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Coastal dune dynamics along the northern Curonian Spit, Lithuania: toward an integrated database

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Sand dunes are the most prominent subjects of geological and geomorphological interest along the Curonian Spit – a mega-barrier that separates the Curonian Lagoon from the Baltic Sea. To date, an assessment of various parameters of migrating dunes along the spit has been based on comparative analysis of old maps or aerial and satellite images, as well as geodetic measurements. These investigations have allowed assessment of dune dynamics over a relatively short historical period (~1700s to present). The most recent detailed investigations of the Dead (Grey) Dunes along the Lithuanian part of the spit using ground-penetrating radar (GPR) and magnetic susceptibility (MS) surveys, supported by a radiocarbon (^{14}C) chronological framework of palaeosols and infrared optically stimulated luminescence (IR-OSL) ages of sand horizons, have advanced our understanding of aeolian landscape evolution. The interpretation of dune activity and stability phases has been generally based on IR-OSL dating results of the sand layers located between radiocarbon-dated palaeosols. However, the influence of soil-forming processes on the IR-OSL dating results related to possible migration of natural radioactive isotopes via aeolian sand layers has not been previously considered. Hypotheses of dune reactivation and migration caused by abrupt regional climate shifts, catastrophic forest fires, anthropogenic influence, and more local forcings have been tested. An integrated approach to dune investigations has offered an estimate of the rates of sand accumulation and key phases of aeolian dynamics during both stormy and calm periods, as well as helped to extend the record of dune evolution to the mid-Holocene. The palaeoenvironmental and palaeodynamic reconstructions of the Dead Dunes suggest that this mid-Holocene phase of dune activity was of a local character and likely did not exceed several centuries.

Key words: palaeosols, ground-penetrating radar (GPR), IR-OSL, radiocarbon, magnetic susceptibility.

INTRODUCTION

Sand dunes are prominent geomorphic features of most coastal barriers along the southern Baltic Sea and serve as archives of regional climate shifts, vegetation dynamics, sediment availability, and human-landscape interaction. However, the sheer size of some dunes makes their investigation a challenge. The present study is focused on the northern Curonian Spit – a massive sandy mega-barrier along the southeastern Baltic that separates the Curonian Lagoon from the Baltic Sea (Fig. 1). This landform is split administratively in half by the Republic of Lithuania (north) and the Russian Federation (south), with both parts having the status of National Parks (Bučas, 2001) and included in the UNESCO list of cultural heritage monuments. From the geological point of view it is still an active environment dominated by aeolian processes that shape the most prominent landforms along the entire ~100 km length of the spit. The research has been concentrated along the western slope of the Great Dune Ridge (GDR) that stretches along the lagoon coast of the spit. This ridge contains the highest dunes in North-

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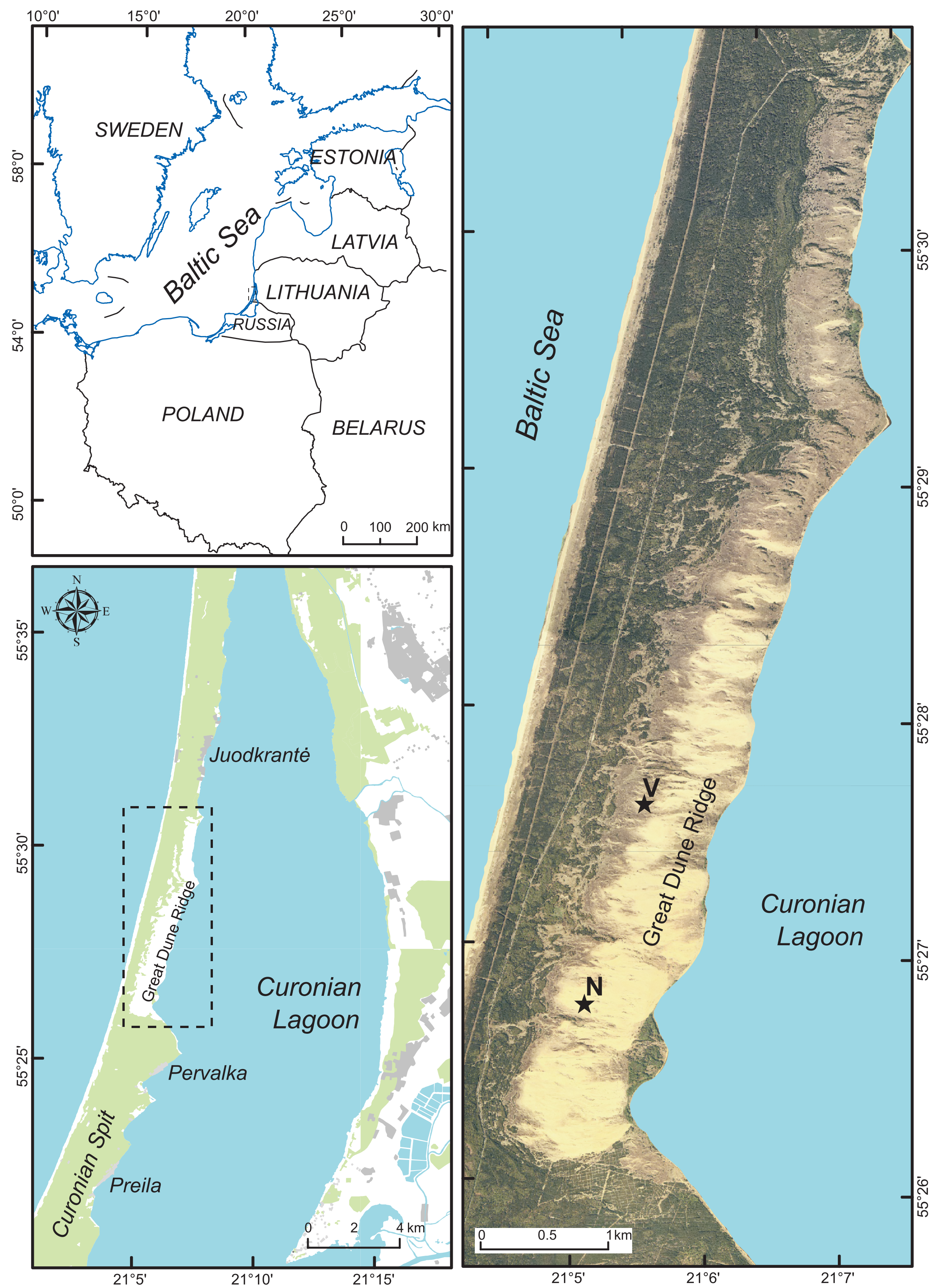

Fig. 1. Study area on the Curonian Spit

Location of the dune sites investigated in detail is marked as follows: V – Vingis dune site, N – Naglis dune site ern Europe, that reach >60 m in many areas along the spit. This landform has received special attention from researchers beginning in the second half of the 19th century (Schumann, 1861; see Wichdorff, 1919; Paul, 1944). These investigations proposed that the ancient dune ridge stretched relatively evenly along the entire area of the Curonian Spit and was only recently remolded into the GDR. This process started in the 16th century due to extremely high aeolian activity influenced by destructive human practices, for instance after the near complete clear-cutting of forests (Gudelis and Michaliukaitė, 1976; Gudelis, 1989–1990, 1998a, b).

Until recently, the assessment of various aspects of dune dynamics along the Curonian Spit has been based on comparative analysis of old maps or aero- and satellite-based images, as well as geodetic measurements that allowed general reconstruction of dune palaeogeography and activity for the relatively recent (~1700s to present) historical period (Minkevičius, 1982; Mardosienė, 1988; Kazakevičius, 1989–1990; Morkūnaitė and Česnulevičius, 2005; Povilanskas et al., 2009; Česnulevičius et al., 2016, 2017). Several chronosequences of buried palaeosols widespread along the Great Dune Ridge served as important indicators of relative stability phases and formed the focus of a number of studies over the past decades (e.g., Michaliukaitė, 1962, 1967; Gaigalas et al., 1991; Gudelis et al., 1993; Moe et al., 2005; Gaigalas and Pazdur, 2008). Most of these investigations involved radiocarbon (^{14}C) dating or pollen analysis of palaeosols. Over the past decade, renewed geological research along the Curonian Spit added modern methods of investigations: high-resolution ground-penetrating radar (GPR) imaging; improved radiocarbon dating of palaeosols by the AMS method; absolute age dating of sand layers using infrared optically stimulated luminescence (IR-OSL); and *in situ* measurements of bulk low-field magnetic susceptibility (MS). These integrated investigations substantially improved the accuracy of subsurface mapping and age-dating, thereby greatly advancing our understanding of aeolian landscape evolution as far back as the mid-Holocene (Buynevich et al., 2007a, b; Dobrotin et al., 2013). According to the results of ^{14}C dating of key palaeosols, at least four soil-forming generations have been distinguished: 5800–4500 cal BP, 3900–3100 cal BP, 2600–2400 cal BP, and 1900 cal BP to present (Dobrotin et al., 2013). Recent work has revealed that ancient forest fires resulted in only local reactivation of aeolian processes and did not trigger substantial migration of the main dune ridge. Still, some issues linked with the rate of sand accumulation and peculiarities of dune palaeodynamics during calm and stormy periods remained unsolved. The aim of this paper is to address some of these important aspects of Curonian dune dynamics through analysis of geochronological datasets in their sedimentological and geomorphological context.

REGIONAL SETTING

Two sites for detailed investigations were chosen in the central part of the Curonian Spit, to the south of Juodkrantė settlement (Fig. 1). At each site, the investigations were concentrated along transects with existing GPR coverage (start – end coordinates of profile): the Vingis dune site: 55°27’35.07"N, 21°05’ 20.13"E–55°27’36.44"N, 21°05’23.98"E; and the Naglis dune site: 55°26’47.64"N, 21°05’1.51"E–55°26’48.88"N, 21°05’4.15"E.

The Vingis dune site is located on the eastward sloping flank of the GDR dune with minor relief, at an elevation of ~10–11 m above mean sea level. The Naglis site has a similar context, but occurs at a higher elevation of ~20–22 m, the geophysical profiles at both sites were established along the inner sections of ancient dunes where the uppermost parts were removed through subsequent deflation. The exposed sections of aeolian sediments are represented by yellow or greyish-yellow sand dominated by quartz (96–98%). The medium-grained, in places coarse-grained, sand sporadically contains thin horizons (typically 0.5–3.0 cm thick) of black or dark grey fine-to-medium-grained heavy-mineral concentrations (HMCs). According to results of previous mineralogical studies (Gudelis, 1989–1990), these HMCs are represented by hornblende, garnet, magnetite, ilmenite, and epidote. In some instances, lithological anomalies are represented by glauconite-coated quartz grains that can be recognized by their greenish-grey colour.

The 300 MHz GPR survey line in the Naglis dune site (Fig. 2) closely followed an earlier 200 MHz line (Buynevich et al., 2007a) and formed the basis for IR-OSL sampling and MS measurements between the two palaeosols P2 (older) and P1.

METHODS

The investigations into the reconstruction of aeolian palaeodynamics consisted of a suite of sequential field and laboratory methods. The research began with an interpretation of air photo images and LIDAR data for identification of exposed palaeosol horizons throughout the Dead Dunes. Subsequently, it was complemented by extensive field mapping, ground-penetrating radar surveys, and sampling for absolute age determinations. Thus, both study sites were specifically selected to span the sections between adjacent palaeosols that have been previously dated by the accelerator mass-spectrometry (AMS) radiocarbon method at the National Ocean Sciences facility of the Woods Hole Oceanographic Institution, USA (Buynevich et al., 2007a) and using a Tri-CarbÒ 3170TR/SL in the Radioisotope Research Laboratory of the Institute of Geology and Geography of the Nature Research Centre in Vilnius, Lithuania (Dobrotin et al., 2013). This most recent phase of investigations included detailed GPR imaging along multiple dip and strike profiles, visual lithological examination and description of aeolian sediments, *in situ* measurements of magnetic susceptibly (MS) of the sediments, and sampling. The laboratory component involved dating of aeolian sediments by the infrared optically stimulated luminescence (IR-OSL) technique (Molodkov and Bitinas, 2008).

GROUND-PENETRATING RADAR (GPR) SURVEY

Two GPR profiles ranging from 50 to 55 m in length were made at each location between two palaeosols in transects perpendicular to the strike of each soil layer (Fig. 2). The survey setup included a *RADAR Systems Zond 12-e* system with a 300 MHz monostatic antenna, 400 V pulse generator (optimized for resolution and depth), and a time window (range) of 100 ns. A relative dielectric permittivity of 5.33 was used for unsaturated dune sand, achieving 6.0–6.5 m penetration at maximum range. The EM signal velocity of 13 m/ns was corroborated by hyperbola fitting. All post-processing was performed with *Halliburton* “*Geographix*” software. Palaeosols

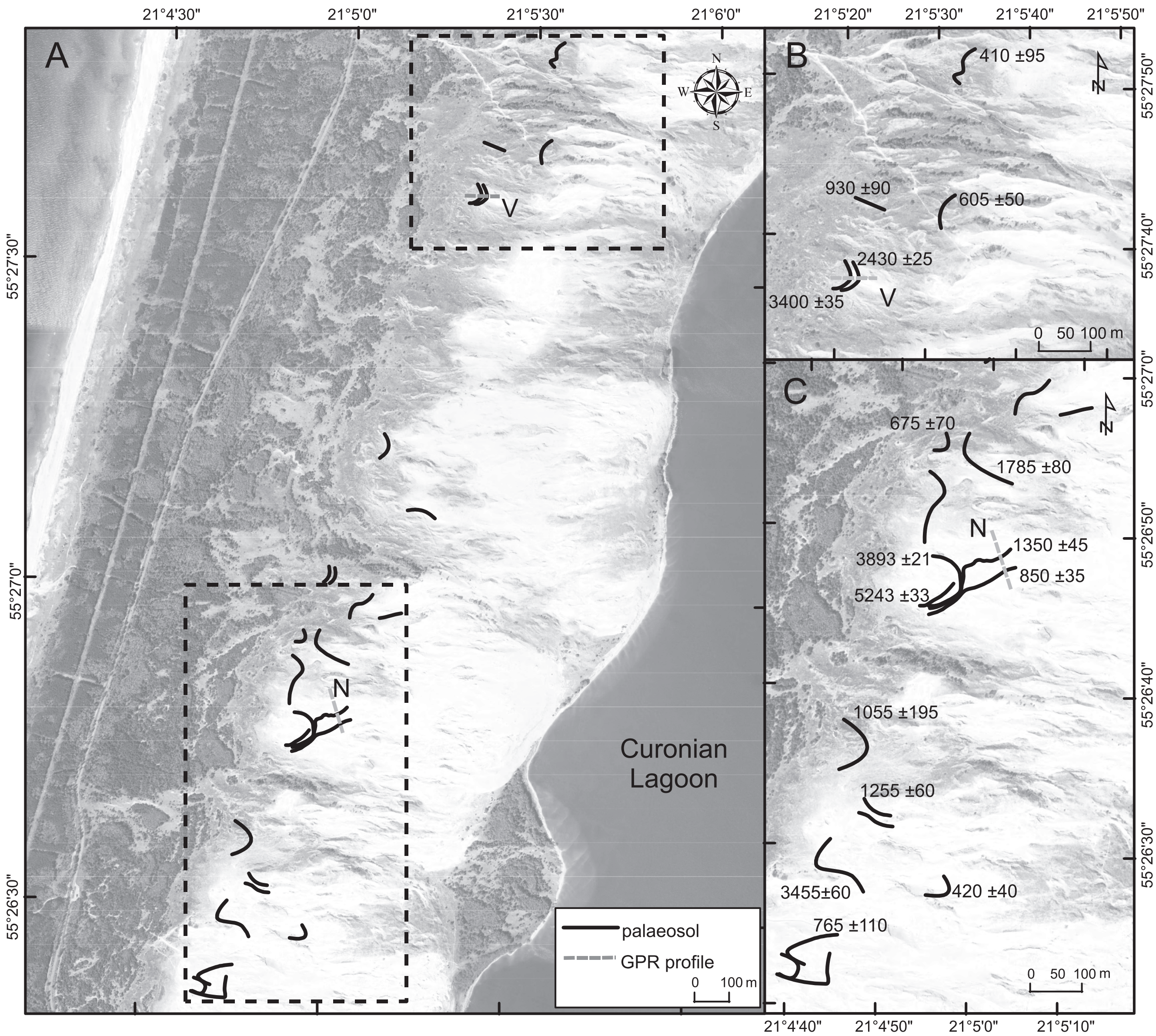

Fig. 2. Distributions of exposed palaeosols along the western slope of the Great Dune Ridge – a brighter shade on the photo-image indicates areas free of vegetation

The dotted rectangles (A) indicate enlarged inserts of the Naglis dune site (B) and the Vingis dune site (C) surroundings: the GPR profiles at both dune sites are marked by the letters V and N respectively; the numbers under the palaeosols show their age (in cal y BP) established by ^{14}C dating (after Buynevich et al., 2007a; Dobrotin et al., 2013)

were traced from surface exposures and interpreted in radargrams based on their strong signal returns and characteristic geometry. Key subsurface reflectors were identified using 1 m deep trenches (Fig. 3).

IR-OSL DATING

Potassium feldspar-based infrared optically stimulated luminescence (IR-OSL) age determinations were carried out at the Research Laboratory for Quaternary Geochronology (RLQG), Institute of Geology, Tallinn University of Technology. These palaeodosimetric dating techniques have long been successfully used in earlier investigations in the southeastern Baltic region (Molodkov et al., 2010; Bitinas et al., 2011), including the Curonian Spit dunes and vicinities of the Curonian Lagoon (Molodkov and Bitinas, 2008; Bitinas et al., 2017). The IR-OSL dating procedure used at the RLQG is the subject of a special methodological paper (Molodkov and Bitinas, 2008).

At the Vingis dune site, five bulk samples for IR-OSL dating were collected between the two palaeosols (Fig. 4). The samples were taken at 0.5 m depth at 5 m intervals between the samples. At the Naglis dune site, the five bulk samples were collected from 0.5 m below the dune surface at 7 m spacing (Fig. 5). At both sites, samples from the W or NW end of the profile were taken 10–15 cm above the older palaeosol, whereas those at the E or SE end were collected ~15–20 cm below the younger palaeosol.

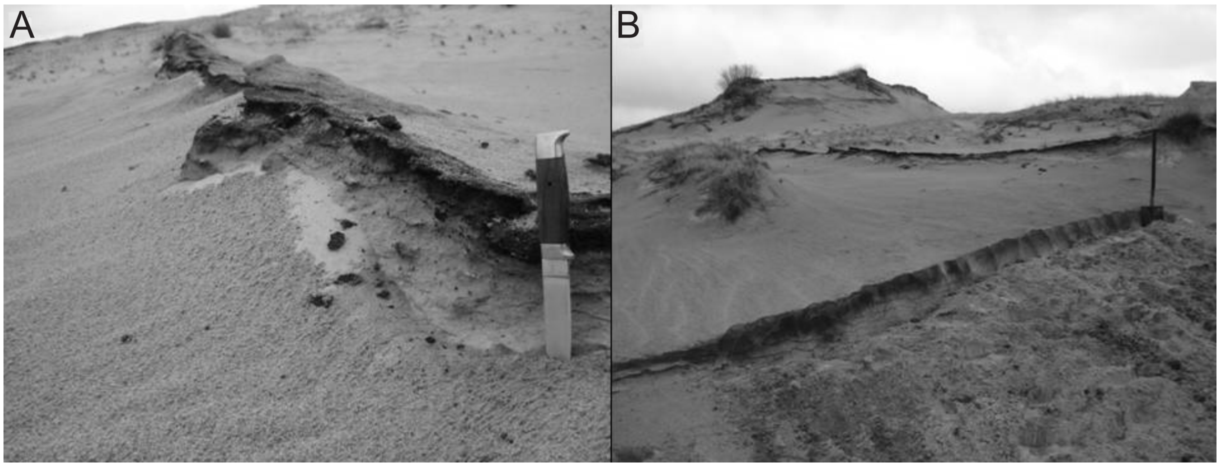

Fig. 3. Segments of exposed palaeosols on the Great Dune Ridge western slope in the vicinity of the Naglis dune site on the Dead (Grey) Dune ridge: a single palaeosol exposed by deflation (A); in many places, palaeosols of different age are situated near each other (B)

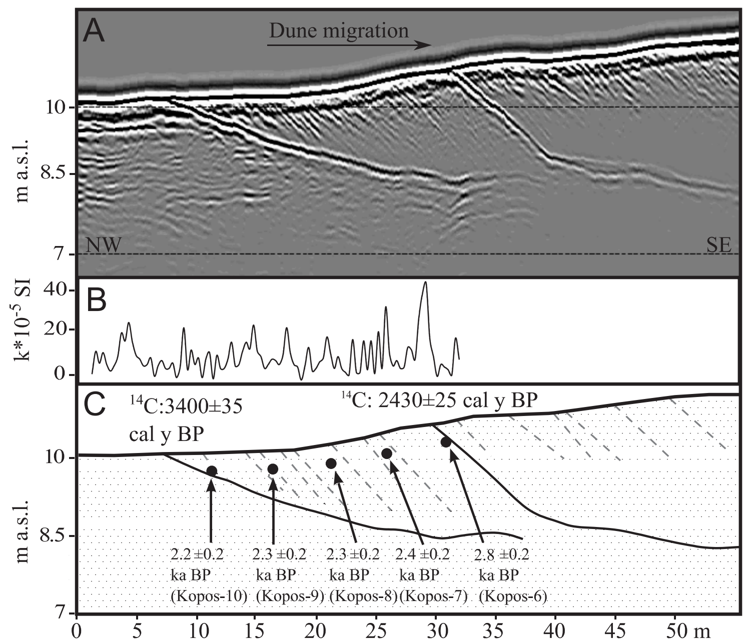

Fig. 4. Profile of detailed investigations at the Vingis dune site

A – ground penetrating radar (GPR) image (radarogram); **B** – curve of magnetic susceptibility (MS); **C** – interpretation of radargram; in the latter section palaeosols are marked by solid lines and interlayers with high concentrations of heavy minerals by dotted lines; the radiocarbon age of the palaeosols (in cal y BP; after Buynevich et al., 2007a; Dobrotin et al., 2013) is included at the top; sampling locations for IR-OSL dating are indicated by black circles; distance along the horizontal scale is marked from the beginning of the GPR profile

MAGNETIC SUSCEPTIBILITY

Measurements of low-field magnetic susceptibility (MS) were collected *in situ* in a 0.4 m deep trench excavated along GPR profiles using a *Bartington MS3* metre with a *MS2K* scanning field sensor (Buynevich et al., 2007a). MS values were obtained on exposed sections of dune slipfaces at all visually distinct lithological changes. At quartz-dominated intervals, measurements were obtained every 10 cm. This allowed direct comparison of magnetic properties (primarily magnetite content) of specific horizons to their electromagnetic signal response as they were traced along the dip in GPR images. All measurements are expressed as bulk susceptibility (mSI).

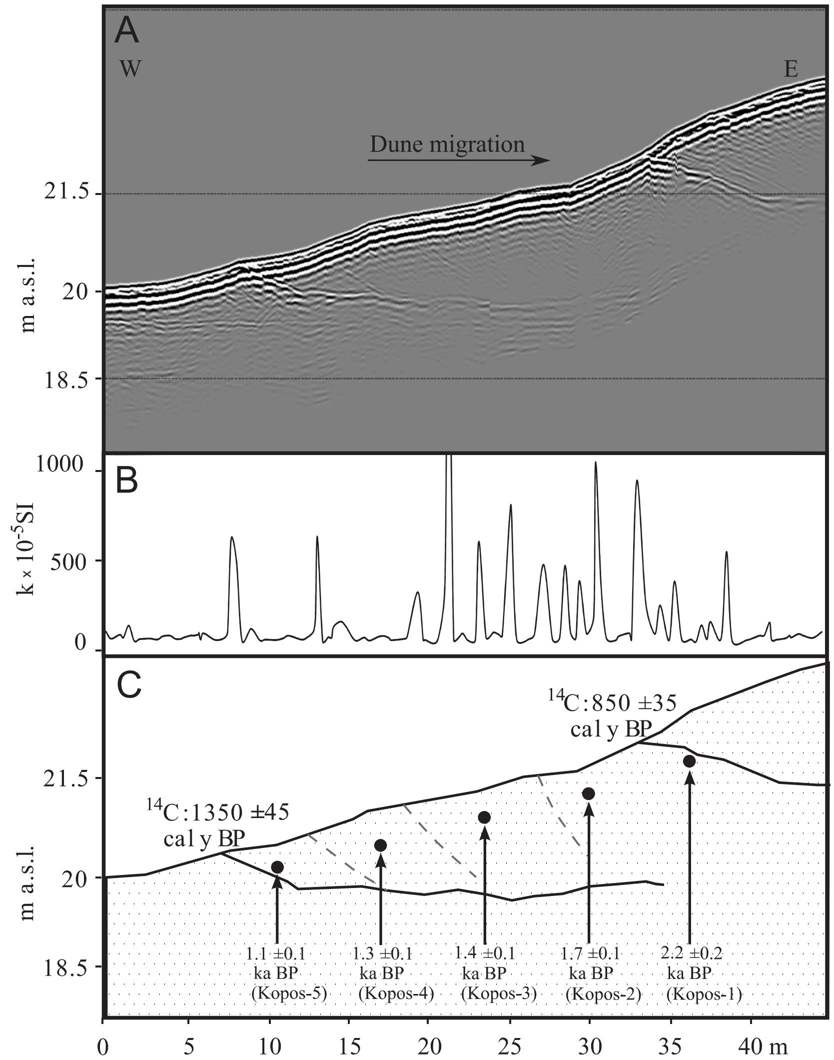

Fig. 5. Profile of detailed investigations at the Naglis dune site

For explanations see Figure 4

RESULTS

GPR PROFILING

Geophysical images from the Vingis dune site reveal two main types of subsurface reflector (Fig. 4). The most prominent reflectors are the palaeosols that outcrop along the present dune surface at horizontal distances of ~8 and 32 m. Both reflections dip east at approximately 6° (older) and 12° (younger palaeosol). Meanwhile the less well-expressed and shorter reflectors (occurring at intervals from 2 to >20 cm) correspond to thin heavy-mineral concentrations (HMCs) that also dip to the east. At the Naglis dune site (Fig. 5), the prominent reflections again begin at palaeosol exposures at 9 and 24 m along the profile. Both reflections dip to the SE at ~8° (older) and 6° (younger palaeosol). The few secondary reflectors coincide, as they do at the Vingis dune site, with thin SE-dipping HMC horizons. The interpretation of GPR reflectors is based on the exposures of aeolian sections along GPR transects, as well as in the shallow trenches excavated for IR-OSL sampling.

DUNES AGE ACCORDING TO IR-OSL DATING RESULTS

The age of the dune segment located between two palaeosols at the Vingis dune site generally falls into the time span between 2.4 ±0.2 and 2.2 ±0.2 ka (Fig. 4; Appendix 1*). Only one sample (Fig. 4, KOPOS-6), located directly below the palaeosol dated at 2430 ±25 cal y BP, shows an older age – 2.8 ±0.2 ka. Whereas, at the Naglis dune site, the IR-OSL dating results demonstrate that the age of sand layers gradually increases from NW to SE – from 1.1 ±0.1 ka to 2.2 ±0.2 ka (Fig. 5, Appendix 1).

* Supplementary data associated with this article can be found, in the online version, at doi: 10.7306/gq.1435

MAGNETIC SUSCEPTIBILITY OF AEOLIAN SEDIMENTS

Measurements of MS along both profiles show a range of values from 8–10 to 20–30 μSI at the Vingis dune site and from 5–10 to 500–1000 μSI (with one anomaly, up to 2027.5 μSI) at the Naglis site (Figs. 4 and 5). At the Vingis site, an increase was largely associated with HMCs. At Naglis, relatively low values of MS were characteristic of the NW (upwind) part of the profile, whereas anomalies >800–1000 μSI were common in the SE half of the profile. The intervals with low values of MS are characteristic of sand layers composed mostly of quartz and feldspar, with the highest values invariably associated with thin HMC interlayers (up to 4–5 cm) (Fig. 6).

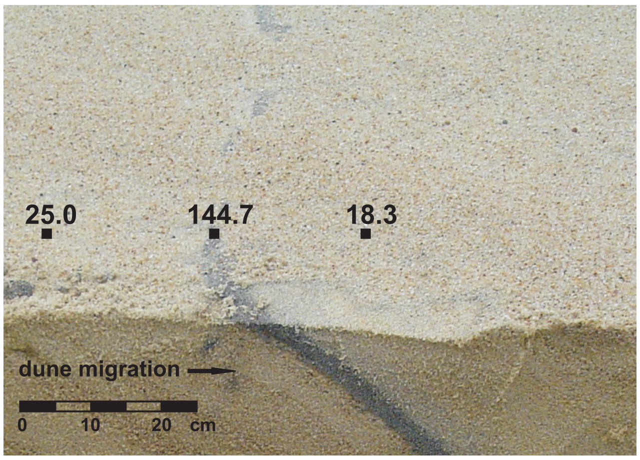

Fig. 6. Section of aeolian sediments along the GPR profile at the Naglis dune site

Above dotted line – deflation surface with measurement places marked by black squares, below – vertical wall of trench, *in situ* values of magnetic susceptibility (μSI) demonstrate a substantial contrast between quartz sand (lowest values) and a dark grey sand interlayer with HMCs (highest value)

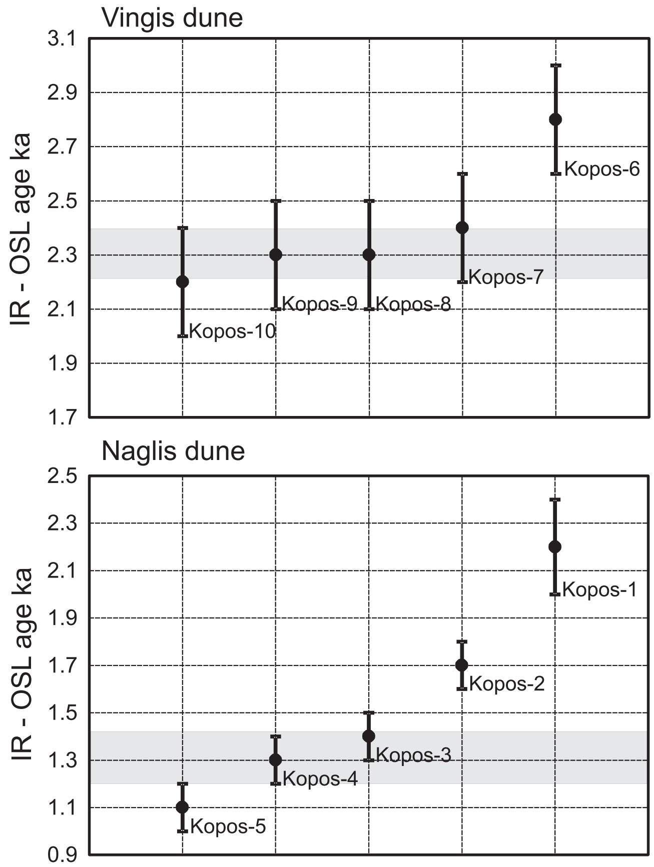

Fig. 7. Results of IR-OSL dating from the Vingis and Naglis dune sites

Proposed periods of aeolian sedimentation are indicated by grey shading

DISCUSSION

The results of geophysical imaging demonstrate the subsurface extension of exposed palaeosols and HMC horizons, providing a means of their mapping and correlation into adjacent dune sections. Magnetic susceptibility values provide a useful independent dataset of mineralogical anomalies that are responsible for specific GPR reflections. Whereas this aspect of field investigations has been successfully tested at the two sites, the bulk of attention should be given to the chronological control.

The results of investigations obtained by different methods of absolute chronology demonstrate the complementary nature of the ^{14}C AMS dating of palaeosols and IR-OSl dating of intervening sand units (Figs. 4 and 5). However, the particular nature of dating results at each site warrants further treatment.

Radiocarbon dating suggests that the dune section investigated in detail at the Vingis site (Fig. 4) represents aeolian activity that post-dates a stable phase that ended ~3400 ±35 cal y BP (older palaeosol). This dune sequence accumulated over a relatively short time span: between 2.4 and 2.2 ka according to IR-OSL dating results (Fig. 7). After aeolian activity ceased, the new palaeosol (dated as 2430 ±25 cal y BP) started to form. Only one anomalous IR-OSL sample (2.8 ±0.2 ka) located directly below the younger palaeosol (Fig. 4, Kopos-6) is not consistent with this interpretation.

Reconstruction of aeolian activity at the Naglis dune site is more problematic. The IR-OSL dating results show that sand accumulation took place over a relatively long time span that began before 2.4 ka and continued until 1000 years before present (Fig. 7). Based on the suite of IR-OSL ages, three samples fall within the relatively short time period before ~1.4–1.2 ka BP (Fig. 7, samples Kopos-3, 4, and 5). Thus, this time span likely reflects the actual age of aeolian sedimentation. In this way, the interpretation of IR-OSL dating results does not contradict the results of ^{14}C AMS dating of palaeosols, i.e. 1350 ±45 and 850 ±35 cal yBP, respectively (Buynevich et al., 2007a).

The most problematic issue of the IR-OSL data interpretation relates to the fact that the oldest dates at both sites (Kopos-1 and Kopos-6) were obtained from the stratigraphically youngest sand horizon. One explanation relates to a possible influence of pedogenic processes, given that the oldest dates come from samples collected directly beneath the palaeosol horizons. As shown in Appendix 1, very low contents of uranium (0.01 and 0.08 ppm) are characteristic of both samples (Kopos-1 and 6). This could have influenced the results of IR-OSL dating. The prevalence of uranium in sandy sediments is associated with common soluble salts of $(UO2)^2$ such as nitrate, chloride, acetate, sulphate, and carbonate that may be easy dissolved during soil-forming processes (Boyle, 1982). As a result, uranium can be transported (eluviated) into underlying sediments (Wintle, 2008). Taking into account the morphology of the ancient dune, the sample Kopos-1 at the Naglis dune site (Fig. 5), may also have been partly influenced by Late Holocene pedogenesis. However, assuming an average of eight uranium content values between 0.20–0.96 ppm (average: 0.47 ppm), the corrected age could be younger by only 200 years if no U migration during soil-forming processes had occurred. Therefore, pedogenesis is unlikely to explain the old age of the stratigraphically youngest samples in both areas. Thus, an alternative explanation is proposed.

In the initial stage of dune movement occurring in calm environmental conditions, low to moderate wind preferentially removes the finest sand fraction. Therefore, the sand particles, before cascading down the steeper, leeward side (slipface) of the dune, were transported for a long enough period to cause full bleaching. Thus, the IR-OSL age of sand interlayers deposited during the initial stage of secondary dune formation shows the real age of sedimentation (~2.4–2.2 ka at the Vingis site and 1.4–1.2 ka at the Naglis site). During the second half of the aeolian phase (corresponding to the anomalously old age of Kopos-6 at the Vingis site and two ages, Kopos-1 and Kopos-2, at the Naglis one) the sedimentation likely occurred during a relatively stormy period. Thus, because sand was deflated from the primary dune, quickly transported and deposited, there was little or no time for bleaching, thereby retaining the "old" IR-OSL signal (i.e. with progenetic palaeodose-related effects in the mineral lattice). This may explain the anomalously old dates at both sites coinciding with the stratigraphically younger dune sand. Moreover, the higher fraction of heavy minerals, even in thin layers, may have influenced the palaeodose, resulting in older ages.

Using multi-dating methods of absolute geochronology and making intercomparison requires consideration of key factors that may influence each technique. In our case, the ^{14}C and IR-OSL methods have different precision and analytical errors by decades and centuries, respectively. Thus, accurate establishing of absolute chronology should proceed with caution. For example, at the Naglis dune site, the age of the older palaeosol (1350 ±45 cal y BP) and the sand layer directly above it (1.1 ±0.1 ka) appear in reverse order. But, taking into account the previously mentioned differences in measurement errors and the observed temporal sequence of IR-OSL dates at this locality, it is possible to accept these dates as relatively reliable. Moreover, for the ^{14}C AMS sampling we used the lumps of charcoal (remnants of burned trees or bushes), as the best dating material. Taking into account that the development of a normal soil horizon in organic-poor sand of the Curonian Spit takes up to 1100–1600 years (Peyart, 2007), the dated charcoal represents only a few decades of this prolonged soil-forming period (Dobrotin et al., 2013). Therefore, we suggest that the dated charcoal represents the latest part of the pedogenesis, when the palaeosol was thick enough and enriched in organic matter, i.e. during conditions more suitable for higher plant growth.

Fluctuations of the MS values of the sandy sediments between the two palaeosols at the Vingis dune site reflect the general dynamic conditions above the dune surface at the time of aeolian activity phases. Whereas the slipface dip reflects the direction of transport, HMCs (i.e., the mineralogical density lag) represent periods of increased near-surface wind speed (Buynevich et al., 2007a). The sections of the MS dataset dominated by low values (10–30 μSI) suggest that relatively calm conditions existed on the Curonian Spit before 2.4–2.2 ka BP. During the next phase, at ~1.4–1.2 ka BP, the palaeoclimatic conditions were different. MS measurements suggest the first half of this period was relatively calm, as only two HMC anomalies occur during the sand accumulation process (Fig. 5). The second half of this period (the ~20–34 m interval) experienced more dynamic transport (MS anomalies >800 μSI). In this part of the profile, many HMCs that yielded high MS values are very thin (<2 cm), so the majority of them are not resolved in GPR images. Investigations of mid and Late Holocene aeolian activity in northwestern Europe by a number of researchers (Jelgersma et al., 1995; Clemmensen et al., 2009; Nielsen et al., 2016) indicate that storminess maxima recurred at ca. 4300, 2800, 1400 and 400 cal BP (Sorrel et al., 2012). The HMCs and anomalously old age of Kopos-6 at the Vingis site as well as the Kopos-1 and Kopos-2 ages at Naglis belong to Holocene storminess phases III (3300–2400 cal BP) and IV (1900–1050 cal BP; Sorrel et al., 2012).

In summary, investigations during the 20th century has led to a dominant opinion that aeolian reactivation and deposition were prolonged processes, possibly linked with large-scale changes in Holocene climate (e.g., Borówka, 1975). These periods of uninterrupted aeolian activity (the so-called "aeolodynamic stages" of Gudelis, 1998b) were dominant during the past two millennia. The results of our study corroborate recent findings (Jelgersma et al., 1995; Wilson et al., 2004; Clemmensen et al., 2009; Nielsen et al., 2016), which suggest that dune activation was triggered primarily by global or hemispheric factors such as abrupt climatic shifts and storminess (Bond et al., 1997; Mayewski et al., 2004; Sorrel et al., 2012). Secondly, re-activation of aeolian processes and re-deposition of dune sand was likely caused by local factors: natural (or human-induced) forest fires, as well as deforestation (in historical times) that operated on decadal to centennial scales (Moe et al., 2005; Buynevich et al., 2007a; Gaigalas and Pazdur, 2008; Dobrotin et al., 2013).

CONCLUSIONS

A substantial intensification of aeolian processes along parts of a massive Curonian dune ridge began at least in the mid-Holocene and was not linked to large-scale climatic change. At the two study sites, phases of sediment remobilization over the past 3,000 years were limited in both space (e.g., triggered by local forest fires and deforestation) and duration (lasting no longer than one to two centuries). At present, aeolian activity is confined to several extensive unvegetated sections, including a continuing slow advance by slipface migration into the Curonian Lagoon.

Ground-penetrating radar images and magnetic susceptibility trends within aeolian sediments that separate palaeosols of different generations demonstrate a variation in heavy-mineral content that can be related to near-surface conditions (relatively calm, windy, or stormy regime), which characterized various phases of dune activity. When integrating absolute geochronological datasets from adjacent aeolian sand intervals and palaeosols, it is necessary to consider geochemical processes related to both pedogenesis and the background radiation regime of the non-quartz fraction. These may have an important influence on bulk-sampled optical dating results and should be addressed in the future if an accurate chronology of dune activity is to be established for this coastal region.

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