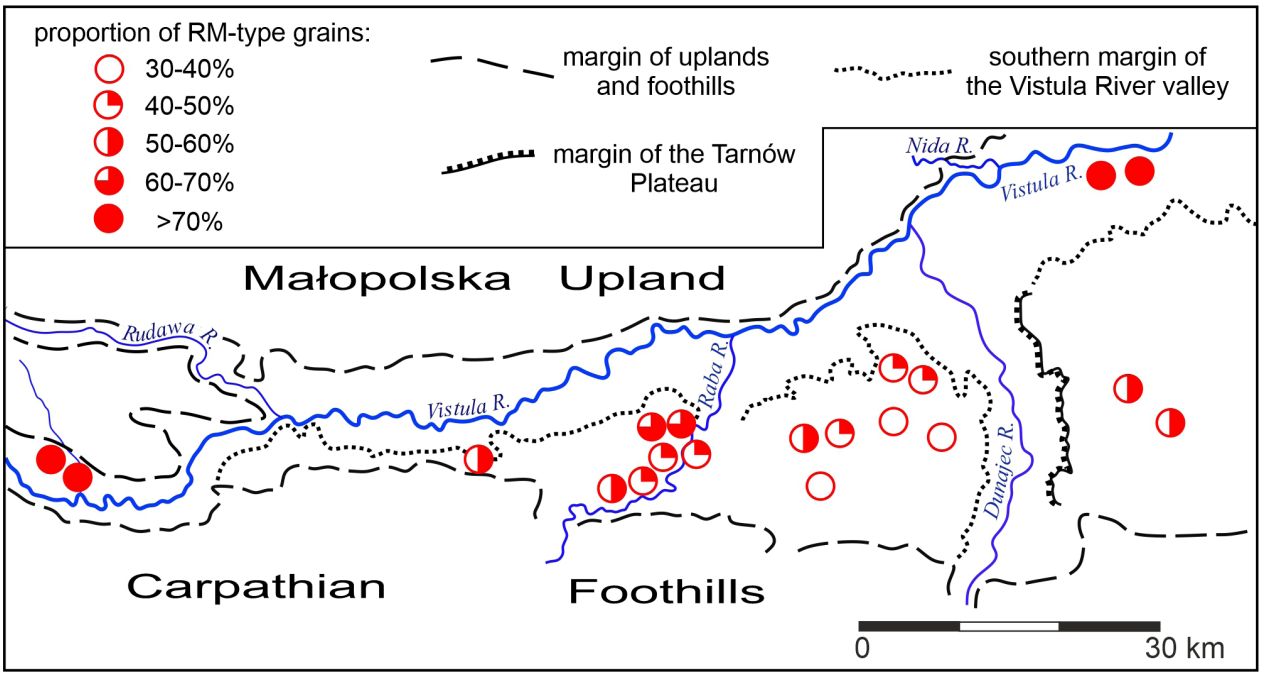

Fig. 6. Map of RM-type grain proportions in the dunes. Some pie charts show average values for several samples.

2. The interfluve between the Raba and Dunajec is composed mainly of glaciofluvial sands with gravels, scattered till patches, and small-valley alluvia. The dunes do not form distinct clusters but are rather scattered. The shape of the grains from these dunes shows much resemblance to the shape seen in the Late Pleniglacial alluvia of the Raba River (Table 1, Fig. 6). Their grain-roundness distributions are bimodal, similar to Raba alluvia, but with ~7% more well-rounded grains (Fig. 5). Notably, RM contents are higher west of the Raba than east of it, suggesting that aeolian transport from the Vistula valley was partly trapped by the Raba channel and its alluvia. Such local contrasts in RM content highlight the importance of geomorphological barriers in directing aeolian supply (Łopuch & Jary, 2023). It can be presumed that sand transported by wind on the Raba River fan did not cross the river as it was incorporated in its alluvial deposits.
3. The Tarnów Plateau, east of the Dunajec, consists mainly of Miocene clays overlain by glaciofluvial sands and gravels with till patches. Its western edge forms a 20–30 m escarpment (Fig. 2), while its northern margin slopes gently towards the Vistula valley. Scattered dunes occur there, with local clustering. Two sampled dunes yielded RM contents of 53%, comparable to Raba Fan dunes (Table 1). Roundness distributions lack clear bimodality, owing to the low proportion of grains <0.4, suggesting limited contribution from Dunajec alluvia. The high western escarpment of the Plateau likely impeded aeolian transport from the Dunajec, indicating that the main source of sand was the Vistula valley. Analogous constraints on aeolian input imposed by topographic barriers have also been described in upland dune systems of central Poland (Goździk, 1986).

5. Discussion

5.1. Quartz grain morphology in Sandomierz Basin dunes and implications for their provenance

In the western Sandomierz Basin sandy alluvia forming extensive terraces and alluvial fans dominate among surface sediments prone to aeolian reworking. These alluvia were deposited by rivers transporting material into the Basin from the Carpathians and the Małopolska Upland, chiefly the Vistula and its Carpathian tributaries, the Dunajec and Raba rivers. These were the most potential sources of aeolian sand redeposition, as they were directly adjacent to the present dune fields. Indeed, in studies of dune sands from the Sandomierz Basin a clear similarity was observed between the shapes of dune sand grains and those of the immediate substrate or nearby sediments (Wojtanowicz, 1970; Izmaiłow, 1975, 1984; Nowaczyk, 1986). Comparative research from other parts of Europe likewise confirms that inland dunes were generally derived from adjacent fluvial, glaciofluvial or glaciolacustrine deposits and transported only over short distances (Kasse, 2002; Vandenberghe, 2013). Moreover, an increase in the proportion of more strongly abraded (i.e. RM) grains was noted in aeolian sediments compared to their substrates, showing that even limited aeolian transport can rapidly produce matt and rounded surfaces on quartz grains (see also Pye & Tsoar, 2009). This suggests that aeolian abrasion processes take place over distances much shorter than previously assumed.

During the Late Pleniglacial, aeolian processes developed differently in the Małopolska Upland (north of the Sandomierz Basin) and the Carpathians (in the south). On the Upland well-rounded matt (RM) grains predominate. Their abundance results from strong aeolian abrasion during long-distance transport (Goździk, 2007a; Goździk & Kobojek, 2016). In contrast, in the Carpathians only silty aeolian covers are present, while sandy aeolian sediments are absent, even within larger intramontane basins. There are no traces of intensive aeolian abrasion in the Carpathian sediments, and subangular to subrounded grains prevail.

5.2. The course of aeolian and fluvial processes in the study area in the Late Pleniglacial

The analysis of dune sands and their potential sources in the western Sandomierz Basin revealed distinct spatial variability in quartz-grain morphology. This reflects contrasting sediment contributions from the northern uplands and those from the south, i.e. from the Carpathians (Woronko et al., 2015).

In the uplands adjacent to the Sandomierz Basin and within the Oświęcim–Cracow Corridor, even Early Pleniglacial alluvia contained a substantial proportion of well-rounded grains, while in the Late Pleniglacial RM grains predominated. In subsequent Pleniglacial phases, alluvia in the Vistula valley adjacent to uplands exhibited similar grain

morphology but with higher EM contents, reflecting minor input of less abraded material supplied by Carpathian rivers (Goździk, 2007a, b; Sokołowski et al., 2014).

In the Carpathian Foothills south of the Basin, no extensive dune or cover sands have been documented. Sediment input during the Weichselian was primarily alluvial. Detailed data on the morphology of the sand grains remain lacking, apart from early reports of low RM contents (Cailleux, 1942). Our analysis of Early Pleniglacial Carpathian alluvia indicates a predominance of poorly to moderately rounded grains, with only a small admixture, to a mere several percent, of well-rounded grains. In contrast, Late Pleniglacial Carpathian alluvia within the Basin reveal marked bimodality (Table 1, Fig. 5): angular grains were either eliminated or reduced, moderately rounded grains increased, and a second population of well-rounded grains emerged, resembling those from Vistula-valley sediments. This indicates deflation and aeolian reworking of local alluvial sands, mixed with aeolian input from upland sources (Gębica, 2004; Woronko et al., 2015).

Within the southern dune zone, spatial variability justified subdivision into three parts separated by the Raba and Dunajec rivers. The dunes on the Raba River Fan and in the Raba–Dunajec interfluve most closely resemble adjacent Late Pleniglacial alluvia. Raba Fan dunes contain the highest proportion of Vistula-like, well-rounded grains, whereas interfluve dunes are enriched in Carpathian-derived grains (Gębica & Woronko, 1998). On the Tarnów Plateau, by contrast, grain-roundness distributions are unimodal, resembling those of the Vistula valley, suggesting northern sand supply; the high western escarpment acted as a barrier to Carpathian aeolian input (Łopuch et al., 2023).

Comparisons with desert dune systems provide a broader context. In hot deserts, dune sands are typically angular and subangular (Tricart & Mainguet, 1965; Folk, 1978). Goudie & Watson (1981) stated "that true roundness is relatively rare, that different ergs have different grain roundness characteristics". These findings have been confirmed by regional case studies in Iraq (Ali & Al Ani, 1983), Arabia (Edgell, 2006), Egypt (Besler, 2008), Argentina (Tripaldi et al., 2010). The sand dune grains from the eastern part of the Arab Peninsula (Abu-Zeid et al., 2001) are classified as more rounded, where as many as 29-40% fall into two classes of the highest roundness, whereas 35-40% belong to the subrounded class. Cold deserts, by contrast, display more variable morphology of grains: in Victoria Valley, Antarctica, dune sands of the 1.0 0.5 mm fraction are well-rounded, while the sand grains of the glaciofluvial sediments occurring in the vicinity showed only slightly less rounding. All the grains were matt reflecting aeolian abrasion. Upon analysing them under a scanning microscope, D. Krinsley stated "that the grains were well rounded and that evidence of wind action was present on most of them" (Calkin & Rutford, 1974, p. 212). Photographs of sand grains made under a scanning microscope, including photographs from the dunes of the Victoria Valley, were presented by Selby et al. (1974). They commented that the grains were well-rounded although grains showing irregularities and traces of fractures were also found. In the outwash sediments, however, the proportion of the latter grains was higher. In the neighbouring region of the Wright Lower Glacier, where extensive aeolian sheets occur, Hambrey & Fitzsimons (2010) found subrounded and subangular grains to be predominant. In the moraine and outwash sediments the shapes of grains were similar. In the Victoria Valley the roundness of grains was thus variable, depending on the location of the aeolian sediments. On Prince Patrick Island (Canada), matt grains (20–30%) were observed, but not fully rounded (Pissart, 1966). This variability highlights the role of local sediment sources and recycling.

Against this background, the bimodal distributions observed in the Sandomierz Basin are instructive. The first population resembles the subrounded/subangular pattern common in desert dunes, while the second population of well-rounded grains – rare in modern deserts – reflects recycling and long-distance aeolian transport from upland sources. The sediments which underwent the Pleistocene aeolian erosion were already moderately-rounded, and often they had an admixture of well-rounded grains (Goździk, 1980, 2007a,b; Kobojek, 1990). In dunes of the western part of the Sandomierz Basin the proportion of grains from the second population is much greater. This is associated with a predominant supply by wind from the uplands situated on the northern side. Well-rounded grains in contemporary deserts are associated with wind handling or long distance aeolian transport and recycling, and these two factors are also primarily responsible for a high degree of grain rounding in the southern part of the upland belt in Poland. The southern part of the uplands was twice located within the cold-desert zone during the maximum glaciation, although it remained outside the ice sheet. As a result, the sand grains could have been subjected to more prolonged wind action, and the underlying sediments were more susceptible to deflation. In the Carpathians, however, rivers

transport great quantities of coarser particles which makes the aeolian erosion of the sandy material very difficult. Similar dual populations, linked to proximal and distal sediment sources, were emphasised in the pattern-analysis approach of Łopuch & Jary (2023), who showed that most dune fields in the central European Sand Belt derived from local, short-range sources, with long-distance transport playing only a limited role.

Over the last two decades, aeolian–fluvial interactions have received growing attention (Bullard & McTainsh, 2003; Liu & Coulthard, 2015). French (2016, 2017) demonstrated that in polar deserts, snow redistribution, permafrost, and rapid melt favour braided river activity despite aridity. The snow is unevenly distributed across the landscape because of transport by wind in winter, its cover is thicker in the valleys. The snow concentrated in the valleys melt in a short period in spring. The presence of impermeable permafrost does not allow snow melt runoff to infiltrate. These factors together with high sediment load derived from weakly consolidated sands and gravels, favour the development of the braided river system. Comparable conditions likely operated in the Upper Pleniglacial of Poland, where sand braided rivers formed along aeolian pathways.

In the Late Pleniglacial Sandomierz Basin, rivers played a crucial role in redistributing aeolian sand. In the north, well-rounded dune and cover sands partly entered tributaries and the Vistula, while migrating dunes also acted as sediment sources for river alluvia. The oblique orientation of the Vistula valley relative to prevailing winds turned the river into a barrier, favouring sand influx to the channel and eastward fluvial transport. In the Cracow Gate, fluvial processes dominated, whereas on the Sandomierz Basin floor, aeolian reactivation prevailed, producing bimodal roundness distributions. The interplay of aeolian and fluvial processes thus alternated between fluvial-dominant and aeolian-dominant modes (Liu & Coulthard, 2015), paralleling findings of Łopuch & Jary (2023), who argued that dune-field migration and morphology in the central European Sand Belt primarily reflect sediment-supply dynamics, geomorphic barriers, and short-range transport rather than long-distance aeolian flux.

6. Conclusions

The shape of sand grains, as one of their key textural characteristics, has proven to be a valuable indicator in determining the provenance and transport pathways of dune sands in the western part of the Sandomierz Basin. Marked differences in grain shape exist between potential sediment source areas located on opposite sides of the Basin. In the northern upland zone, well-rounded grains predominate, whereas in the southern mountain zone, subangular to subrounded grains are more common. These morphological differences have facilitated the identification of the primary pathways of aeolian sand transport and contributed to a partial reconstruction of the processes responsible for grain shape modification. Grain shape analysis also allowed for the estimation of the relative contributions of sediments from each source area to the dune fields situated throughout the western Sandomierz Basin.

During the Late Pleniglacial, sand transport occurred under conditions of interaction between aeolian and fluvial systems. Sediments entering the Basin from both the northern and southern zones were subjected to mixing within these coexisting dynamic systems. The alignment of aeolian transport directions with the flow direction of the Vistula River proved conducive not only to the accumulation of aeolian sands but also to the formation of fluvial alluvia. Particularly favourable conditions were observed in the section of the valley within the Cracow Gate, where high escarpments bordering the valley constrained lateral sediment transport, limiting the supply of material to the aeolian system and restricting the development of aeolian forms.

During the maximum cooling period in cold desert conditions, the results of aeolian processes were clearly different in the areas of the Carpathians and the Małopolska Upland. In the interior of the Carpathians – specifically within the Dunajec and Raba drainage basins – sandy aeolian deposits are absent. In contrast, numerous dunes and sand covers developed in the depressions of the Małopolska Upland. Fluvial sediments of the Carpathian rivers exhibit no significant evidence of intensive grain abrasion, whereas in the Małopolska Upland, such features are clearly present in both aeolian and fluvial deposits. Among the factors controlling grain shape variability, sand supply and sediment availability emerged as especially significant. Fluvial sediments of the Dunajec and Raba rivers are dominated by gravel and cobbles, with relatively minor sand content. The development of deflation surfaces (pavement) on alluvial deposits effectively restricted the availability of sand for aeolian transport.

When interpreting the intensity of past aeolian processes based on the presence of abrasion features, it is essential to consider the possibility of sediment redeposition. Establishing whether such features reflect primary aeolian transport or subse-

quent reworking is critical for paleoenvironmental reconstructions. Therefore, inferences about the magnitude and extent of aeolian activity must be grounded in a careful assessment of the depositional context and timing of the sand accumulation under study.

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Authors' contributions

JG: conceptualization, methodology, sample preparation, writing – original draft preparation. BG: writing and finalisation of the manuscript, revision in response to reviewers comments, and preparation for publication. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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