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# Adding another piece to NE European Aeolian Sand Belt puzzles: a sedimentary age case study of Pērtupe site, eastern Latvia

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**Abstract.** The NE European Sand Belt spreads over three Baltic States and consists of dunefields usually lying directly atop former glacial lakes. Some of these dunefields have so far been investigated in terms of their sediment properties and chronology. Nevertheless, there is a limited number of profiles where both glaciolacustrine and aeolian sediments co-occur and thus provide a unique environmental record where wet and dry conditions alternate. In this study, we investigated the Pērtupe profile, eastern Latvia, that represents sediment transition from glaciolacustrine silt to aeolian sand and along with a few known profiles helps to distinguish three sediment units as glaciolacustrine, transitional, and aeolian. This is most likely typical of the sediments of the NE European Sand Belt. A microstudy of sediments revealed that both aeolian and periglacial conditions alternated. However, this seems to be better expressed through prevalence of weathered quartz grains with some fracturing in the transitional unit. Aeolian deposition did take place in drier conditions, but micaceous interlayers argue for occasional watertable-controlled events.
This study provides one more support regarding a start of aeolian deposition at ca. 11.3 ka in the NE European Sand Belt, which took place instantly after deglaciation rather than after a few-thousand-year hiatus. Enhanced aeolian activity is known from the region at a similar time frame, but mostly as its maximum or termination, meaning that aeolian activity must had been asynchronous.

***Keywords:*** *quartz grains; scanning electron microscopy; luminescence dating; dunefields; aeolian water-controlled environment*

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## INTRODUCTION

Sediments of aeolian origin cover about 6% of global surface (Pye, Tsoar 2009) and constitute numerous sand bodies as deserts, coastal landforms and sand bodies in humid climates mostly understood as dunes, sand sheets or sand stringers (McKee 1979).

Aeolian sediments of cold and dry climates are equally important. Globally, the largest area of glacially linked dunes might be in Northern Europe (Hesse 2019), and it is termed the European Sand Belt (ESB) that covers vast lowland areas from Great Britain in the west to north-western Russia in the east (Kasse 1997; Zeeberg 1998). This means that dunes and/or sand sheets occur in most of the European countries with a clear meridional trend, where sand sheets prevail in the western ESB, whereas dune fields in its central and eastern part (Koster 2009). That is why the ESB has been investigated more or less intensely for nearly 100 years and the first investigations in the past were regarding its sediment deposition, landform distribution and stratigraphy (Van der Hammen 1951;

Van der Hammen, Wijmstra 1971; Wunderlich 1917; Högbom 1923; Lencewicz 1927; Galon 1959). Also, studies in the western ESB seem to be dominating over those in its eastern part. Depositional timing, properties and general paleogeography of aeolian sediments have been investigated in Great Britain (Bateman, Godby 2004; Bateman *et al.* 2000), France (Sitzia *et al*. 2015; Bertran *et al.* 2013, 2011), Spain (Bateman, Herrero 2001; BernatRebollal, Pérez-González 2008), Netherlands (Pierik *et al.* 2018; Sevink *et al.* 2018; van Mourik *et al.* 2010; Vandenberghe *et al.* 2013), Belgium (Beerten, Leterme 2015; Beerten *et al.* 2017, 2014; Crombé *et al.* 2013), Germany (Tolksdorf *et al.* 2010; Küster *et al.* 2014; Tolksdorf, Kaiser 2012), and Poland (Jankowski 2012; Zieliński *et al.* 2016, 2011, 2015, 2019; Kalińska-Nartiša, Nartišs 2016a, b; Kruczkowska *et al.* 2020). The NE ESB has been studied scarcer, and this started at the beginning of the 20th century (Markov 1928; Zemliakov 1935), followed by the first luminescence dating attempts (Raukas, Hüüt 1988; Molodkov, Bitinas 2006), landform and sediment-wise studies (Drenova *et al.* 1997; Zeeberg 1998, 1993), and most recent sedimentary chronology investigations (Kalińska-Nartiša *et al.* 2015b, a, 2016b; Kalińska 2019; Kalińska *et al.* 2019; Konstantinov *et al.* 2019; Nartišs, Kalińska-Nartiša 2017).

In this study, the NE ESB is generally understood as limited to three Baltic States (Lithuania, Latvia, and Estonia; for details see also Kalińska 2019), where dunefields lie directly atop former ice-dammed or glacial lakes (Raukas 1999; Nartišs *et al.* 2009), being strongly dependent on a retreat of the Fennoscandian Ice Sheet (Zelčs, Markots 2004). In other words, a sediment record from wet (lake) to dry (dune) conditions is expected in the NE ESB, and as such it has so far been documented by only a few sediment profiles in Lithuania (Kalińska-Nartiša *et al.* 2015; Molodkov, Bitinas 2006), Latvia (Kalińska-Nartiša *et al*. 2016), and Estonia (Kalińska 2019).

Therefore, the Pērtupe profile, eastern Latvia, is considered here to be a unique site for the sedimentary age study mostly due to availability of sediment transition from glaciolacustrine silt to aeolian sand along with a relatively fresh outcrop. This study adds another piece of sedimentary and chronological knowledge to the complex NE part of the ESB, and it is obtained in two ways. Firstly, a microscale study of sediment quartz grains as a powerful tool in paleoenvironmental interpretation is considered with a help of both binocular and scanning electron microscope (SEM) techniques and correlated with similar microscale studies elsewhere within the NE ESB. This SEM study is one of the first contributions (except for a few preliminary attempts by Nartišs and Kalińska-Nartiša (2017) and Kalińska (2019)) to the ESB sedimentary insight and interpretation.

Secondly, a single optically stimulated luminescence (OSL) dating provides a starting time for aeolian deposition, thus better constraining the absolute chronology of the NE ESB and, finally, enabling further regional correlation.

## LOCATION AND GENERAL GEOLOGICAL SITUATION

The Pērtupe site is located in the eastern part of Latvia (comprising the East Latvian Lowland), within a prominent ice-marginal zone termed Gulbene and in a foreland of the Linkuva ice-marginal zone. The town Gulbene locates approximately 20 km NW of

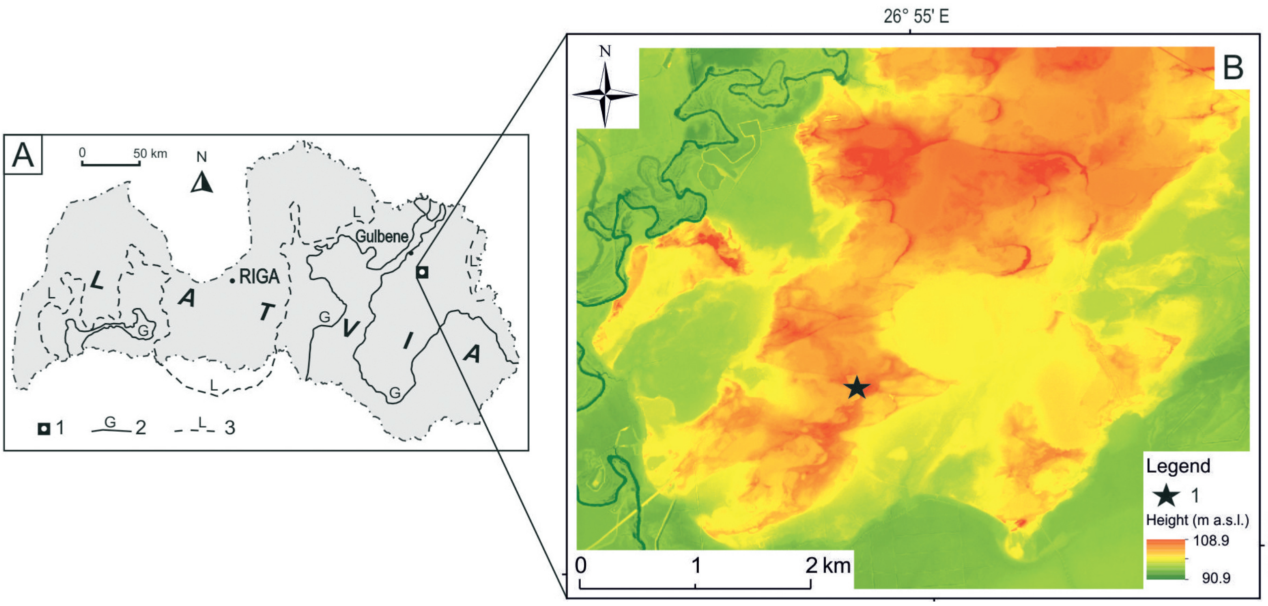


**Fig 1** Location of the study area. **A:** general location in Latvia (1 – study area, 2 – Gulbene phase, 3 – Linkuva phase; Zelčs *et al*. 2011), **B:** Digital Elevation Model (Latvian Geospatial Agency 2018. 1 – Pērtupe site)

the site (Fig. 1A). The $^{10}$Be ages, marking the deglaciation period, have been assigned to between 14.0 ka and 12.6 ka for Gulbene (Rinterknecht *et al.* 2006), and even a wider distribution of ages between 15.4–12.0 ka for the Linkuva zone (Zelčs *et al.* 2011). Such time span seems bigger than the entire glaciation, thus less reliable and likely older by 9–15% than the above ages if considering the $^{10}$Be ages recalculation (Hardt, Böse 2016). The Gulbene recession triggered the formation of large ice-dammed lakes such as Lake Lubāns in the East Latvian Lowland (Zelčs, Markots 2004). Later, during the Linkuva phase, the glacial retreat took place further to the north, thus making most of this area ice free (Zelčs, Markots 2004).

Aeolian activity postdated lake drainage, and a ca. 20 km long and 5 km wide dunefield NE of Gulbene reveals a record of this activity. Distinct parabolic and linear dunes occur in its northern part, whereas southern part carries less distinct and sometimes shapeless forms as high as 108.9 m a.s.l. (Fig. 1B). The Pētrupe site documents this, however considers a horn of a parabolic dune with a high range between 103 m and 105 m a.s.l. The sedimentary succession of the 4.2 m profile at the Pērtupe site reveals an alternation of distinctly and vaguely laminated sand between 1.4 m and 3.0 m depth (Figs. 2A, 3A), representing the likely cross-stratification bedding with thin (up to a few mm) laminae (Fig. 2B). This represents an alternation of finer and coarser sand interlayers. Massive sand with secondary features as signs of bioturbations and precipitation of iron hydroxides locates close to the present-day ground surface. Deeper in the profile at a depth between 3.0 and 4.05 m, brownish fine sand alternates with greyish silt and they constitute sub-horizontal and wavy lamination (Fig. 2C). In the lowermost part, silty interlayers become thicker and turn into entire silt at 4.05–4.2 m of the profile.

## METHODOLOGY

Fieldwork was carried out in June 2011 by documenting sediment properties in an active sand outcrop, which is located NW of Pērtupe village. Six sediment samples (P1-6) of ca. 100–150 g were taken and further subjected to sieving. A 0.5–1.0 mm fraction was isolated in this way and subsampled. The first portion of sediment was rinsed in 10% HCl to remove any carbonates. After rinsing with distilled water several times until decanted water was clear and after room-temperature drying, a portion of sediment was placed under a binocular microscope and ca. 100–150 quartz grains were randomly picked up and classified fol-

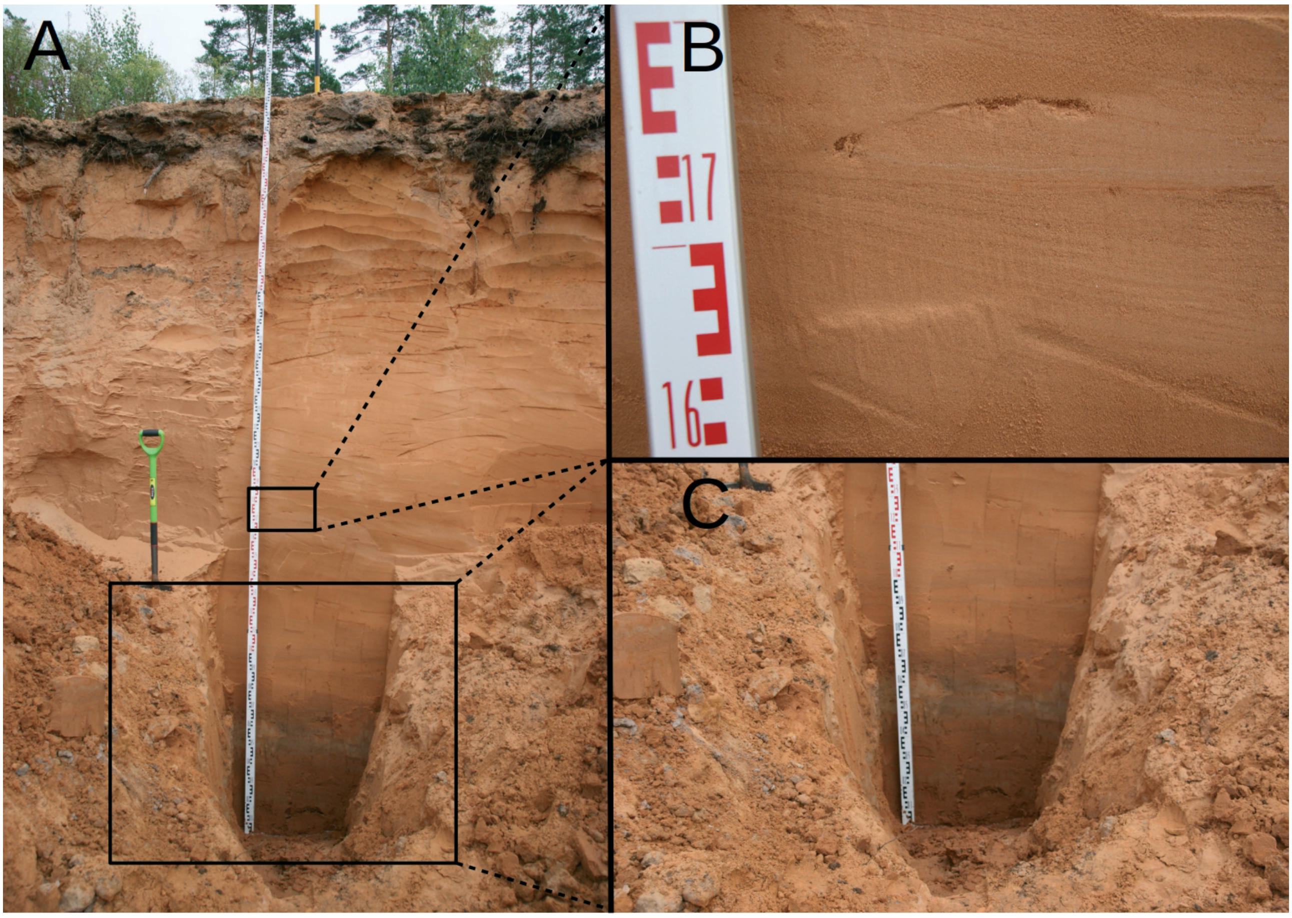


**Fig. 2** General view of the Pētrupe site. **A:** sedimentary succession, **B:** details on cross-stratification bedding with thin laminae, **C:** lower part of the profile with fine sand-silt alternations and final silt in its lowermost part

lowing the proposal of Mycielska-Dowgiałło and Woronko (1998). Two grain properties as grain roundness (well-rounded, partially rounded, non-abraded, cracked) and grain surface (shiny, matte, weathered) were combined, and such combination allowed us to preliminarily state about the sediment environment (Mycielska-Dowgiałło, Woronko 2004; Kalińska-Nartiša *et al.* 2016c). A closer microscale grain inspection is offered by a scanning electron microscope (SEM) analysis, so quartz grains of the 0.5–1.0 mm quartz fraction were randomly selected with a help of a binocular microscope and positioned in rows onto a double sticky tape atop of a SEM specimen holder. A Zeiss EVO MA 15 SEM at the Department of Geology, University of Tartu, Estonia was used for the present study. Numerous magnifications from 100× for observing the general grain outline to 1000× to identify grain microtextures were used. 34 microtextures were further identified with a help of an atlas of microtextures (Mahaney 2002) and environmental discrimination scheme based on the number of grains with a certain microtexture as proposed by Vos *et al.* (2014). Altogether 120 quartz grains (20 per sample) were scanned.

The second portion of the 0.5–1.0 mm sediment fraction was used for the basic mineral content check. To obtain this, ca. 200–250 mineral grains were distinguished and grouped as quartz, feldspars, lithics, and micas.

During field works, a single sand sample for OSL dating was collected at a depth of 3.6 m that refers to the transitional unit (Fig. 3) by hammering a 50 cm long opaque PCV tube into a freshly cleaned wall of the outcrop. A homogeneous bed with no visible traces of post-sedimentary disturbances or erosional surfaces was targeted. A tube with sediment was later stored in dark and cool conditions until laboratory arrival. All preparations and measurements were done at the Gliwice Centre for Absolute Dating (Silesian University of Technology), Gliwice, Poland (2012/13). The 90–125 μm sediment fraction was extracted by wet sieving, followed by chemical treatments and density separation to obtain quartz extracts, and further etched in 40% hydrofluoric acid for 60 min in order to etch the surface of grains and remove other impurities.

The dose rate radioactivity was measured by a germanium spectrometer. We used the average historical water content of 18 ± 4%, which is a mean between current and saturated sediment water contents, and higher than 9–10%, which had so far been used among aeolian sediments of the NE ESB (cf. Kalińska-Nartiša *et al.* 2015, 2016a, b). Since a transitional sediment unit (see study area), but not the entire aeolian unit, was aimed at OSL sampling, the life burial water content should be higher due to water level fluctuations. All in all, the 18 ± 4% water content was used to adjust the dose rates and in final age calculations.

The single-aliquot regenerative-dose (SAR) protocol was used to determine the equivalent dose ($D_e$; Murray, Wintle 2000) based on 16 aliquots, further followed by the Central Age Model (CAM; Galbraith *et al.* 1999).

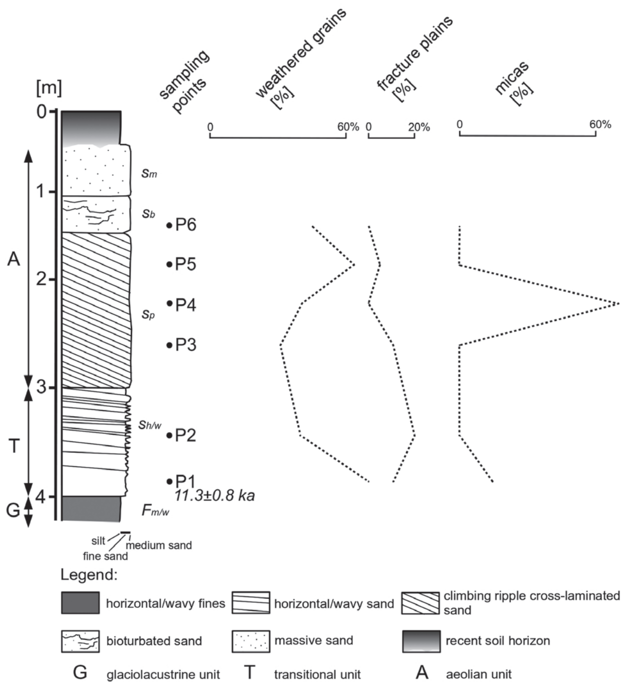


**Fig. 3** Sedimentary log with three units along with sampling points and selected grain properties (see Discussion for details)

## RESULTS

Selected micro-properties of grains are presented in Table 1. In general, two types of quartz grains occur in the investigated profile, and these are grains with matte surface and rounded to some extent (partially rounded, Fig. 4A) along with grains with weathered surface (Figs. 3B, 4B). Aeolian-type grains seem diminished in the lowermost part of the profile, being somehow replaced by weathered grains (up to 70% of the total share, Fig. 3B). However, the latter are similarly found up to 64% in aeolian beddings. A closer inspection with the use of SEM reveals that grains of subangular shape dominate, and rounded grains constitute only up to 30% of the total grain share. Subangular grains usually reveal a medium relief of their surfaces (Fig. 4C), whereas rounded grains are rather of a low relief (Fig. 4D). Among microtextures of mechanical origin, conchoidal features of small (<10 μm), medium (10–100 μm), and big size (>100 μm) occur with arcuate or straight steps on their surfaces (Fig. 4E–F). The occurrence of crescentic marks is moderate (Fig. 4G), but V-shaped

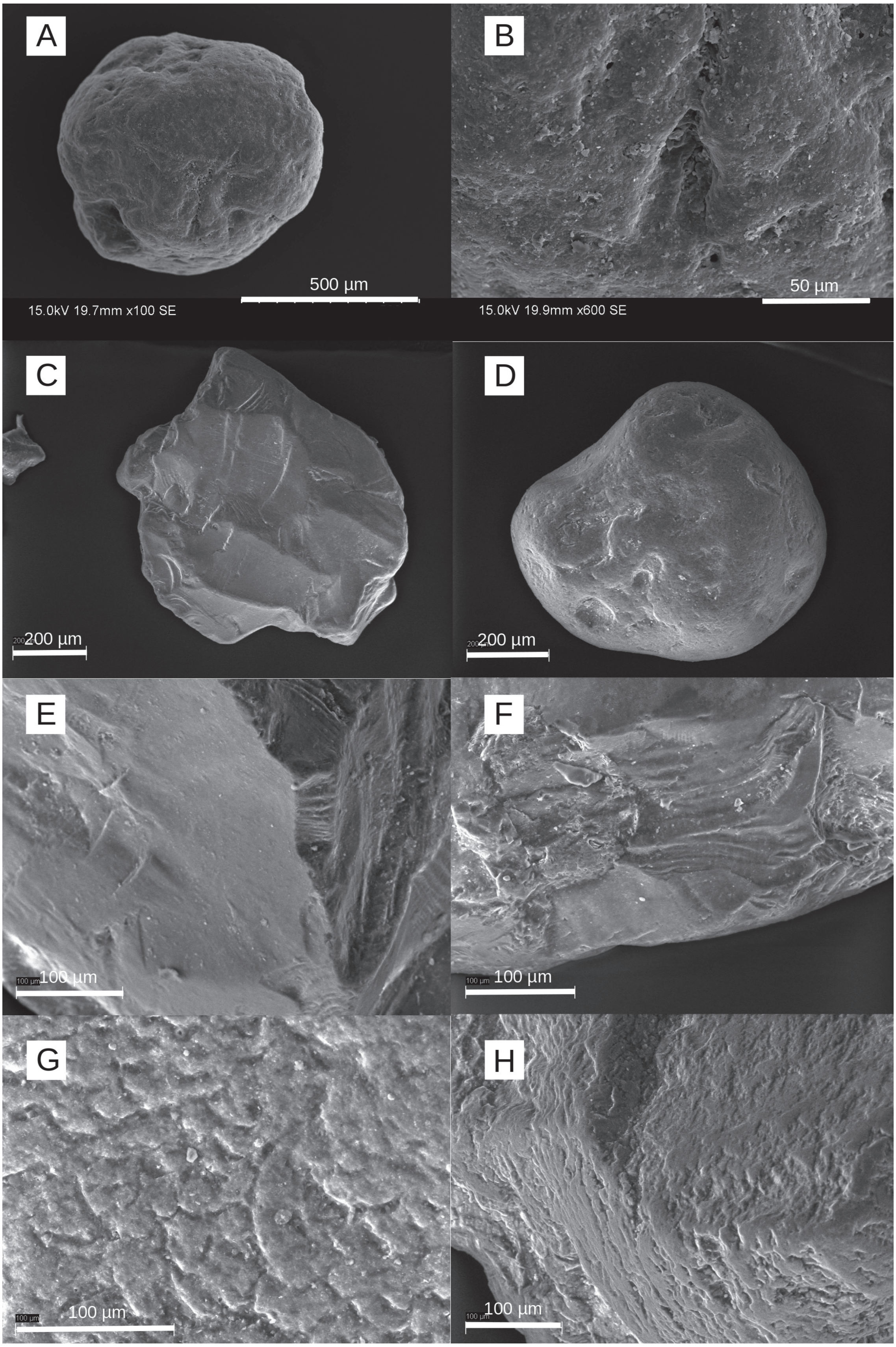


**Fig. 4** SEM microphotographs of 0.5–1.0 mm quartz grains. **A** – rounded/partially rounded grains with matte surface, **B** – details on weathered surface, **C** – subangular grain with medium relief on its surface, **D** – rounded grain with low surface relief, **E–F** – conchoidal features of small (<10 µm), medium (10–100 µm), and big size (>100 µm) with arcuate and straight steps on their surfaces, **G** – crescentic marks and slightly dulled surface, **H** – solution pits and crevasses along with dulled surface of a grain edge

percussion marks are sparse. Nearly all investigated grains carry bulbous edges. Similarly, precipitation along with solution pitting dominate among chemically induced microtextures, followed by moderate or common occurrence of solution crevasses (Fig. 4H). The surface of up to 30% of investigated grains is dulled (Fig. 4G, H).

Among investigated samples, quartz is a dominant component (between 65% and 81%), but not a single sample was found at a depth of 2.2 m, where the content of micas is as high as 69% (Fig. 3B). Up to 14% of micas also occur in the bottommost part of the profile. Otherwise, feldspar content is between 5% and 20% of the total sediment mineral content.

Luminescence study provides two elements with the total dose rate of 1.421 ± 0.058 Gy/ka and the value of $D_e$ of 16.2 ± 0.9 Gy. Combination of these two along with the assumed historical water content of 18 ± 4% corresponds with the final age of 11.3 ± 0.8 ka. Details can be found in Table 2.

## DISCUSSION

A general look into the sediment profile at Pērtupe along with knowledge of only a few similar profiles in the region (Nartišs, Kalinska-Nartiša 2017; Nartišs *et al.* 2009; Kalińska-Nartiša *et al.* 2016) and geological situation allow to distinguish three units both in this investigated profile and in the entire NE ESB: (1) glaciolacustrine silts, (2) transitional unit, where both silt and fine sand alternate, and (3) aeolian sand. All these units are discussed below. As apparent from the units, a primary interpretation might be about some water level fluctuations in the lake followed by its drainage and drying until aeolian deposition occurred. Also, deposition must have taken place under periglacial conditions, since this site locates in the foreland of the Linkuva marginal zone.

### Sedimentary units of NE ESB

#### *Glaciolacustrine unit*

It is generally accepted that ice-dammed lakes remain as deep as up to 40 m in the territory of Latvia (Zelčs, Markots 2004). Laminated sediments are considered to be preserved, while maximum lake depth differs between 15 m and 35 m in case of small lakes (Tylmann *et al.* 2013) but generally exceeds 10 m (Ojala *et al.* 2000; Saarnisto 1986). No varve-resembling sediments have been reached at Pērtupe, most likely due to the major focus of this study on aeolian deposition and only a shallow exploration of glaciolacustrine sediments. Nevertheless, the greyish silt horizon in its lowermost part might be interpreted either as a record of a shallower glacial lake (Ojala *et al.* 2000) or its final stage (Hang, Kohv 2013). As such, the Pērtupe profile contributes to the glaciolacustrine record, known in the region, for example, from the adjacent Mieļupite section (Nartišs, Kalińska-Nartiša 2017), from NE Estonia at the Varesemtsa site, where coarse silts and fine sands are due to nearly standing and/or low energy water conditions in glacial Lake Peipsi (Kalińska *et al.* 2019), or from the Inkliuziai site in Lithuania, representing floodplain/shallow water conditions (Kalińska-Nartiša *et al.* 2015).

**Table 1** Selected micro-properties of the Pērtupe sediment profile as observed in a binocular and SEM

| sample ID | Binocular sediment observations (% of grain/mineral type) | | | | | SEM sediment observations (% of grain/microtexture type) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | grain surface (only % of weathered grains) | roundness of aeolian grains | | dominant minerals | | grain outline | | grain relief | | collision marks on grain surface | | bulbous edges | precipitation | dulled surface |
| | | partially rounded | well rounded | quartz | feldspars | subangular grains | rounded grains | medium relief | low relief | crescentic marks | V-shaped percussion marks | | | |
| P6 | 44 | 35 | 12 | 76 | 19 | 85 | 15 | 70 | 20 | 10 | 0 | 100 | 85 | 25 |
| P5 | 64 | 25 | 3 | 81 | 15 | 85 | 10 | 65 | 25 | 5 | 5 | 90 | 85 | 30 |
| P4 | 38 | 40 | 9 | 28 | 3 | 70 | 30 | 55 | 25 | 30 | 5 | 100 | 75 | 25 |
| P3 | 31 | 47 | 9 | 70 | 25 | 90 | 10 | 65 | 25 | 20 | 0 | 100 | 85 | 35 |
| P2 | 47 | 35 | 5 | 79 | 20 | 80 | 20 | 60 | 35 | 30 | 10 | 100 | 75 | 10 |
| P1 | 69 | 15 | 7 | 65 | 19 | 95 | 5 | 75 | 5 | 40 | 20 | 100 | 90 | 20 |

**Table 2** Summary of radionuclide concentrations, dose rate ($D_r$), equivalent dose ($D_e$) and age. S.E. – standard error

| Field ID | Laboratory ID | Radionuclide concentration ± S.E. | | | Dose rate ± S.E. | | | | | Measured water content (%) ± 5% | Number of aliquots | Equivalent dose (Gy) | Age (ka) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $^{232}$Th (Bq/kg) | $^{238}$U (Bq/kg) | $^{40}$K (Bq/kg) | α-Dose rate | β-Dose rate | γ-Dose rate | Cosmic dose rate | Total dose rate ($D_r$) | | | | |
| Pērtupe 3.6 | GdTL-1590 | 6.59 ± 0.28 | 4.5 ± 0.16 | 411 ± 12 | 0.0136 ± 0.0025 | 0.896 ± 0.054 | 0.372 ± 0.014 | 0.139 ± 0.014 | 1.421 ± 0.058 | 10.9 | 16 | 16.2 ± 0.9 | 11.3 ± 0.8 |

### *Transitional unit*

Over 1 m thick sandy-silty sediment alternation reveals changes in water level in the lake with occasional emerging/dryness events, however gradually going towards drier conditions. Additionally, dunes are parabolic with their horns standing against the prevailing wind, which means that dune bed is rather moist. This is another example of glaciolacustrine-aeolian transition that occurs regionally. A similar record of moist/dry conditions, where silty and sandy layers alternate and gradually turn into sand, has been diagnosed at the above-mentioned Mieļupite section (Nartišs, Kalińska-Nartiša 2017) along with two sections in eastern Latvia (Kalińska-Nartiša *et al.* 2016b; Kalińska, unpublished data) and NE Estonia (Kalińska, unpublished data). This confirms that glacial lakes did not drain rapidly but rather gradually with clearly marked emerging events unless a typical dry aeolian deposition started.

### *Aeolian unit*

A glimpse into the aeolian unit reveals that it is composed of two parts – lower and major. In the lower part, climbing ripple cross-lamination occurs and clearly marks the dominance of aeolian accumulation on a dry surface (Zieliński *et al.* 2015) with a wind speed between 4 and 8 m/s (Zieliński, Issmer 2008). Atop this part, a massive and bioturbated part occurs and as such makes up the uppermost part of profiles within the NE ESB (cf. Kalińska-Nartiša *et al.* 2015a). Considering bioturbations, this massive part is likely to be of post-sedimentary origin (Pye 1983). Nevertheless, the massive structure might also be part of a dune, for example, in its lee face (Zieliński, Issmer 2008). These two clearly distinguishable aeolian parts (sequences) can be traced throughout the NE ESB. A cross-/low-angle lamination in the lower part along with the uppermost massive sequence occur in most of the investigated dune profiles in Lithuania (Kalińska-Nartiša *et al.* 2015b) and Latvia (Kalińska-Nartiša *et al.* 2016). In other profiles, the leeward slope is visible through sand sequence with high-angle inclined stratification (Kalińska-Nartiša *et al.* 2015a; Kalińska *et al.* 2019). The aeolian unit also reveals a much coarser fraction compared with the fine-grained glaciolacustrine unit, and thus a question remains why dune sediment has become so coarse. Assuming local sourcing, explanation for this might be seen in selective grain removal *in situ* (cf. Folk 1971).

## Microstudy versus environment

The quartz sand grain findings do not give an entirely clear answer regarding sediment origin, because two different grain genetic groups alternate within the investigated profile and thus reveal environmental alternation. Matte grains with bulbous edges and crescentic marks are usually thought to be of aeolian origin (Costa *et al.* 2013; Mahaney 2002; Kalińska-Nartiša *et al.* 2017), and as such they contributed to sediments of the NE ESB (Kalińska 2019; Kalińska *et al.* 2019) and are largely seen in aeolian sediments of the central ESB (Kalińska-Nartiša *et al.* 2016c; Zieliński *et al.* 2019, 2016). This new study is one more support of the general prevalence of aeolian grains in sediments of the ESB. However, the second group must be considered, and this group is represented by grains with weathered surface, which is due to strong chemical and mechanical weathering *in situ* in the periglacial environment (Woronko, Hoch 2011). These grains seem to be particularly typical of the transitional unit along with some enriched interlayers in the aeolian unit. Periglacial conditions are about the occurrence of the active layer along with numerous factors that influence the final grain look, such as the number of freeze-thaw cycles, freezing rate, sustained subzero temperatures in moist and porous rocks, the type of rock, the pre-weathering history of grains, the presence of weakness zones in the grain, and finally the degree of grain rounding (Woronko 2016). All these factors are expected to produce fracture plains, scaling and silica precipitation on grain surfaces, which serve as the main indicator of periglacial conditions (Woronko 2016; Woronko, Pisarska-Jamroży 2016). In this SEM study, no grains with scaling features have been found, and fracture plains occur only on 10–20% of investigated grains and only in sediments of the transitional unit. Precipitation dominates atop all grains, thus hampering its environmental meaning. If so, only the occurrence of fracture plains on grains (SEM study) along with the prevalence of weathered grains (binocular study) in the transitional unit (Fig. 3B) explain permafrost conditions that exceptionally occurred in Latvia up to the Holocene Thermal Maximum (Stivrins *et al.* 2017). Micas (mostly muscovite) are also present in the transitional unit, suggesting an occasional submerging, since muscovite keeps very resistant under subaqueous conditions (Anderson *et al.* 2017). The same experimental study reveals that just 4 days are needed to reduce muscovite by aeolian processes to less than 500 μm (Anderson *et al.* 2017). In this study, the 0.5–1.0 mm sediment fraction was used for mineral content check, and no micaceous minerals were found in the aeolian unit, thus suggesting their rapid abrasion. Nevertheless, a mica-rich interlayer in the aeolian unit is about the watertable-controlled environment (Kalińska-Nartiša, Nartišs 2017; Marcinkowski, Mycielska-Dowgiałło 2013) that has been observed in sediments of the NE ESB (Kalińska *et al.* 2019).

## Luminescence result and chronological context

A single OSL result obtained from the transitional unit allows to position a start of aeolian accumulation at ca. 11.3 ± 0.8 ka and onwards and thus is possibly correlating with transition between the Younger Dryas and the Preboreal Oscillation (Blockley *et al.* 2012). Nevertheless, aeolian sediments border directly glaciolacustine ones, meaning that the timing of the last (Gulbene) deglaciation provides a maximum age for aeolian deposition. Ages of this deglaciation are however uncertain (see study area), and the time for ice-dammed lake drainage must also be considered prior to aeolian deposition. Previous results from the region point out two scenarios – either aeolian deposition instantly followed deglaciation (most of investigated cases; Kalińska 2019) or a few thousand years must have passed to trigger its start (one case: Nartišs, Kalińska-Nartiša 2017). Considering a deeper part of the investigated profile, where glaciolacustrine sediments occur along with the obtained OSL age result, deposition at Pērtupe must have instantly followed Lake Lubāns drainage. Details on how long this accumulation took place cannot be provided because of only a single date result. One can presume that aeolian deposition continued further into the Holocene. Deposition at Pērtupe might resemble in a way the deposition known from southern Lithuania with some aeolian sediment delivery that continued during the mid- and late-Holocene (see Fig. 2 for details in Molodkov and Bitinas 2006). On the other hand, rapid aeolian deposition of a few meter thick sand is not unusual in the NE ESB (Kalińska-Nartiša *et al.* 2015; Kalińska 2019), meaning that such deposition could also have taken place at Pērtupe. However, only future OSL dating of higher sampling resolution can either support or deny this.

Aeolian events of a similar time frame are so far known only from a few sites of the NE ESB, for example, from the adjacent Strenči area, eastern Latvia, at 11.9–11.8 ka BP (Nartišs *et al.* 2009). Similarly, dune deposition took place in southern Estonia at ca. 11.4 ka (Kalińska-Nartiša *et al.* 2016) and southern Lithuania at ca. 10.6 ka (Molodkov, Bitinas 2006). In NE Estonia, aeolian deposition terminated between ca. 11.3 and 11.1 ka (Kalińska *et al.* 2019), meaning that these aeolian events seem to have temporarily shifted in the region and dunefields acted independently of each other.

The new result of 11.3 ka pointing out to aeolian deposition within the ESB corresponds to some enhanced aeolian events of a similar time frame in the central part of ESB in Poland (Zieliński *et al.* 2016, 2019) and in Germany (Hilgers 2007). However, this record looks scarce among similar records elsewhere in the W ESB. For example, a corresponding event at ca. 11 ka so far detected only partially in the Netherlands is likely to be due to the occurrence of rapid vegetation (Vandenberghe *et al.* 2013). This is documented by some OSL dating results obtained by Fink (2000) and Vandenberghe *et al*. (2004) and further interpreted as dry aeolian deposition in low dunes and as wet aeolian deposition in the produne area during the Younger Coversand II in the Netherlands (Kasse, Aalbersberg 2019). Apart from this, it clearly shows that vegetation growth was somehow hampered deeper in the European continent, thus allowing aeolian activity at ca. 11 ka in Latvia. A cause of this might be explained through occurrence of continental climate with a stronger cooling during the Younger Dryas and periglacial conditions. The latter are recorded by the dominance of weathered grains and many crescentic marks atop of them (see sample P1 in Table 1).

A single OSL result obtained in this study cannot help in sediment rate determination. However, according to a previous study in eastern Latvia nearly 5 metres of sand sediment might have accumulated in less than 3,000 years, thus pointing out a rather rapid aeolian accumulation (Kalińska 2019). In this study, a 3.6 m thick aeolian sand postdates a start of aeolian accumulation at ca. 11.3 ± 0.8 ka, and considering a rapid accumulation rate along with a limited erosion in the region but rather continuous aeolian deposition (Kalińska *et al.* 2019; Kalińska 2019), ca. 2,000 years were most likely needed for dune construction as documented at the Pērtupe site. However, only denser luminescence sampling and dating would help to resolve this.

## CONCLUSIONS

The Pērtupe site, eastern Latvia, is considered in this study and adds another knowledge puzzle to a complex glaciolacustrine-aeolian system of the NE ESB. Three sediment units are visually seen in the study site, such as glaciolacustrine, transitional, and aeolian, and they correspond to the general regional sediment trend of the NE ESB.

The SEM microstudy clearly shows that two groups of quartz grains constitute the sediment, and these are aeolian and periglacial-type grains. They dominate in the transitional unit along with some occasional peaking in the aeolian unit. Combined with the occurrence of mica in some laminas, environmental conditions must have been sometimes water-controlled but mostly dry as seen through aeolian-type quartz grains and lack of micaceous, wind depleted minerals.

A single OSL dating, as apparent from the transitional unit, gives a result of 11.3 ± 0.8 ka and marks a start of aeolian activity that instantly followed deglaciation in the region. Aeolian activity was already enhanced in some other parts of the NE ESB at this time, or alternately, around its termination. Periglacial conditions prevailed during deposition of the lowermost sample P1 followed by milder and cooler climate alternation. Aeolian deposition was asynchronous in the region and rather independent among dunefields. The duration of aeolian activity and accumulation rate are unknown and can only be transformed from a previous study. Future OSL sampling at higher resolution and regional mapping of paleosols in aeolian deposits might solve the issue.


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