Sedimentary record and luminescence chronology of the Lateglacial and Holocene aeolian sediments in Lithuania

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Sand dunes are common along the sea coasts of Lithuania and in some regions of the mainland part of the country. Until recently, the age of the aeolian deposits was only approximate because of the lack of radiocarbon-dating of soils buried in dune deposits. A relatively new alternative method to direct dating of organic-free deposits is infra-red optically stimulated luminescence (IR-OSL). Using this method, we investigated the sedimentary history of some Lateglacial and Holocene depositional sites of Lithuanian dunes. The samples for IR-OSL dating have been taken from boreholes (Mančiagirė, Smalininkai, Žalioji Giria) and outcrops (Mančiagirė and Ventės Ragas) in different dune massifs. The results indicate that the aeolian sedimentation in Lithuania started during the Younger Dryas. The termination of the aeolian processes in the continental part of Lithuania is correlated with the end of the Atlantic or the beginning of the Subboreal period; this can be explained by significant climatic changes during the Atlantic period. There were several periods of high aeolian activity during the Holocene, but these are asynchronous in different dune massifs and variations in the sedimentation rate occurred both vertically over the section and spatially across the massif.

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Notwithstanding that aeolian deposits cover only about 2.6% of Lithuania (Guobytė *et al.* 2001), they are generally concentrated in a few regions of the mainland (Fig. 1) and on the Baltic Sea coast; the continental dune massifs prevail over the coastal areas and are vegetated. Until recently, the age of aeolian deposits in Lithuania was only approximately estimated based on very few radiocarbon ages from buried soils found inside the aeolian deposits (Gudelis & Michaliukaitė 1976; Gaigalas *et al.* 1989; Gudelis 1998). The limited amount of radiocarbon-age data is due to the absence of soils or any other organic-rich material in many localities of aeolian dune massifs, especially continental ones.

Although the ^{14}C dating method has proved the most useful radiometric dating technique for Quaternary palaeosols, its application is often problematic (Geyh *et al.* 1983; Matthews 1985). This is mostly related to a general problem of potential contamination sources (for details, see e.g. Scharpenseel 1971; Aaby 1983; Evans 1985; Frink 1992; Chichagova & Cherkinsky 1993).

An alternative method for direct dating organic-free deposits is optically stimulated luminescence (OSL), which was introduced almost 20 years ago by Huntley *et al.* (1985). Sand grains in aeolian deposits are likely to have experienced several bleaching cycles while washed on the beach and during subsequent aeolian transport, before finally being buried in coastal or mainland dunes. Therefore, the optical dating method is especially well suited for these deposits. In recent years, the optical dating of relatively young (Lateglacial and Holocene) aeolian sediments has been progressively used in different countries (e.g. Raukas & Hütt 1998; Käyhkö *et al.* 1999; Lian & Huntley 1999; Murray-Wallace *et al.* 2002). The first attempt at optical dating of aeolian sediments in Lithuania was associated with large-scale geological mapping projects of the Geological Survey of Lithuania, especially those in the Lithuanian Maritime Region. Along with the dating of inter-till deposits and sediments associated with different stages of the Baltic Sea development, some tens of samples from aeolian deposits were dated using the thermo- and optically stimulated luminescence methods (Satkūnas *et al.* 1991; Bitinas *et al.* 2000, 2001). An overview of the first results of optical dating of Lithuanian aeolian deposits was published by Bitinas (2004).

The aim of the present paper is to report the new results obtained through study of the sedimentary history of some Lateglacial and Holocene depositional sites of Lithuanian dune massifs and to assign absolute ages to some of the dune profiles. This may help in our understanding the processes that lead to the formation of aeolian landforms during the long-term development of dynamic aeolian system responding quickly to changing environmental conditions.

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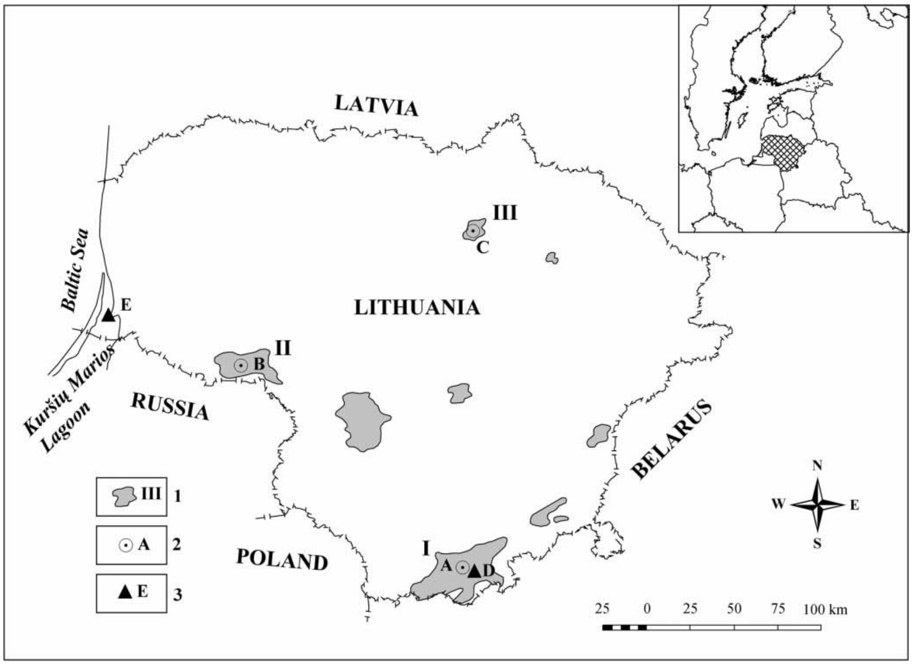


Fig. 1. The biggest massifs of continental dunes of Lithuania and study sites dated by the infra-red optically stimulated luminescence (IR-OSL) method. 1 = investigated aeolian massifs: I, Dzūkija; II, Viduklė, III; Žalioji Giria; 2 = investigated boreholes: A, Mančiagirė; B, Smalininkai; C, Žalioji Giria; 3 = investigated outcrops; D, Mančiagirė; E, Ventės Ragas.

Investigated sections and sampling

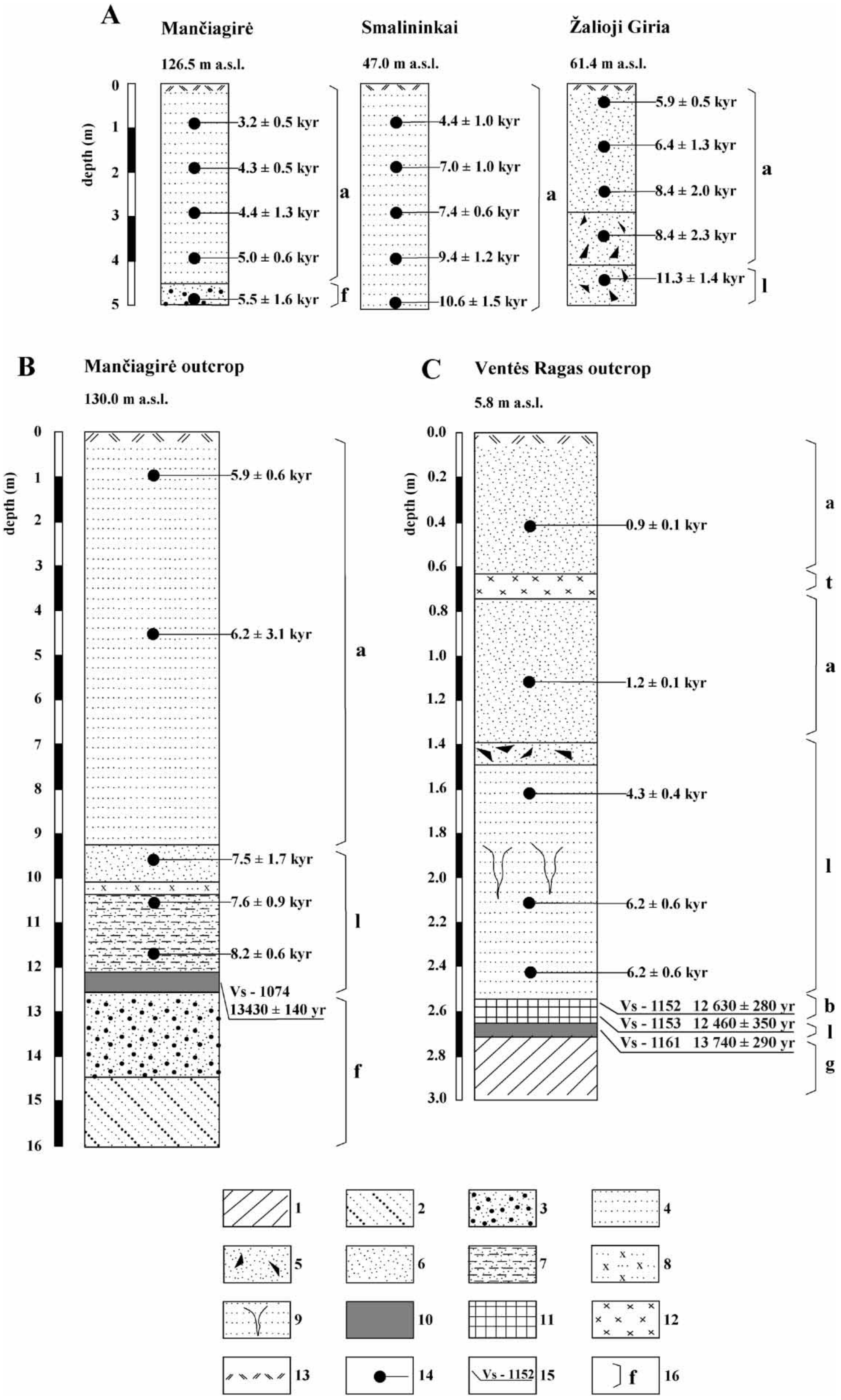
The samples for optical dating were taken from three boreholes in three different continental dune massifs of Lithuania and were named according to Česnulevičius & Morkūnaitė (1997) as Dzūkija (borehole Mančiagirė), Viduklė (borehole Smalininkai) and Žalioji Giria (borehole Žalioji Giria). Samples were also taken from two natural outcrops: Mančiagirė, which is about 1.7 km from the Mančiagirė borehole, and Ventės Ragas, which is from the cliff of the Kuršių Marios Lagoon in the coastal part of the Baltic Sea (Fig. 1). The samples were taken from dunes with similar morphological shape in each continental dune massif, i.e. from the very central part of elongated, slightly curved barchan type dunes. The relative height of the investigated dunes varies from 3 m to 5 m in Žalioji Giria and Mančiagirė to 15 m in the Smalininkai aeolian massif. The boreholes for sampling were drilled by hand auger to a depth of 5.0 m. The samples were taken at 1-m intervals (Fig. 2A) and were collected and stored in light-proof packages that also served to protect the natural moisture of the sediment.

In the Žalioji Giria borehole, two layers of genetically different (lacustrine and aeolian) sediments were sampled (Fig. 2A). Both the lacustrine and aeolian sediments were represented by fine-grained (particles of 0.25–0.10 mm in size) and very fine-grained (0.10–0.05 mm) sand, making up about 90–95% of the total sediment volume. Carbonates, feldspar and quartz generally represent the lacustrine brownish-yellow sand with small admixture of very fine particles of organic matter (charcoal). The aeolian deposits are represented by bright yellow sand composed generally of feldspar and quartz. In the lower part of the unit (depth 2.9–4.1 m), a very small admixture of charcoal was observed. One sample for optical dating was taken from lacustrine sand and four samples from aeolian deposits.

The Smalininkai section (Fig. 2A) is represented by brownish-yellow fine-grained aeolian sand (55–60% of the sediment volume consisting of 0.25–0.10 mm particles). Feldspar and quartz dominate in the sand.

The lowermost part of the Mančiagirė section (Fig. 2A, depth 4.6–5.0 m) consists of variously grained brownish-yellow, probably glaciofluvial, sand formed in the extraglacial environment (Blažauskas *et al.* 1998a) and composed mainly of carbonates, feldspar and quartz. The aeolian sediments occur in the uppermost part of the section at a depth of 4.6 m and are represented by medium-grained and fine-grained sand (particles 0.50–0.25 mm and 0.25–0.10 mm in size comprise >85% of the total sediment volume). The sand is composed mainly of feldspar and quartz. One sample for dating was taken from glaciofluvial sediments, the other four samples from aeolian deposits (Fig. 2A).

In the Mančiagirė outcrop (Fig. 2B), three genetically different types of sediments were identified by Blažauskas *et al.* (1998a). The two lowermost layers are glaciofluvial sediments presented by bright-yellow variously grained, horizontally (depth 12.55–14.6 m) or cross (depth 14.6–16.0 m) bedded sand. Further up, lacustrine sediments occur composed of dark yellowish-brown gyttja with mollusc remnants (depth


A
Mančiagirė
126.5 m a.s.l.
Smalininkai
47.0 m a.s.l.
Žalioji Giria
61.4 m a.s.l.
depth (m)
0
1
2
3
4
5
3.2 ± 0.5 kyr
4.3 ± 0.5 kyr
4.4 ± 1.3 kyr
5.0 ± 0.6 kyr
5.5 ± 1.6 kyr
a
f
4.4 ± 1.0 kyr
7.0 ± 1.0 kyr
7.4 ± 0.6 kyr
9.4 ± 1.2 kyr
10.6 ± 1.5 kyr
a
5.9 ± 0.5 kyr
6.4 ± 1.3 kyr
8.4 ± 2.0 kyr
8.4 ± 2.3 kyr
11.3 ± 1.4 kyr
a
l
B
Mančiagirė outcrop
130.0 m a.s.l.
depth (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
5.9 ± 0.6 kyr
6.2 ± 3.1 kyr
7.5 ± 1.7 kyr
7.6 ± 0.9 kyr
8.2 ± 0.6 kyr
Vs - 1074
13430 ± 140 yr
a
l
f
C
Ventės Ragas outcrop
5.8 m a.s.l.
depth (m)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
0.9 ± 0.1 kyr
1.2 ± 0.1 kyr
4.3 ± 0.4 kyr
6.2 ± 0.6 kyr
6.2 ± 0.6 kyr
Vs - 1152 12 630 ± 280 yr
Vs - 1153 12 460 ± 350 yr
Vs - 1161 13 740 ± 290 yr
a
t
a
l
b
l
g
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Vs - 1152
15
f
16

12.15–12.55 m) and fine-grained to very fine-grained sand (depth 9.25–12.15 m), silty in the lower part of the layer, with a thin bed of yellowish-brown fine-grained sand cemented by limonite. The aeolian brownish-yellow fine-grained massive sand occurs in the uppermost part of the section (depth 0.20–9.25 m). Three samples for optical dating were taken from the lacustrine sediments and two samples from the overlying aeolian deposits.

The Ventės Ragas outcrop (Fig. 2C) displays a number of genetically different layers. Brownish-grey till of the last (Late Nemunas/Late Weichselian) glaciation (depth 2.7–3.0 m) is found at the base of the section. Lake sediments are represented by greenish-grey gyttja with remnants of freshwater molluscs (depth 2.65–2.70 m) and by fine-grained yellowish-brown sand typically composed of feldspar and quartz (depth 1.40–2.55 m). Bog deposits – brownish-black compact peat – are intercalated with the lower part of lacustrine sediments (depth 2.55–2.65 m). The greyish-yellow fine-grained and very fine-grained aeolian sand composed of feldspar and quartz is found in the upper part of the outcrop (depth 0.05–1.40 m). A thin layer of anthropogenic deposits (depth 0.65–0.75 m) represented by loam with ceramic shards occurs in the middle of the aeolian sediments. Three samples were taken from the lacustrine sediments and two from the aeolian deposits.

Optically stimulated luminescence dating

Luminescence dating works on the principle that naturally occurring minerals, such as quartz and feldspar, behaving as a palaeodosimeter, store the energy deposited by natural ionizing radiation. The basic premise is that the latent signal in these minerals was reduced to a low level by daylight during predepositional transport of the mineral grains (luminescence clock zeroing). During subsequent burial, the minerals absorb the radiation energy, the amount of which is related to the time elapsed since mineral grains were last subjected to light. In principle, the luminescence age can be calculated knowing the total absorbed energy and the energy absorption rate. Further discussion of these and related principles is provided by Aitken (1985, 1998).

Alkali feldspars separated from the sediments were used for luminescence dating. Small aliquots of K-feldspar were stimulated by infra-red (IR) light, and the violet luminescence emitted was measured. In the case of infra-red stimulation, the emitted light and the dating technique are often called infra-red optically stimulated luminescence (IR-OSL).

The sediments were prepared for the luminescence analysis according to standard laboratory procedures. Briefly, alkali feldspar grains in the size range 100–150 μm were extracted from the sediment under subdued filtered light in the laboratory following a procedure that included wet sieving, heavy liquid flotation (collecting 2.54–2.58 g cm^{-3} fraction) and treatment by 20 to 40% HCl acid to remove carbonates. The alpha-affected surface layer of the K-feldspar grains was removed by etching in 10% HF for 15 min. The IR-OSL was measured with a computer-controlled Ingrid-Type SLM-1 reader using 860 nm stimulation by short 3 s laser pulses. The light beam power on the aliquots was 5 mW/cm^2. The IR stimulated luminescence from K-feldspar was measured in the 380–430 nm wavelength range using a combination of 3 mm SZS-22 (blue-green), 3 mm PS-11 (purple) and 2 mm FS-1 (violet) colour glass filters manufactured by the LZOS, JSC (Lytkarino Optical Glass Factory), Russian Federation. This filter combination gives a signal-to-noise ratio of about 40 for natural late Holocene samples and up to about 2500 for natural Pleistocene samples. Background counts were about 30 c s^{-1}. For laboratory irradiation, a precisely calibrated ^{60}Co source delivering 6.5×10^{-2} Gy s^{-1} of gamma radiation was used.

After laboratory irradiation of the feldspar samples, a low-temperature thermoluminescence (TL) peak centred at about 180°C (for a heating rate of 2°C s^{-1}) is usually observed (Duller 1997). In addition, glow curves of the potassium-rich feldspars typically exhibit two natural signal peaks occurring at around 330°C and 260°C (Duller 1997) with the lifetimes of about 0.7×10^6 and 0.4×10^6 years, respectively (Mejdahl 1988). Usually, these two relatively low-temperature signals at about 180°C and 260°C are removed when the samples are preheated – typically for 10 min at 220°C (Aitken 1998). However, in many K-feldspar samples studied in the present and some recent works, the contribution of these relatively low-temperature and unstable signals to the infra-red-stimulated luminescence was not detected. This can be interpreted as indicative of no IR-OSL from the traps responsible for the strong 180°C and 260°C TL

Fig. 2. Geological sections of the investigated boreholes (A) and outcrops (B, C) with the IR-OSL and ^{14}C calibrated dating results. 1 = till; 2 = various-grained sand, cross-bedded; 3 = various-grained sand; 4 = fine-grained or/and medium-grained sand, massive; 5 = fine- to very fine-grained sand with organic matter (charcoal, plant remnants); 6 = fine- to very fine-grained sand; 7 = very fine-grained sand with silt intercalations; 8 = fine-grained sand cemented by limonite; 9 = traces of albeluvic tonguing; 10 = gyttja; 11 = peat; 12 = anthropogenic layer (loam with ceramics shards); 13 = soil; 14 = sampling sites for IR-OSL dating; 15 = sampling sites for ^{14}C dating; 16 = origin of sediments: g = glacial; f = glaciofluvial (fluvial); l = limnic; b = peat bog; v = Aeolian; t = anthropogenic. ^{14}C data after Blažauskas *et al*. (1998) and Bitinas *et al*. (2002).

peaks in the samples studied, which seems to be consistent with the preheating results presented by Duller (1997) and Bøtter-Jensen (2000). This allows preheating of the K-feldspar samples before the measurements and potential complications connected with this procedure to be avoided (e.g. preheating of the sample prior to measurement can result in thermal transfer from shallow, light-insensitive traps to the traps sampled during the OSL measurement (Wallinga 2002), in charge redistribution (Trautmann *et al.* 2000), in changes in the charge trapping probability (Wallinga *et al.* 2001), in interference between the orange and blue emission bands, etc.). Therefore, instead of preheat we store samples for about 1 month at room temperature to allow the decay of post-irradiational phosphorescence.

However, there is another problem concerning the use of feldspars for dating applications. According to Wintle (1973), this mineral, especially when extracted from volcanogenic deposits, may suffer from a specific phenomenon known as anomalous fading, whereby the luminescence intensity spontaneously declines over time after artificial irradiation, possibly due to localized transition (Templer 1986) or quantum-mechanical tunnelling (Visocekas 1985). The increasing number of studies shows that most varieties of feldspars fade (Spooner 1994) and feldspar-based luminescence dates are therefore suspected to be underestimated by up to 30–50% over the entire dating range of this mineral (Lamothe & Auclair 1999; Huntley & Lamothe 2001; Wallinga *et al.* 2001; Balescu *et al.* 2003).

Recently, a method was proposed for direct detection of the tunnel transitions from the dosimetric traps utilizing the specific features of the low-temperature (down to liquid nitrogen temperature) dependencies of the luminescence intensity stimulated in the IR region (Vasil'chenko *et al.* 2005). With this method, the indications of tunnelling were actually revealed for the dosimetric traps. But especially important is the observation that the tunnelling process quickly (within several days) fades and during 1-month storage of the samples does not reveal any appreciable influence on the value of the reconstructed palaeodose. This circumstance meant that we could reject the procedure of testing samples being dated for anomalous fading, which is usually carried out by measuring feldspar samples immediately after artificial irradiation and then after storage at ambient temperature for several months. This finding has significant practical implications for dating of the feldspars because the fading test is tedious, extremely time-consuming and often inaccurate due to the scatter of data points and the great difference between the laboratory and geological time scales.

The validity of the above observations concerning opportunities to reject preheating of the samples and testing for anomalous fading is also proved by cross-dating, when samples taken from one and the same layer, or from the layers with the independently determined stratigraphic order, are dated by different dating methods.

The cross-dating results were obtained on 20 middle and late Pleistocene samples by 3 different methods (ESR, OSL and IR-OSL) using 3 different minerals: feldspar, quartz and biogenic carbonate (Table 1). The results indicate no evidence of noticeable athermal emptying of the feldspar dosimetric traps even over the geological time scale. Nor do these results indicate any noticeable contribution from the traps responsible for the 180°C and 260°C TL peaks to the IR-stimulated luminescence signals from feldspars.

Determination of equivalent dose, D_e, was performed by extrapolating the dose-response curves to zero OSL intensities using the multiple-aliquot additive-dose technique. Additive-dose growth curves were constructed using 7–11 dose points each consisting of measurements of 5 separate aliquots (Fig. 3).

The external beta and gamma contributions to the total dose rate, *D*, were estimated in the laboratory from the contents of natural radioactive elements, $^{238}U + ^{235}U$, ^{232}Th and ^{40}K in the sediments assuming secular equilibrium and using the dose-rate conversion factors of Adamiec & Aitken (1998). For detecting and identifying naturally occurring radioactive elements in the surrounding matrix, a multichannel gamma-ray spectrometer with a 150 mm dia × 100 mm dia low background sodium iodide crystal was used. Representative samples of about 1.5–2.0 kg in weight were used for assessment of the gamma and beta contribution to the external dose rate. Attempts were made to take all samples from within a 30 cm sphere of uniform layers, or at least 15 cm from the nearest sedimentary boundary. The contribution of cosmic rays to the total dose rate was calculated using the formula of Prescott & Hutton (1994). The intensity of cosmic rays decreases with depth. In order to take into account the increase in the thickness of the deposits during burial, we used half of the present depth for calculation of cosmic ray dose as an approximation of the mean burial depth over the dated period. The *in situ* water content was used in calculating the dose rate. The internal beta dose from the decay of ^{40}K and ^{87}Rb within K-feldspar grains was obtained from the concentration estimates recommended by Huntley & Baril (1997) and Huntley & Hancock (2001), respectively, and using the beta attenuation factors reported by Mejdahl (1979).

Dating results and their stratigraphic interpretation

According to the IR-OSL dating results (Table 2) in the Žalioji Giria section (Fig. 2A), the lacustrine sediments below the aeolian layer were deposited at the very end

Table 1. Mollusc-based ESR, feldspar IR-OSL and quartz OSL cross-dating results.

No.	Section	Location	Sampling depth (m)	Mollusc-based ESR age (kyr)	Feldspar IR-OSL age (kyr)	Quartz OSL age (kyr)
1	U-XXII	~67.9°N 60.1°E	7.5	72.0±4.8[a]	74.7±8.3[a]	
2	U-VII	~67.8°N 60.7°E	6.4	107.6±12.4[a]	109.8±6.9[a]	
3	Varzuga	~66.4°N 36.6°E	16.0	103.0±4.2[b]	104.0±8.3[b]	
4	U-VII	~67.8°N 60.7°E	12.0	90.3±10.9[a]	88.2±5.4[a]	
5	Vilkiškės	~54.8°N 25.4°E	14.5			129.0±24.0[c]
6	Vilkiškės	~54.8°N 25.4°E	14.0		136.7±8.8[d]	
7	Vilkiškės	~54.8°N 25.4°E	14.3		147.1±9.4[d]	
8	Vilkiškės	~54.8°N 25.4°E	17.8			150.7±5.8[c]
9	Vilkiškės	~54.8°N 25.4°E	25.7			211.0±16.0[c]
10	Vilkiškės	~54.8°N 25.4°E	29.5		230.2±16.2[d]	
11	Vilkiškės	~54.8°N 25.4°E	33.0		273.3±16.0[d]	
12	Vilkiškės	~54.8°N 25.4°E	34.3		307.1±17.4[d]	
13	Chavan'ga	~66.0°N 37.8°E	4.0		63.6±8.0[e]	
14	Chavan'ga	~66.0°N 37.8°E	8.5	99.0±7.6[e]		
15	Strel'na	~66.0°N 38.5°E	6.5		85.6±6.6[e]	
16	Strel'na	~66.0°N 38.5°E	25.8	90.4±6.7[e]		
17	Strel'na	~66.0°N 38.5°E	29.8		101.9±12.2[e]	
18	Strel'na	~66.0°N 38.5°E	32.2	111.5±12.4[e]		
19	Ludyanoy	~66.3°N 39.9°E	8.3		80.5±7.0[e]	
20	Ludyanoy	~66.3°N 39.9°E	12.7	85.5±6.6[e]		

[a] Molodkov, unpubl. data. [b] Molodkov & Yevzerov (2004). [c] Fedorowicz (2003). [d] Satkūnas & Molodkov (2005). [e] Korsakova *et al*. (2004).

of the Younger Dryas (11.3±1.4 kyr, sample 1410-043; N.B. All ages given here are in cal. yr BP). Aeolian activity and redeposition of lacustrine sediments started, in all likelihood, directly after the basin drainage in the Boreal (8.4±2.3 kyr, sample 1409-043) and ended in the Atlantic period (5.9±0.5 kyr, sample 1406-043).

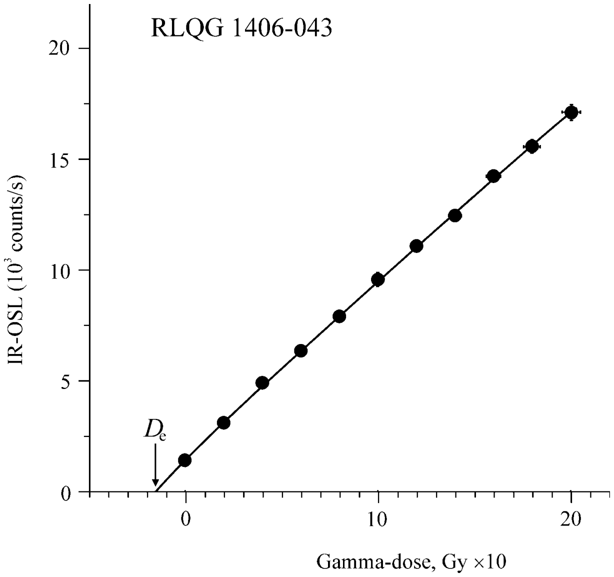


Fig. 3. Example of the method used for evaluation of the equivalent dose, D_e. Shown is the multiple-aliquot additive-dose response curve for the 6.2 kyr old sample RLQG 1406-043 from the Žalioji Giria section. Exponential fitting of the data points was used as the basis for extrapolation. Each point used to construct the dose-response curve is the mean of five read-out values from five aliquots at natural, and each added dose. Error bars on symbols indicate standard deviation; where absent, bars fall within symbols.

A similar situation is observed in the Smalininkai section (Fig. 2A). Although the borehole penetrated only the uppermost part of the aeolian deposits, it can be concluded that the aeolian sedimentation there was still active at the end of the Preboreal (10.6±1.5 kyr, sample 1415-043) and continued in the middle of the Subboreal period (4.4±1.0 kyr sample 1411-043).

The lowermost part of the section in the Mančiagirė borehole (Fig. 2A), which was attributed to extraglacial glaciofluvial sedimentation (Blažauskas *et al.* 1998a), was formed at the beginning of the Subboreal period (5.5±1.6 kyr, sample 1425-043), i.e. significantly later than glaciofluvial processes ended in the territory of Lithuania. It is thus possible to maintain that the lowermost layer of the Mančiagirė borehole section represents glaciofluvial sediments remoulded by wind activity. However, it cannot be excluded that these sediments are of fluvial origin. The aeolian activity in the vicinity of Mančiagirė continued until the end of the Subboreal period (3.2±0.5 kyr, sample 1421-043).

The IR-OSL dating results from the Mančiagirė outcrop (Fig. 2B) indicate that lake sediments above the gyttja formed during the Atlantic period (8.2±0.6 to 7.5±1.7 kyr, samples 1416-043 to 1418-043, respectively). The aeolian processes probably started directly after the drainage of the lake and continued during the Atlantic period. It is not possible to determine the end of aeolian deposition in this locality because the uppermost part of the aeolian unit has been removed by river erosion. The IR-OSL dating is consistent with data of radiocarbon analysis indicating that the gyttja

Table 2. Luminescence and radioactivity data for the samples analysed in this study. U, Th, K are the uranium, thorium and potassium content in sediments as determined from laboratory gamma-ray spectrometry; W is the *in situ* water content; D_c is the cosmic dose rate (Prescott & Hutton 1994); D is the total dose rate (that due to cosmic ray, gamma and beta radiation); D_e is the equivalent dose. All of the samples reported in this article were dated at the Research Laboratory for Quaternary Geochronology, Institute of Geology, Tallinn University of Technology.

No.	Lab. code* and sample no. RLQG	Site	Depth (m)	U (ppm)	Th (ppm)	K (%)	W (%)	D_c (µGy/yr)	D (µGy/yr)	D_e (Gy)	IR-OSL-age (kyr)
1	1406-043	Žalioji Gira	0.45	1.34±0.05	2.17±0.11	1.38±0.02	0.1	203.8±40.8	2737.2±136.9	16.0±0.9	5.9±0.5
2	1407-043	Žalioji Gira	1.45	1.85±0.07	2.80±0.14	1.26±0.02	0.1	190.9±38.2	2777.6±138.9	17.9±2.1	6.4±1.3
3	1408-043	Žalioji Gira	2.45	1.16±0.05	4.00±0.20	1.74±0.03	0.1	178.9±35.8	3155.7±157.8	26.5±3.7	8.4±2.0
4	1409-043	Žalioji Gira	3.45	0.59±0.02	2.75±0.14	1.58±0.03	0.2	167.9±33.6	2751.5±137.6	23.3±3.7	8.4±2.3
5	1410-043	Žalioji Gira	4.45	0.42±0.02	1.28±0.06	1.36±0.02	16.6	157.1±31.4	2085.8±104.3	21.6±7.5	10.3±1.4
6	1411-043	Smalininkai	0.95	0.61±0.02	2.92±0.15	1.15±0.02	0.2	197.2±39.4	2380.6±119.0	10.5±1.2	4.4±1.0
7	1412-043	Smalininkai	1.95	0.80±0.03	2.85±0.14	1.19±0.02	0.7	184.8±37.0	2440.9±122.0	17.2±1.5	7.0±1.0
8	1413-043	Smalininkai	2.95	0.77±0.03	2.95±0.15	1.23±0.02	0.6	173.3±34.7	2464.3±123.2	18.2±1.2	7.4±0.6
9	1414-043	Smalininkai	3.95	0.12±0.01	1.32±0.07	1.21±0.02	0.4	162.6±32.5	2164.4±108.2	20.4±2.4	9.4±1.2
10	1415-043	Smalininkai	4.95	0.27±0.01	1.39±0.07	1.20±0.02	0.4	152.8±30.6	2194.6±109.7	23.3±2.0	10.6±1.5
11	1421-043	Mančiagirė borehole	0.95	3.23±0.13	3.49±0.17	0.76±0.01	0.9	196.6±39.3	2646.8±132.3	8.5±1.0	3.2±0.5
12	1422-043	Mančiagirė borehole	1.95	0.41±0.02	2.46±0.12	1.00±0.02	1.0	184.8±37.0	2128.9±106.4	9.3±0.8	4.3±0.5
13	1423-043	Mančiagirė borehole	2.95	0.36±0.01	1.68±0.08	0.89±0.02	2.1	173.3±34.7	1930.0±84.2	8.5±1.5	4.4±1.3
14	1424-043	Mančiagirė borehole	3.95	0.46±0.02	1.83±0.09	0.97±0.02	1.6	162.6±32.5	2033.0±101.7	10.3±0.9	5.0±0.6
15	1425-043	Mančiagirė borehole	4.95	0.51±0.02	1.84±0.09	0.92±0.02	0.8	152.8±30.6	1997.4±100.1	11.0±2.3	5.5±1.6
16	1420-043	Mančiagirė outcrop	1.00	0.49±0.02	1.52±0.08	1.01±0.02	1.5	196.6±39.3	2090.9±104.5	12.4±0.7	5.9±0.6
17	1419-043	Mančiagirė outcrop	4.50	0.24±0.01	0.86±0.04	0.86±0.02	1.7	157.1±31.4	1803.9±90.2	11.2±3.3	6.2±3.1
18	1418-043	Mančiagirė outcrop	9.60	0.24±0.01	0.38±0.02	0.85±0.02	2.4	115.6±23.1	1704.4±85.2	12.8±1.8	7.5±1.7
19	1417-043	Mančiagirė outcrop	10.40	0.41±0.02	1.92±0.10	1.01±0.02	2.1	110.4±22.1	2002.4±100.5	15.2±1.3	7.6±0.9
20	1416-043	Mančiagirė outcrop	11.70	0.50±0.02	1.62±0.08	1.06±0.02	0.6	102.6±20.5	2070.5±103.5	17.0±1.0	8.2±0.6
21	1373-051	Ventės Ragas	0.40	0.32±0.01	0.65±0.03	0.84±0.02	6.9	204.5±40.9	1770.3±88.5	1.6±0.1	0.9±0.1
22	1375-051	Ventės Ragas	1.10	0.60±0.02	1.26±0.06	0.99±0.02	5.9	195.3±39.1	2014.7±100.7	2.4±0.2	1.2±0.1
23	1376-051	Ventės Ragas	1.60	0.52±0.02	1.21±0.06	0.92±0.02	3.0	189.0±37.8	1967.8±98.4	8.5±0.6	4.3±0.4
24	1377-051	Ventės Ragas	2.10	0.61±0.02	1.05±0.05	0.81±0.01	2.7	183.0±36.6	1867.1±93.4	11.5±0.7	6.2±0.6
25	1378-051	Ventės Ragas	2.40	0.71±0.03	2.23±0.11	0.81±0.01	12.3	179.5±35.9	1843.1±92.2	11.5±0.8	6.2±0.6

*The laboratory code (RLQG) is omitted in the text and only sample numbers are indicated where necessary.

at this site was formed during the Bølling (Blažauskas *et al.* 1998b).

The Ventės Ragas outcrop (Fig. 2C) is one of the key sections among the few outcrops along the Lithuanian Baltic Sea coast. Some of the data obtained from this section have already been used for the palaeogeographical reconstruction of the Nemunas River Delta region (Bitinas *et al.* 2002). According to the new results of IR-OSL dating, the lacustrine sandy sediments formed in two stages (obvious traces of soil-forming processes – albeluvic tonguing – were observed in the middle part of the sand layer, suggesting a sedimentological break), that is in the Altlantic and Subboreal periods (6.2 ± 0.6 and 4.3 ± 0.4 kyr, samples 1378-051 to 1376-051, respectively). These results do not contradict the radiocarbon ages that suggest the gyttja and peat both formed in the Allerød and Younger Dryas (Bitinas *et al.* 2002). The first stage of the aeolian activity started during the Subatlantic period (1.2 ± 0.1 kyr, sample 1375-051), whereas the next stage (0.9 ± 0.1 kyr, sample 1373-051) is correlated with the Historical period. Both these units of aeolian deposits are separated by a thin bed of anthropogenic deposits (artificial loam with ceramic shards) that probably served as the floor for a medieval building. According to the preliminary interpretation of archaeological findings they belong to the Middle Medieval period (AD 1200–1400, V. Žulkus, pers. comm. 2004), so the date obtained is quite close to the expected one.

Discussion and conclusions

Sand dune systems, which are naturally dynamic, can cause problems when dating by the luminescence method. Sand moves in response to various climate factors. Parts of the dunes can be stabilized, being buried by younger sand, and age-discordant layers can therefore be encountered in one and the same vertical profile of the dune. A similar problem may arise if samples are taken from proximal or distal sides of the dune.

Another problem is that even aeolian deposits may consist of a mixture of fully and partly bleached grains of feldspar and quartz used for luminescence dating of sand dunes. That is, the sample may have been composed of mineral grains with different levels of residual luminescence. This would result in a greater degree of scatter in the data points and, consequently, in less accurate ages. When sediments were not exposed to sufficient sunlight prior to burial, the ages obtained

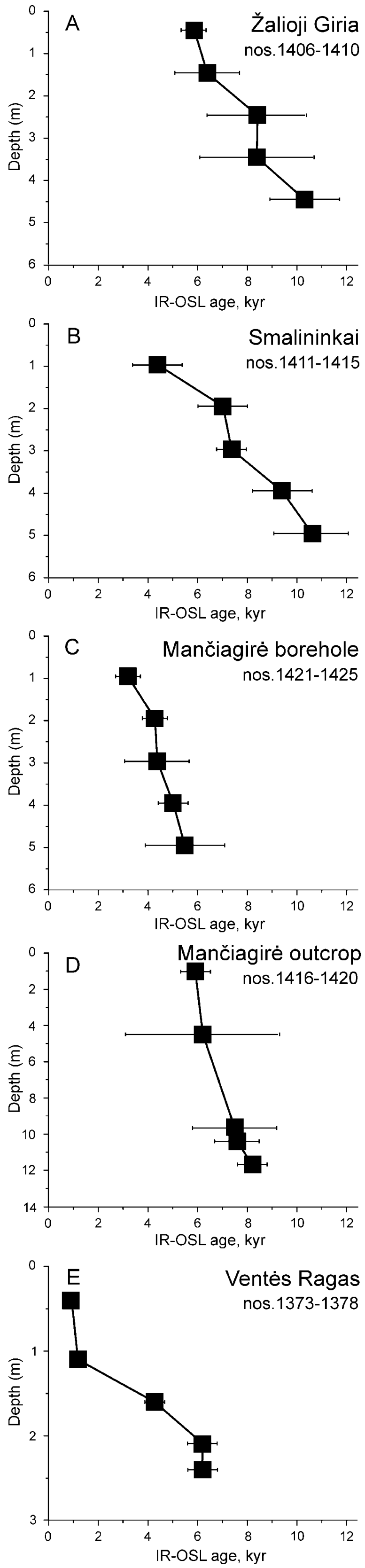


Fig. 4. IR-OSL ages (solid squares) of the samples (Table 2) plotted against their sampling depths. Error bars on symbols indicate standard deviation; where absent, bars fall within symbols.

from these samples may be overestimated (Lian & Huntley 1999).

However, based on the recent optical dating results on the extremely young (a few years) dune sand samples (Ballarini *et al.* 2003), there is good reason to believe that in most cases the optically stimulated signal in the sand dune studied may be completely reset at the time of deposition. Our previous and current results suggest that this was also the case with the aeolian deposits investigated in different sites of Lithuania.

The previous results of OSL dating of aeolian deposits (Bitinas 2004) showed that the age of these deposits varies from several thousands to a few hundred years. It has been suggested that periods of aeolian activity for massifs of continental dunes and dunes of the Baltic Sea coast were different. In a few massifs of continental dunes the aeolian processes started in the Lateglacial after the drainage of meltwater basins and generally ended after the Atlantic climatic optimum of the Holocene. The formation of ancient coastal dunes is closely related to different stages of the Baltic Sea development. The most active aeolian processes occurred directly after the regressions of the Baltic Ice Lake and during the Post-Litorina Sea stages when sandy sediments of former littoral areas were exposed to deflation. The Medieval period of activation of aeolian processes caused by deforestation is represented as aeolian deposition as well (Bitinas 2004).

The present results of IR-OSL dating confirm the above framework. According to the dating from the Žalioji Giria and Smalininkai sections, the aeolian sedimentation started directly after the drainage of lacustrine basins, i.e. during the Younger Dryas or Preboreal when aeolian processes were widespread in western and central Europe (Böse 1991; Manikowska 2000; Ujhazy *et al.* 2003). The termination of these processes in the continental part of Lithuania is generally linked with the end of the Atlantic and could be explained by sharp changes in climate during this period. Warm and wet climate resulted in an increase of vegetation (Kabailienė 1998) which, in turn, terminated the aeolian processes and created relatively stable landforms. However, it is still difficult to explain why aeolian processes continued until the Subboreal period in some localities.

From our relatively limited data set, it is clear that sedimentation processes in our study regions were not linear and usually developed periodically, as illustrated in a plot of sand dune ages versus depth (Fig. 4). The Mančiagirė section (Fig. 2A, B and Fig. 4C, D) is represented on the plot by multiple intervals of sedimentation and by the highest rates of accumulation (Fig. 4C, D). In contrast, the sedimentation rates at the Žalioji Giria and Smalininkai sites (Fig. 2A) seem to have been much lower (Fig. 4A, B). Accumulation dynamics at the Ventės Ragas site (Fig. 4E) are evidently variable.

Taking into account the results of detailed investigations of continental aeolian deposits in neighbouring Poland, based on pollen analysis and radiocarbon-dating of buried soils, there were several periods of aeolian activity during the Holocene, but these periods are asynchronous in different massifs of continental dunes (Nowaczyk 1986). Our results also indicate that noticeable variations in the rate of sedimentation in massifs of continental dunes of Lithuania occur both vertically through the section and spatially across the massif. Variations are controlled mainly by the interaction of surface relief with mechanisms of aeolian sediment redistribution and accumulation. As we have shown, the sedimentation rate is not constant or synchronous in different dune massifs of Lithuania either, not at least for millennium-scale intervals. To distinguish separate erosional/depositional phases of aeolian activity at various sites in different dune massifs, much more detailed luminescence analyses are needed to provide a higher resolution chronology for aeolian deposition over the range of depths examined.

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