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# Understanding a continuous inland aeolian deposition: a closer look into a chronological and sedimentary record of the north-eastern European Sand Belt

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**Abstract.** A belt of inland aeolian sand sediments termed the European Sand Belt (ESB) runs throughout Europe, and  its western part has gained greater attention, while attention to the eastern part has been limited. Whereas clear aeolian–paleosol sequences that reflect colder–-armer phases are known from its western part, such alternation is practically undetectable in the eastern part. This study combines the available chronological and sedimentary data from the north-eastern part of the ESB, with a special focus on the Baltic State region. Here, aeolian deposition took place between 15.9±1.0 ka and 8.5±0.5 ka, almost instantly following a deglaciation and drainage of paleolakes, and thereafter practically without longer-term stability. Lack of paleosols is likely due to the prevalence of pioneer vegetation, reflecting dry and cold climate conditions, and thus giving limited opportunity for soil development.

**Key words:**
inland dune,
optically stimulated luminescence (OSL),
pulsed OSL,
rounded quartz grains,
Baltic States

## Introduction

Rapid climatic and environmental changes occurred during the last glaciation (Weichselian, marine isotope stage 2 = MIS 2) and the Holocene (Feurdean et al. 2014; Toucanne et al. 2015), and may be seen through a specific record in numerous sediments. For example, alternation between sand units and organic-rich soil horizons is apparent in dunes due to alternation between glacial and interglacial periods, respectively (Derese et al. 2010). In other words, phases of intense aeolian activity and its stability have been found especially in regards to so called the European Sand Belt (ESB), which occupies large areas of Europe (Zeeberg 1998; Fig. 1A). The north-western and central parts of the ESB have certainly been better recognised, and its numerous stratigraphic subdivisions are apparent through a strong chronological record as obtained both from optically stimulated luminescence (OSL) and from radiocarbon dating techniques (Vandenberghe et al. 2013; Beerten and Leterme 2015; Zieliński et al. 2015; Kalińska-Nartiša and Nartišs 2016a, b; Beerten et al. 2017; Sevink et al. 2018). Also, the north-eastern part of the ESB has recently gained a primary time frame of deposition (Kalińska-Nartiša et al. 2015a, b; Kalińska-Nartiša et al. 2016; Nartišs and Kalińska-Nartiša 2017). Nevertheless, stratigraphic subdivisions are rather unclear in this part of the ESB, largely because no paleopedological marker horizons have so far been found in the investigated inland dune sections. In contrast, these sand sediments are enriched in quartz, and thus only OSL dating serves as a powerful tool to provide information on time of deposition. In general, organic-rich material is scarce in the region (Gaigalas and Pazdur 2008), and only one radiocarbon dating as obtained from a gyttja horizon below the sediments of the ESB is known from southern Lithuania (Blažauskas et al. 1998) along with few result from the coastal sections (Dobrotin et al. 2013 ; cf. Buynevich et al. 2015).

This study complies available chronological and sedimentary data from the north-eastern ESB from previous original research (Kalińska-Nartiša et al. 2015a, b; Kalińska-Nartiša et al. 2016a; Nartišs and Kalinska-Nartiša 2017) and, along with the paleoenvironmental studies in the region, discusses causes of the absence of organic matter in aeolian sediments. Additionally, some luminescence characteristic and tendencies in the region are addressed for the first time in terms of their determinant factors.

## Study area

In this study, the north-eastern part of the ESB is understood as surficial inland aeolian deposits in the Baltic States, despite the fact that these deposits continue beyond the Baltic States' borders into Belarus and Russia. Aeolian deposits form parabolic dunes and/or shapeless coversands, and these landforms are typically limited to basins of former glacial lakes, for example to the Peipsi Glacial Lake in Estonia (Raukas 1999), to the Smiltene-Strenči ice-dammed lake in Latvia (Nartišs et al. 2009), or the lower Nemunas region in Lithuania (Guobytė and Satkūnas 2011). As apparent from this, aeolian sediments border directly with the glaciolacustrine sediments, and these latter formed in lakes during the retreat of the Fennoscandian ice sheet (cf. Zelčs and Markots 2004). The deglaciation history in the region is largely supported by $^{10}$Be dates (Rinterknecht et al. 2006, 2008) along with OSL (Saks et al. 2012; Lasberg and Kalm 2013; Lamsters et al. 2017) and radiocarbon results (Amon et al. 2016; Fig 1B). Glaciolacustrine fine-grained sediments are usually of wavy or horizontal lamination, whereas aeolian sands reveal either an alternation of numerous sedimentary structures as climbing translatent stratification and with tabular cross-stratification, or sand with high-angle inclined stratification (Kalińska-Nartiša et al. 2015a, b; Kalińska-Nartiša et al. 2016).

## Material and methods

Altogether, 14 aeolian sediment sections (Fig. 1B) were investigated in detail with a special focus on OSL dating and sedimentary proxy as apparent from the previous original studies (Kalińska-Nartiša et al. 2015a, b; Kalińska-Nartiša et al. 2016a; Nartišs and Kalinska-Nartiša 2017). A primary objective was to document both aeolian and glaciolacustrine sediments, and this was done in four sections (Silezers, Inklužiai, Mieļupīte and Mustjõgi; see Figure 1B for location). Otherwise, only aeolian sediments were documented. All luminescence measurements were undertaken on automated Risø TL/OSL readers (model DA-20) at the Nordic Laboratory for Lumi-

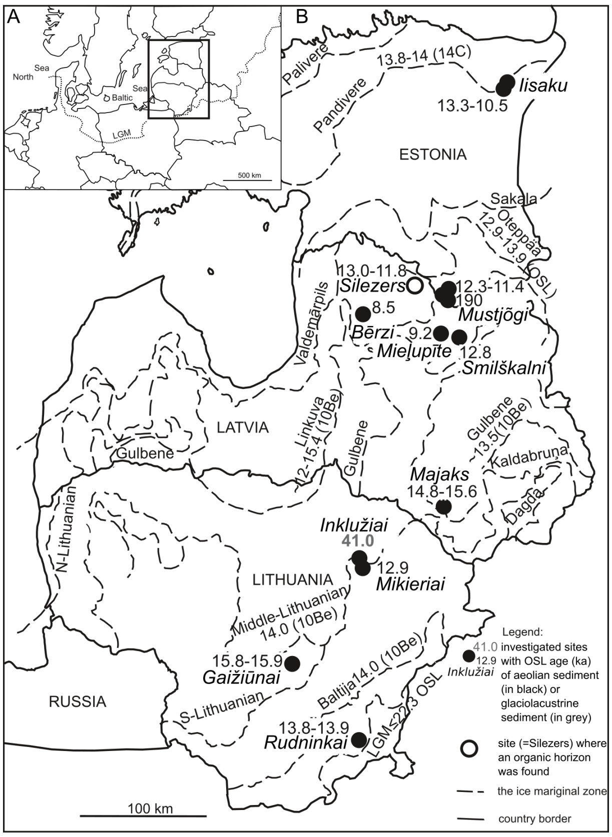

Fig. 1. A: Location of the investigated area in the ESB (Zeeberg 1998). LGM refers to the Last Glacial Maximum. B. Location of the investigated sites along with the ice marginal zones of the Fennoscandian ice sheet (deglaciation age is given in ka and follows the $^{10}$Be, OSL and $^{14}$C methods – see Study area for details)

nescence Dating, Risø, Denmark. Standard procedure was followed to obtain the 180–250 μm quartz extracts as wet sieving, 10% hydrochloric acid (HCl), 10% hydrogen peroxide ($H_2O_2$), followed by heavy liquid separation to separate quartz and feldspars. Later, quartz extracts were treated by 40% HF and 10% HCl. Standard tests were implemented prior to final equivalent dose ($D_e$) measurements; these were the OSL/IR depletion test (Duller 2003), the preheat plateau test and the dose recover test. Risø Analyst software was used to calculate $D_{e.}$ following the single-aliquot-regenerative-dose protocol (SAR; Murray and Wintle 2000). To obtain the $D_e$s, between 8 and 37 aliquots per sample were measured. Altogether, 21 OSL ages (19 for aeolian sediments and 2 for glaciolacustrine sediments) were obtained. A high-resolution gamma spectrometer was used for radionuclide concentration measurements, and further converted into beta and gamma dose rates as suggested by Olley et al. (1996). Prior to radionuclide concentration measurements, the dose rate subsamples were dried, ignited at 450°C for 24 h, homogenised and cast in wax in a fixed geometry. Later, these casts were stored for at least 3 weeks (Murray et al. 1987). Details on luminescence data can be found in Table 1. Among sedimentary methods, sediment structures and textures were considered (Fig. 2). In this study, textures are primarily understood as the rounding and character of quartz grain surfaces, and since aeolian quartz-dominated sediments are investigated, quartzy aeolian grains are also considered, following the methodology of Mycielska-Dowgiałło and Woronko (1998). This is a binocular-based method, where grain edges and surface character are particularly considered. An additional supplement as provided by a scanning electron microscopy (SEM), giving a valuable insight into grain microtextures atop of its surface (see for details: Mahaney 2002; Vos et al. 2014).

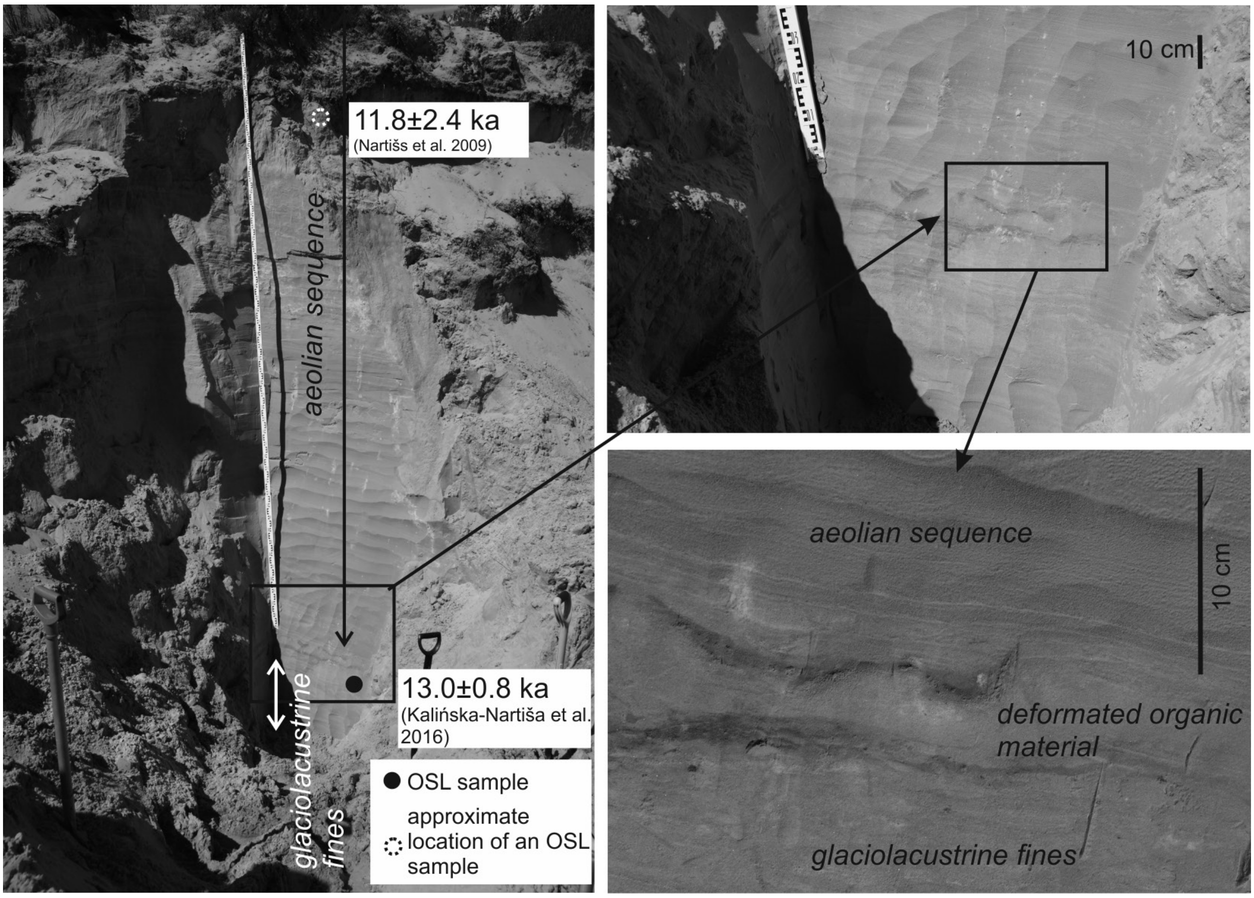

Fig. 2. An example of the Silezers Aeolian sequence from Latvia (see Fig. 1 for location) that borders directly the glaciolacustrine fines. Deformatted and diffused organic material occurs between both sequences

## Results and discussion

All luminescence data along with a single radiocarbon result as obtained by Blažauskas et al. (1998) are combined in this study and further tested for a better understanding of whether aeolian deposition of the north-eastern part of the ESB was continuous. Additionally, standard luminescence tests revealed that quartz extracts are rather a combination of a mixed quartz-feldspar sample, and not even re-etching of extracts helped in quartz purity (cf. Kalińska-Nartiša et al. 2015a). This aside, of this, quartz sand grains reveal an interesting textural properties. All these issues are discussed in the following sections.

### Feldspar contamination

As apparent from the preliminary OSL/IR test, quartz extracts reveal two tendencies. A large group of samples contains a proportion of non-quartz and feldspar grains and/or inclusions, and these are all Estonian samples along with most of the Latvian samples. Considering such properties, these samples were measured with so-called post-IR pulsed blue OSL. This technique is generally based on the fact that quartz and feldspar have very different luminescence characteristics (see for details Thomsen et al. 2008), and therefore the signal decays significantly faster from feldspar than from quartz (Clark et al. 1997). Since in pulsed OSL the stimulation light is delivered in pulses, and emitted luminescence is measured between these pulses, quartz-dominant signal might be extracted from a mixed sample (Thomsen et al. 2008). No such mixture has been observed in the second group as that originating from the Lithuanian sites and one Latvian site, meaning that these quartz extracts are pure, and blue stimulation was used. However, to make things more complex, alkali feldspars were used for luminescence dating (infra-red optically stimulated luminescence – IR-OSL) of some aeolian sections in Lithuania (Molodkov and Bitinas 2006), meaning that quartz was likely not suitable for dating. In general, it is not really clear what causes feldspar contamination. A realistic explanation may be related to the dominance of Silurian and Devonian siliciclastic rocks in Estonia and Latvia, which mineralogically contain between 50% and up to 95% of quartz depending on the formation (Kleesment et al. 2012). Since these rocks directly border the Quaternary sediments (Kalm et al. 2011), feldspar contamination may be inherited from feldspar-rich formations, for example the Aruküla formation, which is dominated by arcosic arenites with only 50–70% of quartz (Kleesment et al. 2012). On the other hand, one Latvian site (Bērzi) did not reveal an occurrence of feldspars, although located within the arcosic arenites of the Kernave formation. This case makes the relation between bedrock characteristics and feldspar contamination of aeolian sediments more complex and surely requires further investigation. Examples of decay and growth curves along with equivalent dose distributions can be seen in Figures 3 and 4, respectively.

### Aeolian deposition in Estonia

As apparent from two dated dune fields in north-eastern and southern Estonia, aeolian deposition took place between 13.3±1.2 ka and 10.9±0.8 ka (Kalińska-Nartiša et al. 2015a; Kalińska-Nartiša et al. 2016b). Nevertheless, this first aeolian influx was surely strongly controlled either by a deglaciation (the Pandivere recession phase at ca. 13,800–14,000 cal yr BP; Amon et al. 2016) and water fluctuation in the Peipsi Glacial Lake in north-eastern Estonia as happening, for example at 13,300 cal yr BP (Vassiljev and Saarse 2013), or in the delta of the Mustjõgi river in southern Estonia (Kalińska-Nartiša et al. 2016a). Sediments of this delta reveal a luminescence age of 190±19 ka (Kalińska-Nartiša et al. 2016a), which is unrealistic, since the OSL age is largely overestimated, and the delta itself likely formed in the Late Glacial. Initially, four phases of aeolian activity have been distinguished so far in Estonia, as (1) at 13.3 ka and onwards, (2) between 12.7 and 12.3, thus correlating with the 1300-year-long Younger Dryas cold abrupt reversal (Fiedel 2011), (3) between 11.5 and 10.9 ka clearly indicating that aeolian deposition took place in the Preboreal, Holocene, and finally (4) at 10.5 ka. However, if considering the age error bars along with a general sedimentary record of these sediments, these ages overlap within errors. Additional-

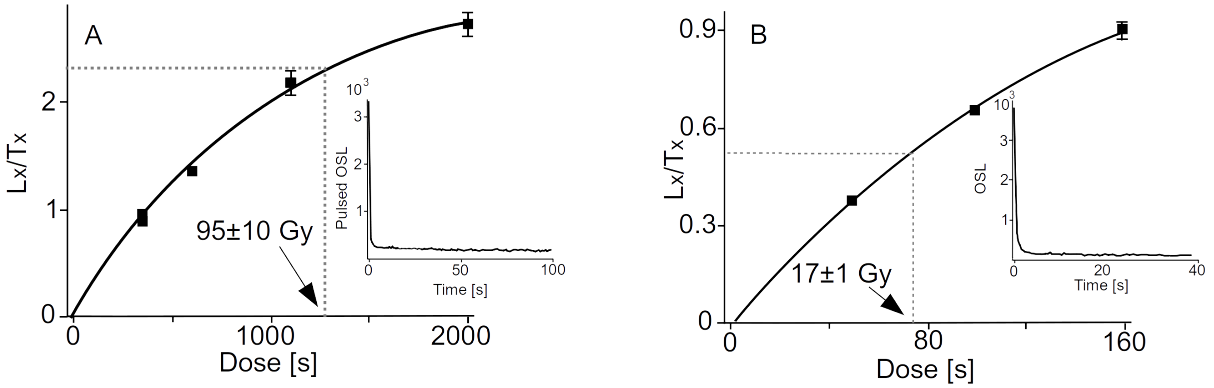

Fig. 3. Examples of growth and decay curves for Mustjõgi 1 (A) and Rudninkai 0.9 (B) samples.

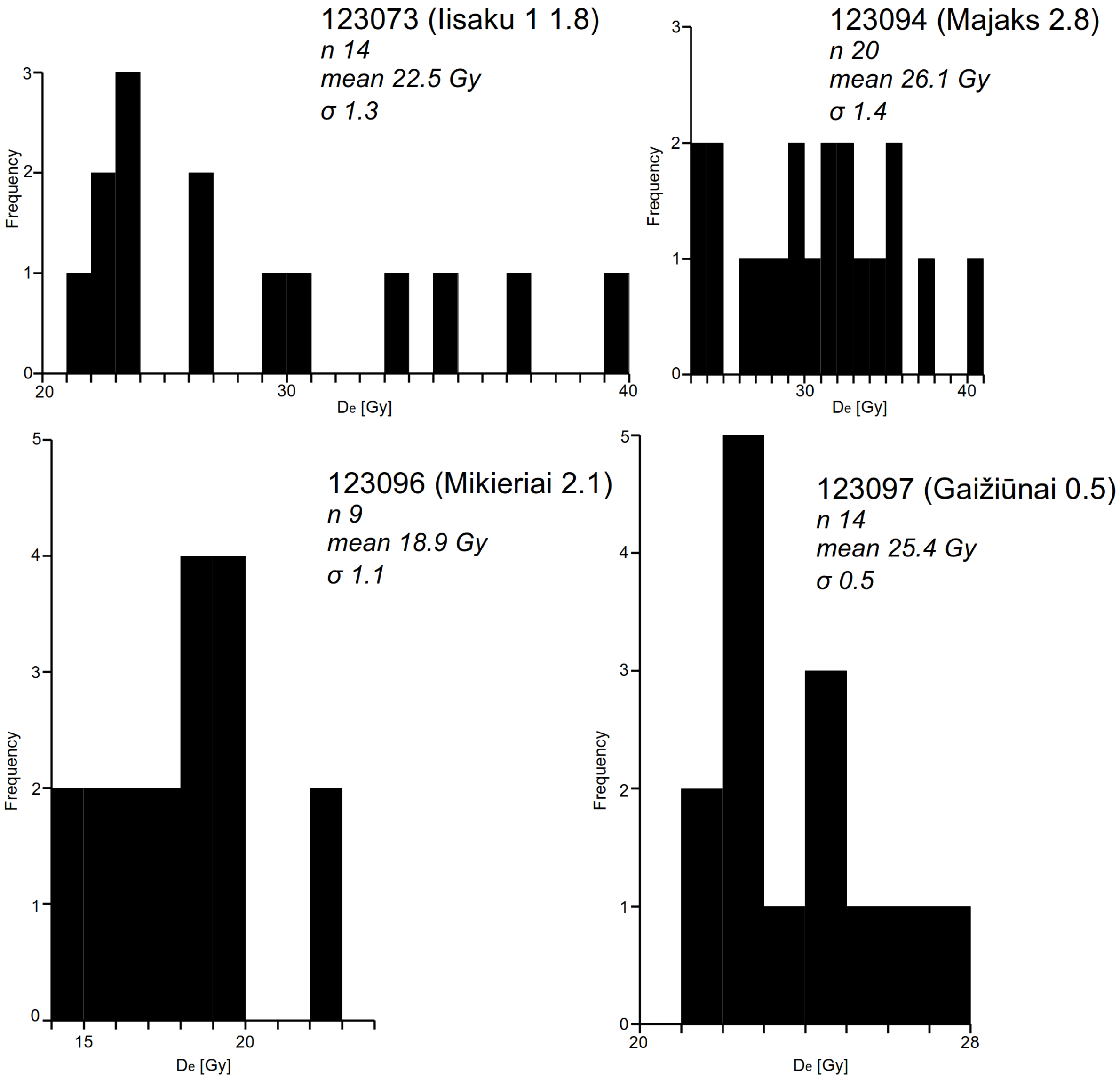

Fig. 4. Examples of equivalent dose ($D_e$) distribution: “n” refers to number of aliquots

ly, no hiatuses or any serious erosional surfaces have been observed in the investigated sections, but rather continuous and monotonous deposition of translatent stratification with coarser- and finer-grained laminae (Kalińska-Nartiša et al. 2015a), along with lack of organic remains (Ratas et al. 2015).

Another age dataset is provided by Raukas (1999) and Raukas and Hüüt (1988), who stated that aeolian accumulation occurred only in the Holocene. However, these results seem inconclusive due to large error bars and serious age inversion.

## Aeolian deposition in Latvia

Aeolian sand accumulation took place between 15.6±1.1 ka and 8.5±0.5 ka (Kalińska-Nartiša et al. 2016). Since OSL dates of aeolian sediments are still limited in Latvia, these results give only a general insight into a timeframe of deposition. The oldest ages of 15.6±1.1 ka and 14.8±1.1 ka coincide with the age of deglaciation (the Gulbene phase in Latvia), which took place around 15.5 ka and 14.5 ka (Zelčs et al. 2011). Such a coincidence may be explained through systematic uncertainties in different age estimations (Kalińska-Nartiša et al. 2016), along with the fact that aeolian deposition may have just started instantly after deglaciation. Later, between 13.0±0.8 ka and 11.8±2.4 ka an aeolian event took place (Kalińska-Nartiša et al. 2016a; Nartišs et al. 2009, respectively), and this might be to some extent treated as a separate and younger depositional event. However, deposition at 13.0±0.8 ka does not look entirely aeolian, but rather a water-controlled environment, as reflected by the wavy-horizontal structures along with a higher occurrence of muscovite (Kalińska-Nartiša et al. 2016), which tends to high abrasion resistance in subaqueous transport processes (Anderson et al. 2017). A darkish and deformed organic horizon is located just above the strata dated to 13.0±0.8 ka, which in contrast was not dated itself, likely due to its lens- and diffuse-like characteristics. Nevertheless, this organic material clearly attests to some reduction in aeolian activity or, if considering the underlying strata as being of subaqueous (glaciolacustrine?) origin, the termination of an ice-dammed lake. On the other hand, this organic horizon is somehow deformed, meaning that material might also have been redeposited. Further, a consistent aeolian accumulation continued up to 11.8±2.4 ka as apparent from the same section (Fig. 2), meaning that nearly 5 metres of sand sediment was accumulated in less than 3,000 years. This clearly supports the fact that aeolian accumulation was rather rapid. The Holocene sand influx at 8.5±0.5 ka seems somehow separated from the Late Glacial activity, thus likely representing a separate redistribution.

## Aeolian deposition in Lithuania

Two aeolian phases look to be more clearly distinguishable in Lithuania than anywhere else in the Baltic States. An older aeolian series was deposited at 15.9±1.0 ka and 15.8±0.9 ka in Central Lithuania, whereas the younger aeolian series was deposited at 14.0±0.8 ka and 12.0±0.8 ka in south-eastern and north-eastern Lithuania, respectively (Kalińska-Nartiša et al. 2015). Again, neither traces of organic horizons nor any serious erosional surfaces have been found in the investigated sections. Nevertheless, organic-dominated deposition as visible through a gyttja horizon with mollusc remains took place at 13,430±140 cal. years (Blažauskas et al. 1998), marking, however, limnic deposition prior the aeolian event (see Fig. 2 in Molodkov and Bitinas 2006).

Additionally, dating of other aeolian sections in Lithuania reveals a similar trend as observed in Latvia: aeolian sedimentation started almost directly after the drainage of the basin that took place at 11.3±1.4 ka, followed by aeolian activity in the entire Holocene period between 10.6±1.5 ka and 3.2±0.5 ka (Molodkov and Bitinas 2006). As comparable with Latvian OSL results, a similar Holocene time frame of deposition has been observed among Lithuanian inland aeolian deposits, apart from a few much-younger results.

## Aeolian sand quartz grains

In general, grains with rounded edges and matt surface across their whole surface are considered to be of aeolian origin (Costa et al. 2013; Kalińska-Nartiša et al. 2017; Rychel et al. 2018), and thus expected in inland dune sediments. In this study, some of the sediment samples reveal an occurrence of partially rounded grains (Fig. 5A–B), likely meaning that aeolian abrasion was limited (cf. Mycielska-Dowgiałło and Woronko 2004). Nevertheless, nearly perfectly rounded grains with smooth-over depressions and meandering ridges are also present (Fig. 3C–D). One may expect that aeolian grain delivery diminishes in warmer periods due to limited aeolian activity, and conversely, increases when a cold and dry period arrives. For example, less aeolian-like grains are observed at ca. 14.8±1.0 ka in the Majaks profile, Latvia (see Fig. 1B for location and Fig. 6 for grain percentage), which may correlate with a stabilising phase known as the Lower Loamy Bed (Vandenberghe et al. 2013). Otherwise, aeolian grains alternate both in warmer and colder climate conditions (Fig. 6).

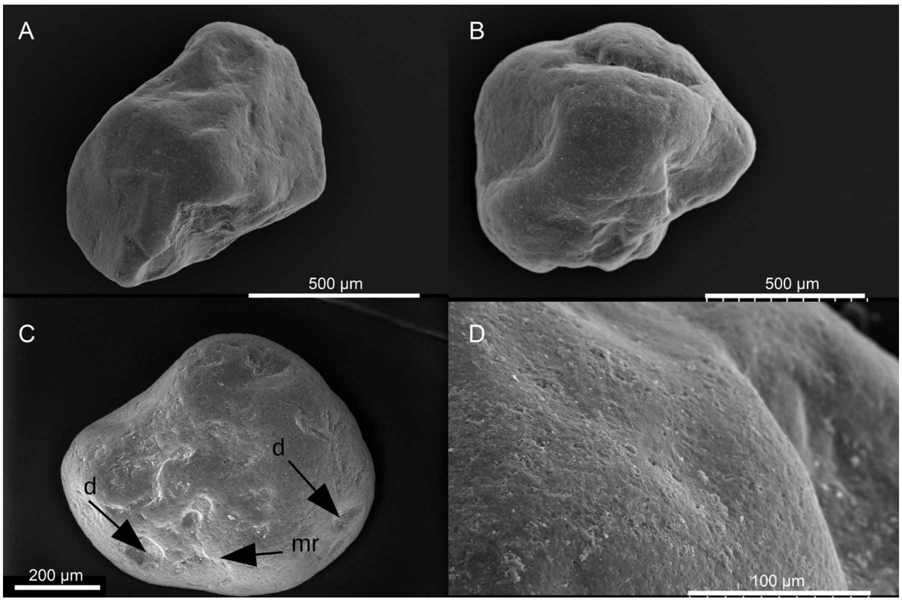

Fig. 5. Examples of scanning electron micro-graphs showing types of aeolian sand grains from inland dune sediments of the north-eastern part of the ESB: A–B – partially rounded grains; C – well-rounded matt grains with meandering ridges (mr) and smooth-over depressions (d); D – details of the convex and rounded grain edge

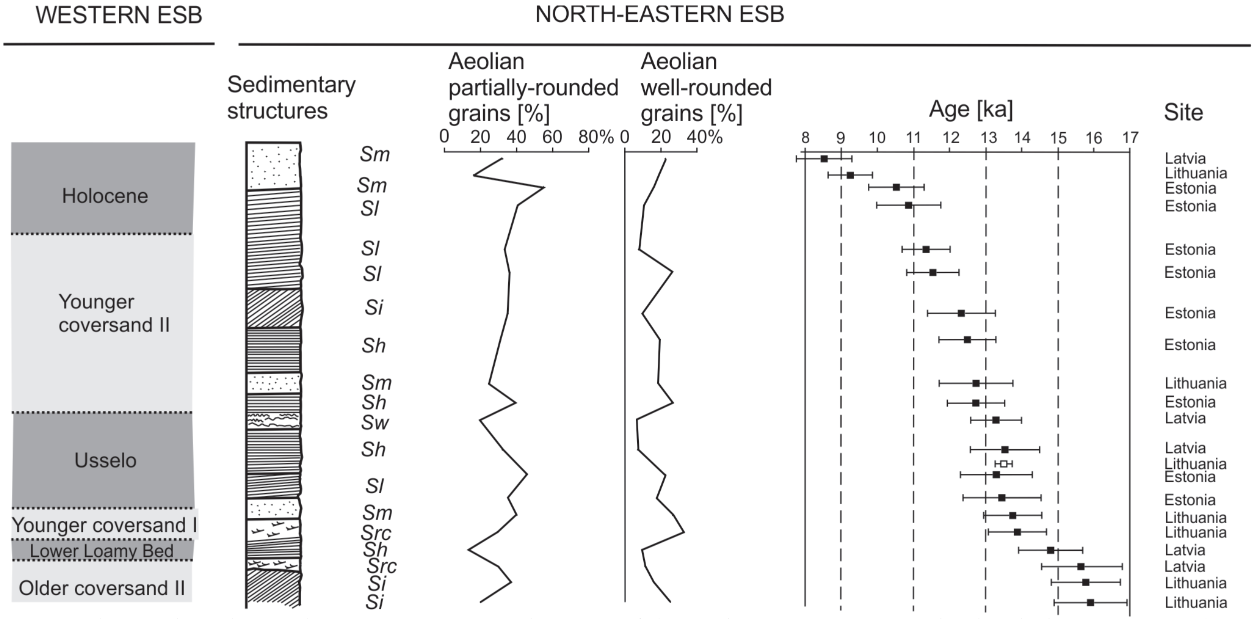

Fig. 6. Sediment chronology, sedimentary structures and textures of the north-eastern ESB as correlated with the western ESB (Vandenberghe et al. 2013). OSL dates (black squares) and radiocarbon date (white square; Blažauskas et al. 1998) are provided with their error bars. Symbols of the sedimentary structures (Zieliński and Pisarska-Jamroży 2002): Sm – massive sand; Si – sand with low-angle inclined stratification; Sl – sand with high-angle inclined stratification; Sh – horizontal sand; Sw – wavy sand; Src – sand with climbing ripples

## Continuous aeolian deposition and sediment sterility

Traditionally, the aeolian–paleosol sequence is understood as being caused dune accumulation followed by a period of dune stability during which soil formation takes place (Rohdenburg 1970), and this pattern seems valid in the western and central part of the ESB. Nevertheless, this aeolian–soil alternation is not always as straightforward, since, for example sand availability determines sand deposition itself, and soils may be soil sediments rather than being formed *in situ* (Roskin et al. 2013). There are several factors that strongly control inland dune stabilisation, such as increased vegetation along with weaker winds (Xu et al. 2015; Guo et al. 2018) such that these combine to decrease the mobility of particles transported by the ambient wind regime (Sun and Muhs 2007). Sand availability in the NE part of the ESB was generally not a problem, since directly bordering sediments of glacial lakebeds, outwash fans and glaciofluvial terraces provided an excellent and likely longer-term unhampered source material for dune formation. Undoubtedly, changes in the uncovered water table were those that controlled sand particle activity.

OSL dating, along with field observations, clearly shows that inland aeolian sediments in the Baltic States were mobile rather than stable throughout the Late Glacial and further in the Holocene, and no stabilisation has so far been detected in the investigated section, except for one diffuse organic horizon. The easiest explanation for the lack of organic horizons is erosional processes. However, practically no erosional surfaces have been observed in the investigated outcrops, and this additionally argues for limited landscape dynamics (cf. Hošek et al. 2017).

The major reason that paleosols are absent is that a dry climate prevailed in this region. It is known that during the Last Glacial Maximum, precipitation in Eastern Europe was largely reduced compared to recent climate conditions, and to Western Europe, where rainfall was enhanced (Ludwig et al. 2017). If a similar trend had also continued beyond the glacial maximum, dunes were likely unstable, unless climatic conditions favourable for vegetation occurred. For example, in the earliest stage of the Late Glacial the occurrence of cold-tolerant species along with low organic productivity is reflected in the sediments in Lithuania (Stančikaitė et al. 2008). During the entire Late Glacial, Estonia remained treeless (Amon et al. 2014) with a prevalence of pioneer vegetation (Amon et al. 2016), and thus dry and cold conditions with an open arctic landscape (Laumets et al. 2014). Sparse tundra communities are additionally known from lake sediments in Latvia between 13,000 and 12,700 cal. BP (Stivrins et al. 2015) along with a lower algae turnover between 14,500 and 11,700 cal. BP (Stivrins et al. 2018). These harsh climate conditions seem in contrast to the central and western part of the ESB, where a denser vegetation cover encroaches, even during the colder events (Karasiewicz et al. 2017; Bos et al. 2018), thus further giving an opportunity for soil development (Kaiser et al. 2009; Jankowski 2012; Hirsch et al. 2017; Zieliński et al. 2019).

## Conclusions

The following conclusions are drawn from a compilation of an available chronological data within the north-eastern ESB:

1. A traditional aeolian–paleosol alternation, as known from the western and central part of the ESB, is practically undetectable in its north-eastern part.
2. Chronological data are largely provided by optically stimulated luminescence techniques, since aeolian sediments are generally considered to be good candidates for OSL dating. In contrast, radiocarbon dates are much scarcer, because organic-rich material is found rarely. In this study, no radiocarbon dates are provided, since no suitable dating material was found.
3. Aeolian deposition took place between 15.9±1.0 ka and 8.5±0.5 ka in the north-eastern part of the ESB, further followed by younger reactivation events.
4. A large group of luminescence samples contains non-quartz/feldspar particles instead of pure quartz extracts, thus forcing the use of pulsed OSL stimulation in further equivalent dose determination. The cause of feldspar contamination is unknown, but feldspar-rich rock formations, such as

those directly bordering the Quaternary deposits, are likely responsible for this.

5. Aeolian-type quartz grains occur in the investigated sediments, but these grains do not mark phases of aeolian activity versus stability, as initially expected, except in the Majaks profile in Latvia dated to ca. 14.8±1.0 ka, where aeolian grains diminish.

6. As apparent from the existing proxies, inland aeolian sediments were largely mobile throughout the Late Glacial and in the Holocene without serious events of stability. This latter is visible through the lack or limited number of paleosols. Additionally, aeolian deposition seems to nearly instantly follow the drainage of glacial lakes.

7. Sediments of the western and central part of the ESB provide the most straightforward evidence for the Late Glacial climate changes, whereas these changes are less clear in the north-eastern part of the ESB. Considering the prevalence of pioneer vegetation in this latter part, and thus dry and cold conditions, there was a limited opportunity for soil development.

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## Disclosure statement

No potential conflict of interest was reported by the authors.

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