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Holocene aeolian sand mobilization, vegetation history and human impact on the stabilized sand dune area of the southern Nyírség, Hungary

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ABSTRACT

Almost 20% of the territory of Hungary is covered by stabilized dunes formed during the Pleistocene. With the climate amelioration during the early Holocene the aeolian activity ceased. However, various environmental and anthropogenic factors could have reactivated the aeolian processes. Today, there is an increasing climatic stress on the dune fields of the Carpathian Basin, which is coupled with inadequate land use. It is therefore necessary to determine the timing and circumstances of sand mobilization during the Holocene. The site of the present study is located in a dune–interdune system on the southern part of the Nyírség alluvial fan, where periods of Holocene aeolian activity and environmental change were investigated using palynological and sedimentological methods, optically stimulated luminescence and radiocarbon dating. The data achieved show climate-driven Boreal aeolian activity at approximately 8.2 ka, and also demonstrate for the first time that during the Atlantic Phase (6.4 and 5.3 ka), in spite of the relatively humid climate and dense vegetation, aeolian activity has taken place, induced probably by agricultural practices. Following Subboreal morphological stability, aeolian activity occurred several times in the Subatlantic Phase (2.4–2.2, 1.2–0.8 and 0.4–0.1 ka) as a result of vegetation changes and human activity.

Introduction

At the end of the Pleistocene, major aeolian periods ceased on the alluvial fans of the Carpathian Basin (Borsy, 1990). During the Holocene, due to various environmental and anthropogenic factors, the stabilized dune fields were affected again by aeolian processes: blowouts were formed, and the eroded material was deposited in sand sheets and at the front of Pleistocene dunes (Kiss, 2000).

Previously, Holocene aeolian phases have been studied at the largest sand regions of the Carpathian Basin (Nyírség alluvial fan and Danube–Tisza interfluve, Fig. 1), but the causes, and the spatial and temporal extent of wind erosion and dune accumulation have not been assessed in detail. Earlier researches assumed the occurrence of significant aeolian activities in the Carpathian Basin during the Preboreal, Boreal and in the drier periods of the Atlantic Phase, with clear morphological features superimposed on Pleistocene blown-sand deposits (Borsy, 1990; Borsy et al., 1991; Gábris, 2003; Újházy et al., 2003; Félegyházi and Lóki, 2006; Kiss et al., 2006). Concerning Boreal aeolian activity, contradictory statements exist since according to Borsy (1991), the sand layers identified by various authors before Braun et al. (1992) did not provide "clear evidence".

The possibility of Atlantic Phase aeolian activity was demonstrated only by one previous study (Borsy, 1990), and none of the authors claimed the occurrence of Subboreal sand movement, mainly because of the humid climate of these phases. However, on the Danube–Tisza interfluve the renewal of deflation has been proved by numerous archeological and some optically stimulated luminescence (OSL) data, referring to Subboreal—Bronze Age aeolian activities at 3.3–3.7 ka (Lóki and Schweitzer, 2001; Gábris, 2003; Kiss et al., 2006). Both on the Nyírség and on the Danube–Tisza interfluve several Subatlantic aeolian events were identified, occurring between the 5th and 8th and in the 13th centuries AD (Gábris, 2003; Újházy et al., 2003), mostly due to overgrazing (Kiss et al., 2006), and between the late 17th and 19th centuries AD due to forest clearing (Borsy, 1990; Braun et al., 1992; Kiss and Sipos, 2007). Most of the authors claim that in the second half of the Holocene, deflation was in close relation with human activity; however, no clear evidence on the exact causes has been provided so far.

According to studies conducted on various dune fields of the world, the return of aeolian processes on previously stabilized sand dune areas is primarily determined by changes in vegetation, fixing dune forms (Arens, 1996; Leenders et al., 2007; Nordstrom et al., 2007). One of the major controls on vegetation is climate, and thus episodic renewal of wind erosion can also be a marker of climatic fluctuation. Numerous authors have reported on climate-driven aeolian activities induced, for example, by frequently returning droughts or permanent dry periods (Koster, 1988; Szczypek and Wach, 1991; Muhs and Holliday, 1995;

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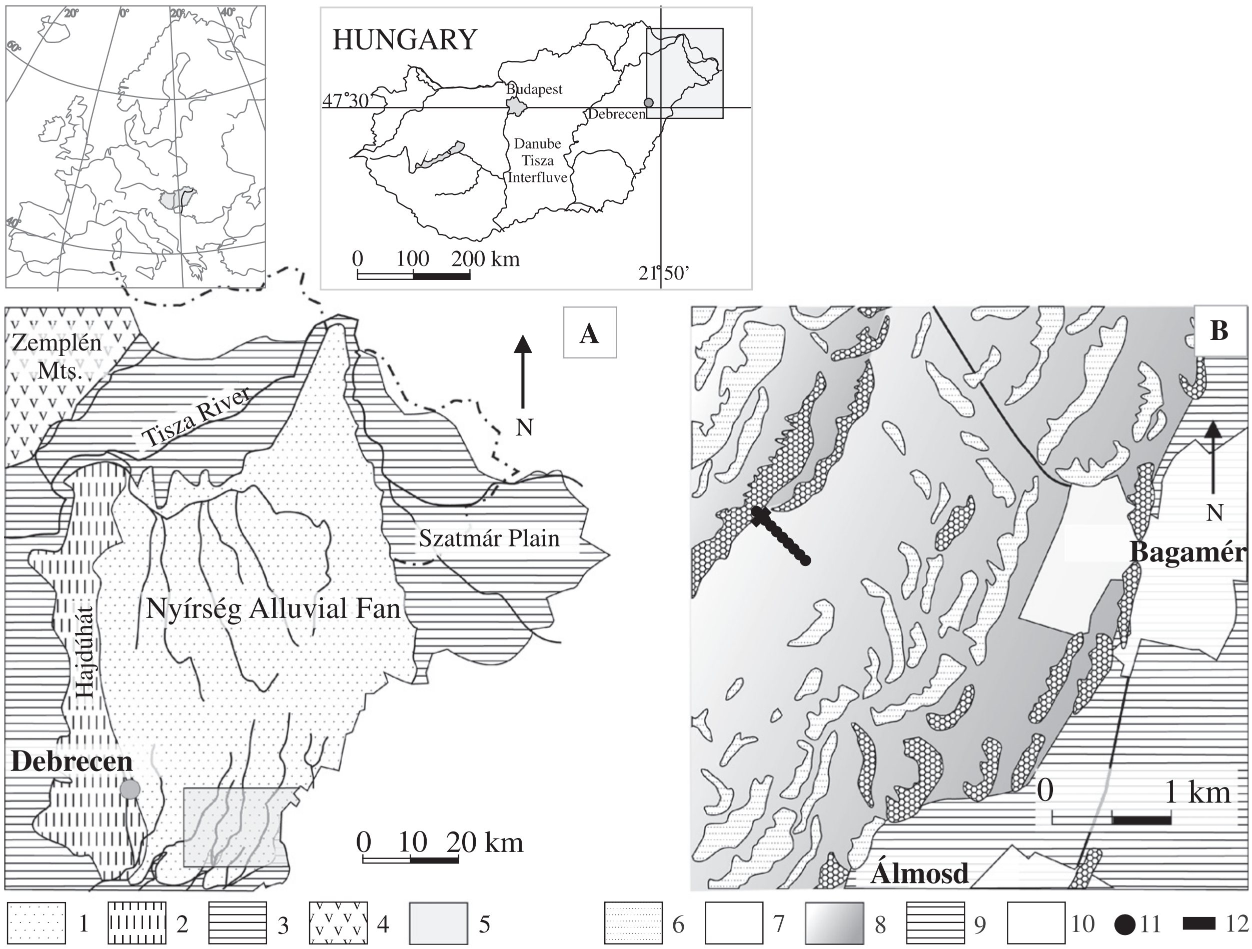

Figure 1. The study area is located on the Southern edge of the Nyírség alluvial fan, Hungary. (A) The main morphological regions of NE Hungary and the location of the study area. 1: aeolian sand, 2: loess, 3: alluvium, 4: volcanic rocks, 5: study area. (B) The sediment samples were collected from a paleo-valley dividing two dune-fields. 6: sand dune, 7: highly eroded sand dune, 8: paleo-valley and dune field system, 9: alluvium, 10: settlement, 11: sampling points, 12: sampling pit.
Map source: Kiss et al. 2009.

Clarke and Rendell, 2003; Wolfe et al., 2006), alteration in surface and subsurface hydrological regime (Clarke and Käykhö, 1997; Mason et al., 2004), decrease of sea or lake levels (Forman and Pierson, 2003), naturally occurring fires (Lytle, 2005; Lynch et al., 2006) or glacial retreat (Mayer and Mahan, 2004).

The second major control on vegetation and sediment availability is human activity, becoming more and more intensive during the late Holocene. Wind erosion in historical times primarily occurred in territories that were inhabited permanently and where population density was relatively high. In the humid regions the most frequently assigned anthropogenic causes for secondary aeolian activity are water control works and desiccation projects (Gill, 1996), deforestation and forest fires (Borsy, 1990; Böse and Brande, 2000; Magri and Parra, 2002), pasturing (Su et al., 2005), certain agricultural practices (Murray and Clemmensen, 2001; Roberts et al., 2001) and present-day mining and quarrying (Pelka-Gosciniak, 2000). Usually these human influences are superimposed on climatic controls and strengthen their effects (Gill, 1996; Magri and Parra, 2002). Moreover, under present climatic processes the vulnerability of stabilized sand dune areas is increasing continuously and aeolian activity might affect them again in the near future.

The above review suggests that several factors can lead to renewed aeolian activity on previously fixed sand dune areas. However, in Hungary these causes and the exact timing of Holocene aeolian events have not yet been revealed. Therefore the major goal of the present research is to set up a Holocene chronology of aeolian activity and vegetation history in the context of human inhabitance on the southern edge of the Nyírség alluvial fan. Furthermore, we also aim to compare the significance of climatic and anthropogenic factors leading to vegetation change and sediment relocation. The results of this chronological study will also enable the calculation of depositional rates in a previously stabilized dune–interdune environment, contribute to the aeolian history of the Carpathian Basin and facilitate regional comparisons.

Study area

Geomorphology

In the Carpathian Basin the Nyírség is the second largest sand dune area (ca. 4600 km^2), formed on the alluvial deposits of the Tisza River and its tributaries (Fig. 1A). At around 20 ka, fluvial processes terminated on the territory; and during the rest of the Pleistocene, aeolian processes prevailed (Borsy, 1990). Nevertheless, abandoned paleo-valleys had a key role in determining the pattern of dune formation (Kiss et al., 2009).

The dunes of the Nyírség are formed by northwesterly winds and belong to the parabolic dune association (Borsy, 1991). Parabolic dunes formed from oval shaped hummocks, which left behind their blowouts. By reaching the wet paleo-valleys the wings of the SE migrating dunes straightened, and parabolic forms metamorphosed into linear “valley-marginal dunes” (Kiss et al., 2009).

The studied valley-marginal dune and paleo-valley are situated 2 km west of the village of Bagamér (Fig. 1B). The dune is the largest and highest form of the southern Nyírség, with a crest length of 3 km, and a 15 m height above the valley bottom. As a consequence, this dune is one of the most sensitive forms in terms of wind erosion. The studied paleo-valley downwind of the valley-marginal dune is 450 m wide (Fig. 2). It is the deepest in front of the SE face of adjacent dunes. The poorly drained wet valley has been operating as a sedimentary basin throughout the Holocene; thus, the material eroded from the studied dune was deposited here.

Climate and vegetation

The climate on the study area is continental, with a 10°C annual mean temperature and a 21°C mean annual variation. The annual sum of precipitation is 560–590 mm, although there is a significant year-to-year variability (since measurements started, min = 337 mm [1961], max = 876 mm [1915]), and seasonal fluctuations are also high. The predominant wind direction is northeastern; however, the much less frequent westerly winds are significantly stronger. As March and April are mostly dry months when westerly winds over 3.5 m/s dominate, modern wind erosion of open surfaces occurs only during this time of the year (Borsy, 1961).

The Nyírség is situated in the forest steppe zone. The natural vegetation in historic times was dominated by oak forests, although at present the dunes are mainly covered by planted forests (*Robinia*, *Pinus* and *Populus*). On the southern slopes arenaceous grassy associations do also exist. Interdune depressions and paleo-valleys with high groundwater levels sustain marshes with tussock and meadows with turf species (Borhidi and Sánta, 1999).

Human inhabitance and land use

According to archeological evidence, the Nyírség has been inhabited since the Neolithic Period; however, the first permanent settlements date back to the 10th century AD (Szabó, 1971). Based on the spatial distribution of findings, Neolithic tribes preferred the top of the dunes, and mainly practiced slash-and-burn agriculture (Kalicz, 1970). During the Copper Age (2.7–4.5 ka BC) animal breeding became characteristic (Szabó, 1971). Bronze Age people (2.7–0.9 ka BC) also practiced pasturing, but introduced crop-farming as well, although findings are sparse, since the territory was not entirely suitable due to the poor quality of soils and inter-dune swamps (Szendrey, 1984). The Iron Age Nyírség had a low population density due to its border situation between major cultures (Szendrey, 1984). However, Late Iron Age Celtic inhabitants brought new techniques of agriculture to the territory (Szabó, 1971). During the Migration Period (4th–9th centuries AD) pasturing groups occupied the area. Hungarians settled in the region between the 10th and 13th centuries AD, and according to historical resources, the village of Bagamér (Fig. 1B) was also founded at this time. From the 15th century AD, vineyards were established on the southern slopes of dunes, and in the meantime forests were intensively cut (Mezősi, 1943). During the Turkish Occupation of the 16th and 17th centuries AD most of the settlements were abandoned. Nevertheless, for a short period in the 17th century Bagamér was declared to be a town. At this time it had a significant population who cleared forests and practiced cattle breeding. Finally, by the end of the 17th century the population density decreased significantly and forests began to reoccupy former grasslands. In addition, from the 18th century a growing number of orchards and vineyards were established (Mezősi, 1943). According to conscriptions and military maps, the area of forests and vineyards simultaneously increased in the 19th century.

Methods

Sedimentological analysis

Ten cores with depths of 180–350 cm were used to set up the stratigraphy of the site (Figs. 1B and 3A). The boreholes were made along a NW–SE axis, starting at the valley-marginal dune and running across the paleo-valley. Sediment samples were taken at every 5 cm (415 samples in all). Grain-size distribution was determined by the Köhn pipette method (Müller et al., 2009). The organic carbon content (%) was measured following the Tyurin method (Kalembasa and Jenkinson, 1973).

The vertical sedimentary zones within the cross-section of the valley were identified by analyzing the grain size distribution, organic content and pollen spectra of the samples. If the proportion of a grain-size class increased by 5–10% in a layer, it received the name of the relevant grain-size class (see Fig. 3).

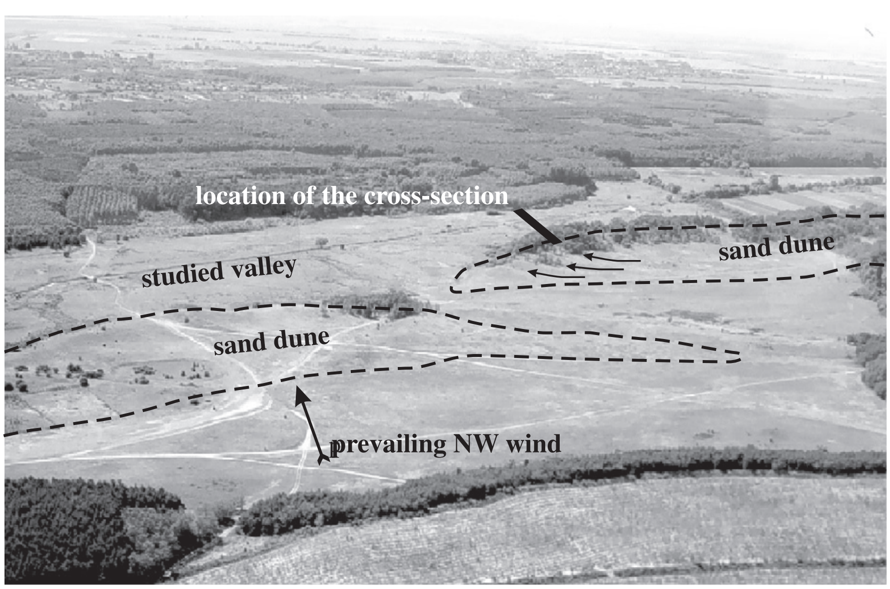

Figure 2. Aerial photograph of the study area. The studied marshy paleo-valley is bordered by valley-marginal dunes (on the distant one blow-out depressions are visible). The studied cross section is located on the downwind side of the southern dune.

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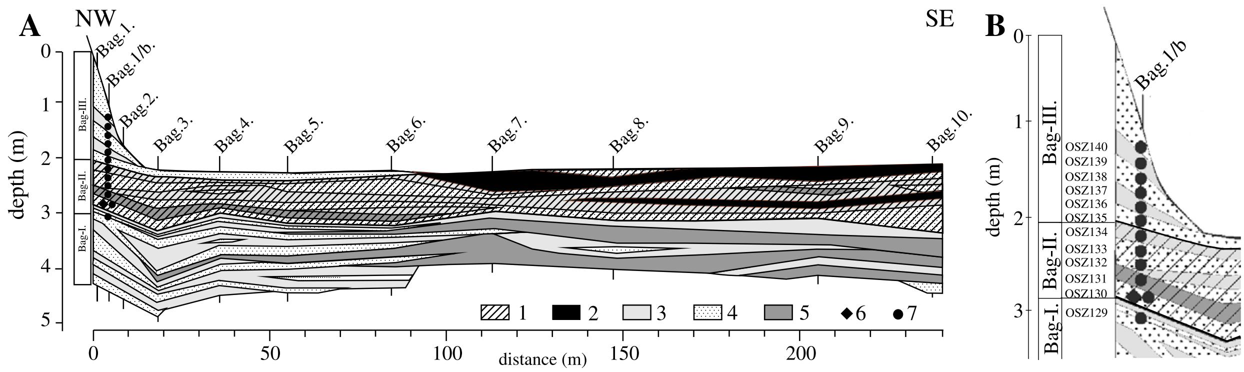

Figure 3. (A) Sedimentary cross-section of the paleo-valley with the location of drillings and (B) samples collected for dating from Bag-1/b sampling pit. 1: high organic carbon content (over 2.5%), 2: increase of silt and clay, 3: increase of very fine sand, 4: increase of fine sand, 5: increase of medium sand, 6: ^{14}C sample location, 7: OSL sample location.

Radiocarbon and luminescence dating

Samples for radiocarbon and luminescence dating were obtained from a 2-m-deep pit made at the foot of the dune (Bag.1/b) in between coring Bag.1 and Bag.2 (Fig. 3B). One sample was collected for radiocarbon dating, but unfortunately no more datable organic material was found in the section. The measurement was made on plant remnants at the Hungarian Atomic Research Institute, Debrecen, with a Canberra-Packard TRICARB 3170 TR/SL type liquid scintillator. The calculation of the calibrated age was made by software CALIB 3.0 (Stuiver and Reimer, 1993).

Twelve OSL samples were taken at regular depth intervals (15 cm). Sample preparation was based on the techniques proposed by Aitken (1998) and Mauz et al. (2002). All procedures were made under subdued red-orange light provided by LED strings, with their emission peak at 621 nm. Quartz grains of 90–150 μm size were isolated for dating. The effect of alpha radiation on the outer parts of grains was eliminated by etching the samples in 48% HF for 60 min. Treated samples were mounted on stainless steel discs with low viscosity silicone oil. From the upper two samples 96 aliquots, while in the case of the other samples 48 aliquots, were prepared to determine the equivalent dose (D_e). An additional 24–24 aliquots were used to perform a preheat plateau test and a dose recovery test for each sample.

Measurements were made on a RISØ DA-15 automated TL/OSL system equipped with a $^{90}Sr/^{90}Y$ beta source providing a 0.114 ± 0.002 Gy s^{-1} dose rate at the time of measurements. Quartz samples were stimulated by 470 nm blue light, detection was made between 290 and 390 nm (Hoya U-340 filter). The D_e of samples was measured using the standard single-aliquot regenerative-dose protocol (SAR) described by Murray and Wintle (2000). The measurement of the natural OSL signal was followed by four regenerative cycles with increasing doses, and a cycle with zero dose. Finally the lowest regeneration dose was repeated for the calculation of the recycling ratio. The sensitivity change of aliquots during the procedure was monitored with identical test doses administered following the measurement of the natural signal and the regenerated signals. The value of test doses was set to be 10–20% of the expected equivalent doses. However, in terms of very young samples a compromise had to be made in order to avoid too short dose administration time (the minimum length of irradiation was 5 s). In these cases the test dose was sometimes in the range of the expected equivalent dose. Nevertheless, according to Banerjee et al. (2000) and Murray and Wintle (2000), high test doses do not affect the applicability of the sensitivity correction. At the end of the SAR cycle an IRSL/OSL test measurement was also inserted in order to determine the IRSL depletion ratio and check possible feldspar contamination (Duller, 2003; Mauz and Lang, 2004). Aliquots showed no evidence of feldspar contamination.

Prior to the actual D_e measurements, preheat plateau tests were made on each sample in order to check the effect of thermal transfer and to define the preheat temperature where reproducibility and precision are the highest (Fig. 4). In most of the cases, preheat temperature was 240°C. Cut heat temperature was set to 160°C (Wintle and Murray, 2006). To check the significance of sensitivity change related to the first heating of the samples dose recovery tests were performed (Fig. 5). The natural signal was cleared by a single 40 s blue stimulation at 125°C. Artificially irradiated doses were close to the expected equivalent dose values. The average of measured/given dose ratio was close to unity in each case, and the standard deviation of the data was also satisfactory (Fig. 5).

The received and corrected OSL data were evaluated by Software RISØ Analyst 3.24 (2007). The integration of the first 0.6 s of the shine-down curve was taken as the OSL signal, and the last 10 s as the background. During calculation of aliquot equivalent doses, a 2.0% systematic error was added in order to reflect uncertainty in the intensity of the OSL stimulation source and the positioning of the aliquot relative to the beta source (Vandenberghe et al., 2004). Some aliquots were rejected and not used for the calculation of mean D_e mainly for the following reasons: the recycling ratio was outside 1.00 ± 0.05 (referring to increased sensitivity change), the error of the D_e was larger than 10% (referring to deviation from linear fitting and error in sensitivity correction), or the recuperation signal was over 5% of the natural signal (referring to significant charge transfer). The majority of rejected aliquots were from young samples (OSZ140, OSZ139), resulting in the loss of 75% of aliquots for further analysis.

Sensitivity-corrected dose responses (L_x/T_x) were fitted with a saturating exponential function ($y = a(1 - \exp(-x/b))$) (Fig. 6). Individual D_e values were plotted on a frequency histogram: mean yielding sample D_e and standard error being sample D_e error. Following calculations, the errors of sample D_e were 11–31% in case of samples younger than 2 ka and 6–9% if older.

Environmental dose rate calculations were based on the ^{232}Th (ppm), U (ppm) and K (%) content of samples, provided by high resolution, low-level gamma spectrometry. Radioactive disequilibrium in the uranium chain was not observed. Dry dose rates were determined after Adamiec and Aitken (1998). The dose rate of beta radiation was corrected using the attenuation factors given by Mejdahl (1979). Wet dose rates were assessed on the basis of in situ water contents (Table 1). Note that relatively high moisture contents and low fluctuation are assumed for the entire examined period, as the samples were taken right above and below the projected surface of the paleo-valley. The rate of cosmic radiation was determined on the basis of burial depth following the method of Prescott and Hutton (1994).

Palynology

Palynological analyses were performed on samples from every second boring. Extracts were obtained from the sediment cores. In total, 211 samples were analyzed. Pollen extraction followed the

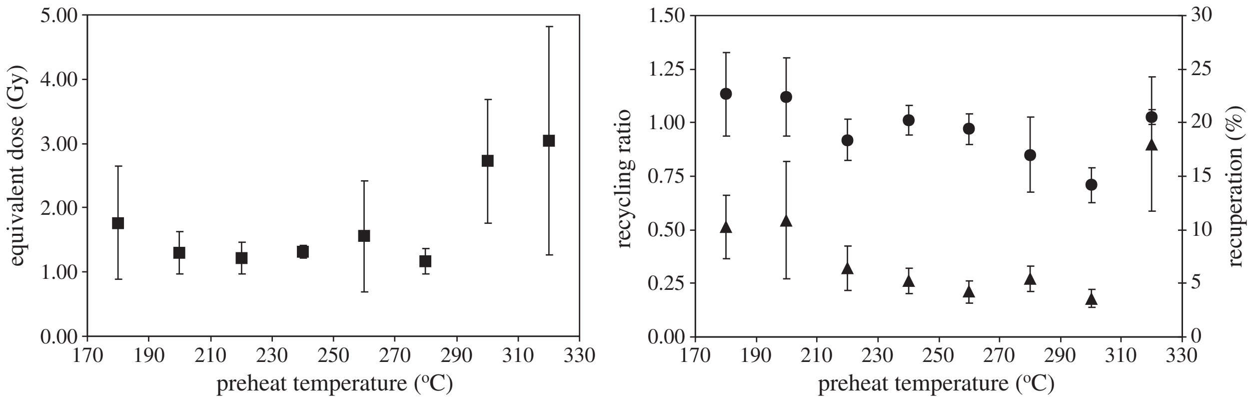

Figure 4. Dependence of measurement precision, reproducibility and recuperation on the variation of preheat temperature in sample OSZ135. Preheat temperature was increased in 20°C steps and was held for 10 s. Cut heat temperature was 160°C during the entire test. Equivalent dose (A), recycling ratio (circles) and recuperation (triangles) (B) values were generated from the mean of three aliquots; error bars represent the standard deviation of data. A preheat plateau can be seen in the 200–240°C region, the most consistent results were received at 240°C.

method of Zólyomi–Erdtman (Zólyomi, 1952). First the carbonate content was removed with hydrochloric acid, then organic and inorganic components were separated through flotation in heavy liquid, finally the organic portion was treated with acetolysis in sulfuric acid and acetic anhydride. Sporomorpha were studied under a 400–600× magnification, and identification was carried out on species, genus and family levels. At least 150 pollen grains were determined for each sample, concentration was expressed as mean grain number per cm^2.

Results were plotted on absolute and relative (AP + NAP + Shrub + Aqua = 100%) pollen diagrams, drawn by Tilia and TiliaGraph software. The identified taxa were classified on the basis of their habitat, and a separate group was formed for taxa indicating human disturbance. For relative dating purposes the local Holocene chronology set up by Járainé-Komlódi (2000) was applied.

Results

Grain-size analyses/sedimentary structure

Based on the results of grain-size analyses, a cross section was drawn on the sedimentary structure of the paleo-valley (Fig. 3A). In each coring the proportion of fine sand was high (50–70%) and rarely decreased below 30%.

The lower zone (Bag-I) is mostly composed of layers of fine sand (the proportion is over 60%). The thickness of these layers decreases towards SE, and they are intercalated by layers of very fine or medium sand (Fig. 3A). At the SE part of the cross section (between Bag.7 and Bag.10) medium sand dominates in the layers, indicating the selective aeolian removal of fine-grained material.

The thickness of the middle zone (Bag-II) ranges between 0.7 and 1.0 m. Its clay, silt and organic carbon contents are higher than that of the lower zone. Bag-V2 also contains limonite nuggets, which were formed in an oxidative environment, supposedly maintained by a permanent, meandering stream (Székyné-Fux, 1942). In the NW part of the valley, fine sand wedging layers can be observed (the proportion of the 0.125–0.25 mm fraction is around 70%). This zone can also be detected below the dune itself, indicating a steady but very slow dune progression towards the valley (see OSL data below).

The material of the valley-marginal dune (upper zone, Bag-III) consists primarily of fine sand (71–81%). In the upper coring (Bag.1) aeolian micro-stratification was quite identifiable; however, at the foot of the dune (Bag.1/b and Bag.2 sites) in the uppermost layers this micro-stratification could not be clearly detected.

Radiocarbon and OSL dating

The calibrated age of the ^{14}C sample was 6.76 ± 0.08 cal ka BP, which is in good agreement with the OSL data obtained from the same, swampy layer (6.60 ± 0.79 ka) (Fig. 3B and Table 1). The bracketing aeolian sediments below and above were dated 8.50 ± 0.85 and 5.46 ± 0.63 ka, respectively.

Based on the OSL data, at least four main depositional phases can be identified in the Holocene (Table 1). The earliest phase occurred at ca. 5.4–8.5 ka. As far as the OSL data of samples OSZ129 and OSZ131 do not overlap, it is probable that the sand deposition was not continuous, and it was divided by periods without aeolian

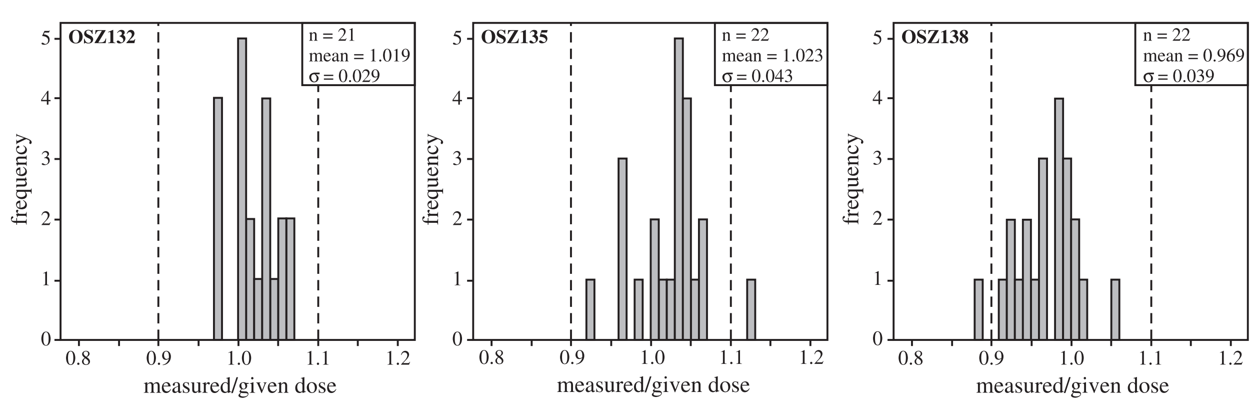

Figure 5. Histograms of results from dose recovery tests in the case of three representative samples. The given doses were 3.3 Gy, 1.65 Gy and 1.1 Gy. Average values were close to unity and varied between 0.96 and 1.04. Only few aliquots were out of the 10% recovery threshold. Tests suggest that samples are suitable for the SAR measurement protocol.

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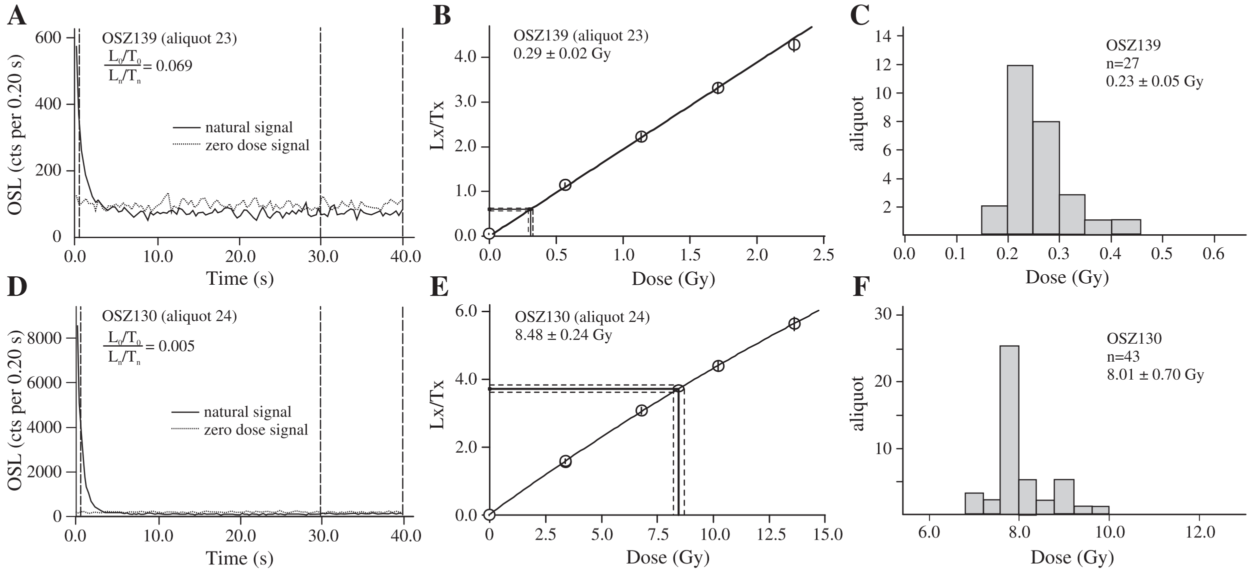

Figure 6. Shine-down curves, dose response curves and distribution of De values in the case of a younger (OSZ139) and an older (OSZ130) sample. Although young aliquots were relatively bright, the recuperation signal was significant (A). Therefore numerous measurements had to be performed to receive the necessary amount of data for further calculations. The minimum length of beta irradiation was set to 5 s (equaling 0.57 Gy) to minimize errors arising from the opening and closing of the beta source window. Although expected equivalent doses were lower than 0.57 Gy, growth curves usually had a good and in fact linear fit, and enabled the extrapolation of the dose response function (B). Nevertheless, the fact of extrapolation possibly contributed to the high dispersion of De values (C). In the case of older samples the analysis was more straightforward (D, E, F).

activity. The subsequent two samples indicate a considerable depositional event at approximately 2.2 ka. The next sand-accumulation period occurred 0.84–1.24 ka, followed by a 0.5-ka interval without deposition. The last aeolian period was around 0.22–0.38 ka, though the uppermost sample is quite young, only about 90–50 yr old.

Sedimentary and palynological record of Bag.4 coring

For detailed sedimentary and palynological description, coring Bag.4 was chosen, as it intersects most of the valley strata and also those that are in direct connection with the valley-marginal dune. As Bag.4 is situated at the deepest and wettest point of the valley, the palynological record was also the most complete here, though pollen degradation could be intensive in some layers as the pollen concentration varied within a great range (0–789 grain/cm^2).

The sedimentary column can be divided into three zones, representing all the zones of the valley's sedimentary cross section (Fig. 7). In the lower zone of the coring (190–70 cm) the proportion of silt and clay is very low (≤5%) but that of fine sand is high (over 70%). The grain size distribution is very similar to that of dune samples, thus these layers presumably have also had an aeolian origin. The zone is not homogenous; slightly finer (i.e., 160–145, 130–120 cm) and coarser layers (i.e., 155–145, 120–110, 80–70 cm) are also represented, though grain size values vary within 5–10%.

In the middle zone (Bag-II: 70–10 cm) the proportion of fine sand decreases (below 50%), and the amount of very fine sand and clayey–silty material increases. Simultaneously, organic carbon content increases as well (4–5%). Stratigraphically this unit is also diverse, as fine sand layers (i.e. 55–50, 10–0 cm) frequently alternate with clayey and silty sediments (i.e. 60–55, 20–10 cm). In the upper zone (Bag-III: 0–10 cm) the proportion of finer material increases, and the fine sand decreases from ca. 60% to 30%.

The pollen record can be divided into three zones, which were fitted to the zones of the valley and the sediment profile. Subzones were distinguished on the basis of the palynological features of the samples (Fig. 8). In the lower part of the profile (190–105 cm) the

Table 1
Dosimetry, equivalent dose and OSL age data for the investigated sand samples.

Sample	Depth (m)	W	^{232}Th (ppm)	U-nat (ppm)	K (%)	D'_{cosmic} (Gy ka^{-1})	D'_{total} (Gy ka^{-1})	Aliquots	D_e (Gy)	Optical age (ka)
OSZ140	0.15	0.15 ± 0.03	8.42 ± 0.06	2.85 ± 0.03	0.06 ± 0.02	0.20 ± 0.02	1.34 ± 0.18	25	0.10 ± 0.03	0.07 ± 0.02
OSZ139	0.30	0.14 ± 0.03	6.18 ± 0.03	2.42 ± 0.01	0.04 ± 0.01	0.20 ± 0.02	1.11 ± 0.15	27	0.23 ± 0.05	0.21 ± 0.05
OSZ138	0.45	0.15 ± 0.03	6.31 ± 0.04	1.95 ± 0.02	0.03 ± 0.01	0.20 ± 0.02	1.01 ± 0.12	33	0.32 ± 0.08	0.32 ± 0.09
OSZ137	0.60	0.16 ± 0.03	7.55 ± 0.07	2.87 ± 0.09	0.05 ± 0.02	0.20 ± 0.02	1.28 ± 0.16	24	0.48 ± 0.15	0.38 ± 0.13
OSZ136	0.75	0.16 ± 0.03	5.77 ± 0.05	1.85 ± 0.04	0.03 ± 0.01	0.20 ± 0.02	1.17 ± 0.14	34	0.80 ± 0.16	0.84 ± 0.19
OSZ135	0.90	0.17 ± 0.03	8.30 ± 0.07	3.08 ± 0.03	0.02 ± 0.01	0.19 ± 0.02	1.32 ± 0.16	40	1.32 ± 0.15	1.00 ± 0.17
OSZ134	1.05	0.16 ± 0.03	7.75 ± 0.09	4.05 ± 0.04	0.05 ± 0.01	0.19 ± 0.02	1.52 ± 0.20	32	1.88 ± 0.40	1.24 ± 0.31
OSZ133	1.20	0.17 ± 0.03	7.81 ± 0.07	4.21 ± 0.05	0.02 ± 0.01	0.19 ± 0.02	1.52 ± 0.19	35	3.36 ± 0.26	2.21 ± 0.32
OSZ132	1.35	0.18 ± 0.03	8.27 ± 0.09	4.28 ± 0.04	0.06 ± 0.02	0.19 ± 0.02	1.58 ± 0.19	40	3.59 ± 0.25	2.27 ± 0.31
OSZ131	1.50	0.19 ± 0.02	7.76 ± 0.05	3.69 ± 0.03	0.02 ± 0.01	0.19 ± 0.02	1.39 ± 0.12	38	7.57 ± 0.60	5.46 ± 0.63
OSZ130	1.65	0.20 ± 0.02	7.39 ± 0.06	3.03 ± 0.03	0.02 ± 0.01	0.18 ± 0.02	1.21 ± 0.10	43	8.01 ± 0.70	6.60 ± 0.79
OSZ129	1.80	0.20 ± 0.02	7.83 ± 0.06	3.75 ± 0.02	0.02 ± 0.01	0.18 ± 0.02	1.38 ± 0.11	41	11.73 ± 0.67	8.50 ± 0.85

W: in situ water content: mass of water/dry mineral mass.
^{232}Th, U-nat, K: thorium, uranium and potassium content determined by high-resolution gamma spectrometry.
D'_{cosmic}: cosmic dose rate calculated on the basis of local data and using the method of Prescott and Hutton (1994).
D'_{total}: total dose rate.
Aliquots: number of aliquots used for the calculation of the equivalent dose.
D_e: equivalent dose.
Optical age: thousand years before AD 2008.

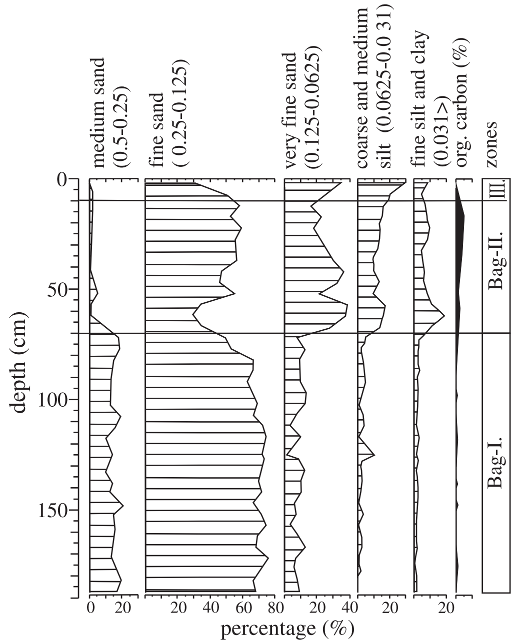

Figure 7. Grain-size distribution (mm) and organic carbon content (%) in Bag.4 core.

average pollen density is low (0–77 grain/cm^2). This can be explained by (1) poor vegetation; (2) inadequate pollen preservation conditions in the easily desiccating sandy deposits and (3) possible relocation of pollen, which is reflected by the high proportion of broken and corroded sporomorphs. In the upper part of the profile (105–10 cm) the pollen density becomes higher: 23–223 grain/cm^2 in lower samples (105–50 cm) (max. density: 789 grain/cm^2), and 111–331 grain/cm^2 in upper samples (50–10 cm). The uppermost part (10–0 cm) of the coring is pollen sterile.

In the Bag-I/a subzone (190–105 cm) *Pinus* is dominant (93–97%), but going upwards certain deciduous trees (*Betula*, *Tilia* and *Corylus*) do also appear. *Artemisia* and *Taraxacum* pollen probably originate from the higher and drier surfaces. The poor vegetation and the absence of hygrophilous plants indicate that a dry and cold climate was typical during the late Pleistocene.

In the next subzone (Bag-I/b: 105–80 cm) coniferous pollen stay the dominant arboreal pollen (64–100%), although the proportion of deciduous trees increases (max. 5.3%), reflecting continuous warming. In addition, *Tilia* and *Corylus*, *Alnus* and *Salix* also appear, indicating increasing precipitation. The NAP reflects these changes too, as the appearance of *Artemisia* and *Gramineae* is followed by plants common in willow swamps (*Filipendula*, *Chrysosplenium*, *Sparganium* and *Pterydophyta*). Based on the pollen data this subzone represents the Preboreal Phase (10.2–9.0 ka), the first half of which is claimed to be dry, while the second was more humid (Járainé-Komlódi, 2000).

In the Bag-I/c subzone (80–70 cm) coniferous tree pollen are still present, but the proportion of angiosperms (*Corylus* and *Quercus*) increases, similar to non-arboreal pollen (NAP: 23.8%). The proportion of plants preferring swamps or wet meadows (*Bellis*, *Filipendula* and *Pterydophyta*) decreases and xerophilous plants become more abundant (*Aster* and *Lychnis*). The vegetation thus indicates a warm and dry climate, which can probably be related to the Boreal Phase (9.0–8.0 ka).

In the Bag-II/a subzone (70–50 cm) the ratio of coniferous pollen drops below 50%. The amount of hygrophilous plants increases (*Alnus*: 32.6%, non-arboreal pollen from swamps and wetlands over 70%). The pollen-spectrum corresponds to a warm and humid climate (presumably the Atlantic Phase 8.0–5.3 ka). The uppermost sample of this unit (55–50 cm) is very poor in pollen grains, but the sample underneath is very rich in pollen, including a large number of burnt, corroded and broken grains and charcoal.

In the next subzone (Bag-II/b: 50–25 cm) the mezophilous *Fagus* and *Carpinus* appear, indicating an even and wet climate. The abundant water supply is also reflected by the great number of *Alnus* and *Pterydophyta* sporomorphs, while the *Viburnum* and *Filipendula* along with pondweeds (*Myriophyllum* and *Sparganium*) suggest the existence of a swamp. The pollen assemblage reflects cool and wet climate, which was typical of the Subboreal Phase (5.3–2.9 ka). In this subzone, some indirect evidence of human impact was identified. The occurrence of *Plantago* indicates disturbance and trapping, while *Centaurea* and the high number of *Gramineae* imply animal husbandry.

The Bag-II/c subzone (25–10 cm) has the greatest pollen density, but *Fagus* and *Carpinus* disappear and the proportion of hygrophilous plants also decreases. These reflect a dryer and more continental climate (the Subatlantic Phase: 2.9–0 ka), though the shift was certainly not dramatic, since *Pterydophyta* is still present. In some samples the pollen of deciduous trees totally or partially disappears, while at the same time the pollen of typical weed associations (*Agrostemma*, *Sonchus* and *Galium*) indicating disturbance becomes abundant. Consequently, the area was presumably deforested, and woods were replaced by meadows and farmlands. In the uppermost samples the proportion of burnt pollen and charcoal is very high.

The samples of the Bag-III zone (10–0 cm) are pollen-sterile.

Discussion

Interpretation of development phases

Based on the pollen record, at the end of the Pleistocene a vegetation of poor diversity covered the territory and the climate was dry and cold. The bottom of the valley was occupied by sparse pine forests and the almost bare dune was certainly the scene of aeolian activity. As the climate became warmer and more humid in the Preboreal Phase, the sand dune became more stabilized by vegetation. On the valley-marginal dune Artemisia steppe advanced, while in the valley an increasing number of deciduous trees mixed into the pine forest. Under the relatively humid climate the stream was lined by alder and willow, and hygrophilous herbs became common. In most of the layers of the Bag-I zone no OSL measurements were made, though its uppermost sand sheet (OSZ129) was deposited 8.50 ± 0.85 ka ago. As this layer stretches just 100 m into the valley, it suggests that the vegetation on the valley bottom was dense enough to stop further transport towards SE. At the beginning of the Boreal Phase the climate turned drier and warmer, and mixed forests were repressed by xerophilous associations.

The sediments in the mid-zone of the valley cross-section (Bag-II) were deposited from the Atlantic Phase. This is demonstrated by both radiocarbon (6.80 ± 0.07 cal ka BP) and OSL data (OSZ130: 6.60 ± 0.79 ka). The climate turned humid and temperate in the Atlantic Phase; therefore, herbs and trees typical for willow- and alder swamps covered the valley bottom, where fine-grained sediments accumulated. In the meantime the sand dune was colonized by deciduous forests. However, during this phase, aeolian activity did occur at 6.60 ± 0.79 ka (OSZ130) and 5.46 ± 0.63 ka (OSZ131). The sand layers stretch into the valley, their thickness decreases towards SE and have a positive inclination from the source (sand dune). All these provide evidence for sand mobilization in spite of the wetter climate. The younger Atlantic sand layer is pollen-sterile and covers pollen-rich sediments which contain a large number of burnt, corroded and broken pollen grains and charcoal. All these suggest forest fires as a cause of subsequent Late Atlantic aeolian activity. The pollen spectrum does not indicate drought or any other natural reasons for fires. Nevertheless, a great number of Neolithic remains (including large number of goat, sheep and cattle bones) and Copper Age pottery was found nearby (Szendrey, 1984) suggesting human-induced fires and

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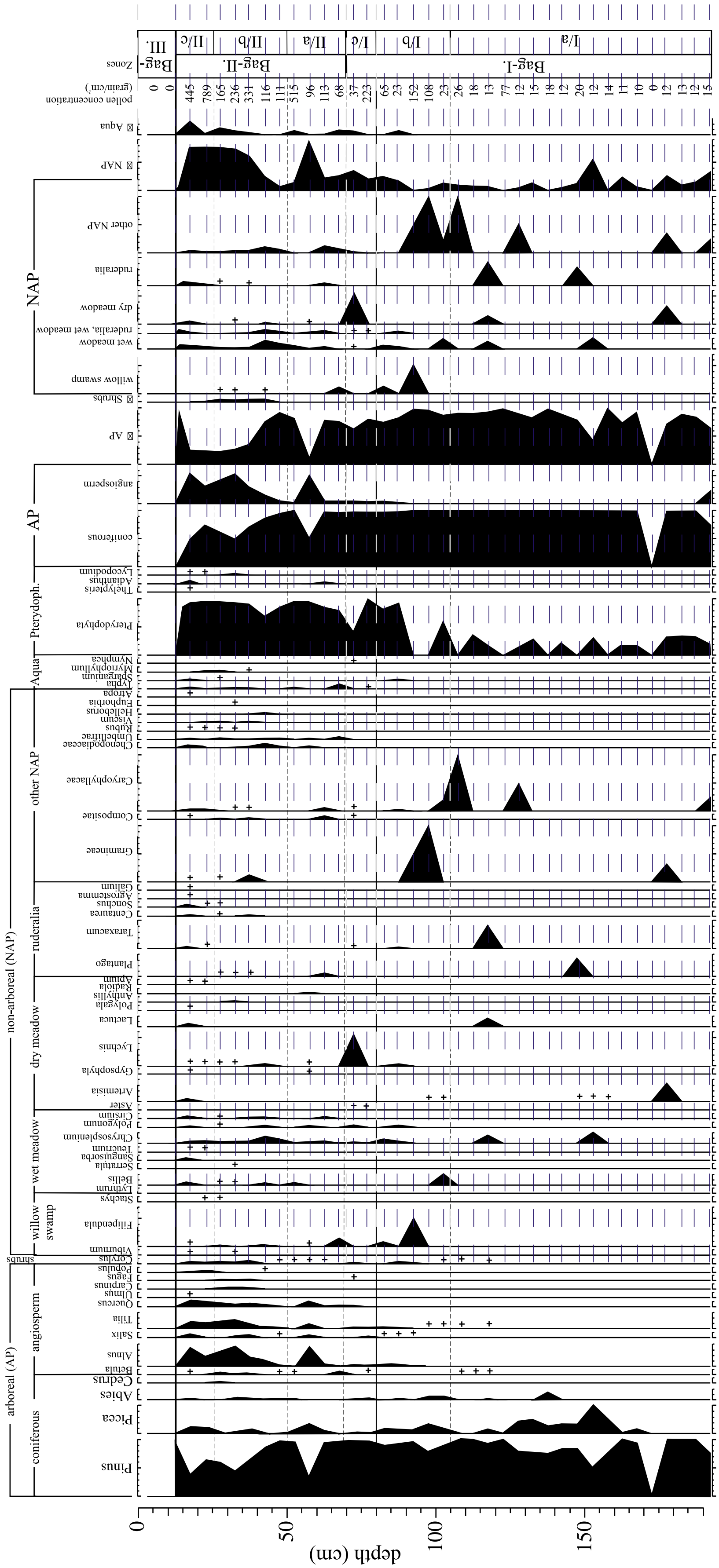

Figure 8. Percentage frequency pollen diagram of Bag.4 core. The presence of grains in less than 1% is indicated by a + symbol. The subzonation of the main pollen zones is indicated by dashed lines.

sand mobilization due to slash-and-burn agriculture and overgrazing in the Neolithic and the Copper Age, respectively. Thus, as early as the Neolithic, agricultural practices could cause local sand drift, and therefore the human alteration of the natural environment in the region might date back to this time.

According to palynological data, the climate during the Subboreal Phase was cooler, more humid and less continental. At this time a dense beech and hornbeam forest covered the sand dune, while on the bottom of the valley a stream was meandering, flanked by an alder forest. The deep waterlogged depressions at the SE part of the valley were occupied by pond-weeds. In this environment, mostly clayey and silty sediments with high organic carbon content were deposited. The pollen spectrum indicates that the surrounding area was grazed, which correlates well with archeological findings from the Bronze Age, when population density was high in the region (Szendrey, 1984). Nevertheless, on the basis of OSL data, no sign of Subboreal aeolian activity was found at the dune front, thus grazing was not intense enough to overwhelm climatic conditions.

The water supply of the valley bottom became moderate in the drier Subatlantic Phase, but under natural conditions the sand dune was still covered by forests. In the meantime, Iron Age Celtic groups increasingly altered their environment (Szabó, 1971) by clearing the forests, creating new meadows and agricultural fields and introducing plowing to the territory, as reflected in the pollen spectra as well. According to the OSL data, these activities resulted in deflation, forming a well-traceable sand sheet in the dune front–valley depositional complex. The aeolian layer covers the Subboreal sediments, and was dated to be minimum 2.21 ± 0.32 ka and maximum 2.27 ± 0.31 ka. Subsequently, the depositional history of the dune front and the valley became separated, as the material deflated from the dune never again stretched deeply into the valley.

The upper zone of the cross-section (Bag-III), representing mostly the pollen-sterile sediments of the dune front, suggests several sand mobilization phases during the Late Subatlantic Phase. Presumably, repeated deposition occurred during the Migration Period and Early Medieval Times (OSZ134: 1.24 ± 0.31 ka; OSZ135: 1.00 ± 0.17 ka), when according to archeological findings, various nomadic tribes inhabited the region and later small villages were established (Kiss, 2000). Under the contemporary climatic conditions, overgrazing could lead to wind erosion at the top of the dune and deposition at its foot. From the 13th century AD some written documents are also available referring to the environmental conditions of the region (Mezősi, 1943). According to them, vast forests covered the area until the widespread establishment of villages in the 12th–13th centuries AD, which might be responsible for the aeolian sediment dated to 0.84 ± 0.19 ka (sample OSZ136). Later, due to increasing population density, land use had significantly changed, and forests were replaced by vineyards and pastures (Mezősi, 1943). The clearing was probably the most intensive in the 17th century, when the nearby settlement (Bagamér) became the largest town in the area. Based on two of the OSL samples (OSZ137: 0.38 ± 0.13 ka; OSZ138: 0.32 ± 0.09 ka) these human activities induced again sand mobilization.

Land use hardly changed by the 18th century AD. The first military map of Hungary (1773) depicts the territory as a sparse grassland ("*praedium*, *desertum*") with vineyards on the southern slopes of the dunes. Under these conditions aeolian activity could occur from time to time as suggested by the OSL dating (OSZ139: 0.21 ± 0.05 ka). Finally, evidence for modern time sand deposition was also found (OSZ140: 0.07 ± 0.02 ka). However, it must be added that these samples were collected from near-surface sediments (0–30 cm), thus their OSL data can have larger errors due to dose rate inhomogeneity.

Throughout the Holocene the net rate of sedimentation in the valley was spatially and temporally balanced (0.06–0.1 mm/yr); however, the rate was slightly higher during the Preboreal Phase (0.2 mm/yr). From the 7th century AD the depositional rate at the dune front increased significantly (0.8 mm/yr). During the Migration Period accumulation was somewhat slower (0.7 mm/yr), but since the 16th–17th centuries AD it has accelerated (1.3 mm/yr). It should be noted that in the sedimentation process of the valley, in addition to the dominant aeolian processes fluvial activity could participate; however, if we consider the low slope (0.00001) of the valley and the small discharge of the brook, fluvial processes probably had a minor role.

Regional comparison and conclusions

Up until now no "clear evidence" (Borsy, 1991) had existed concerning Boreal aeolian activity on the Nyírség alluvial fan. In the present study a Late Boreal event was dated (8.50 ± 0.85 ka), which was presumably driven by a transition from a warm and humid to a warm and dry climate. Previously only one study demonstrated aeolian activity in the Atlantic Phase (Borsy, 1990). We have identified Atlantic deposition not only here (6.60 ± 0.79 ka and 5.46 ± 0.63 ka) but also at a nearby site (Kiss and Sipos, 2007). Based on our palynological analyses and previous research (Kiss and Sipos, 2007), climatic factors were not favorable for aeolian sand transport during this phase. However the area was occupied by Neolithic tribes practicing slush-and-burn farming and Copper Age people who kept large livestock. Therefore we assume that the primary reason for sand mobilization was human impact, namely deforestation and overgrazing.

No Subboreal aeolian activity was identified in the Nyírség region, neither by previous authors nor by us. This can be explained by the humid climate of the phase and insignificant human impact. Early Subatlantic events were proven only by one former study (Kiss and Sipos, 2007). Now we can reinforce that Iron Age agricultural practices were intensive enough to provide enough sediment for aeolian processes at 2.2 ka ago. Concerning more recent activities our data are in agreement with earlier works on 18th–19th century deflation (Borsy, 1990; Braun et al., 1992). However, the occurrence of Migration Period and 12th–13th century sand transport (1.24 ± 0.31 ka, 1.00 ± 0.17 ka and 0.84 ± 0.19 ka) in the Nyírség seems to be also well established by now.

Comparing our results to other regions of the Carpathian Basin (Borsy, 1990, 1991; Borsy et al., 1991; Gábris, 2003; Újházy et al., 2003; Kiss et al., 2006) it seems as if aeolian activity was more widespread in the basin than it was previously suspected. However, compared to the age data originating from the Danube–Tisza interfluve (Kiss et al., 2006), which is the driest sand-covered region of the Carpathian Basin, some events are missing from the Nyírség alluvial fan. This can be explained by the considerable differences in the vegetation and number of inhabitants in the two regions, as the Nyírség alluvial fan has been relatively densely forested (Járainé-Komlódi, 2000; Kiss, 2000), while the Danube–Tisza interfluve has mostly been covered by grassland throughout the Holocene (Borsy et al., 1991), providing a more favorable environment for tribes keeping large livestock (Visy, 2003), hence the potential for overgrazing was greater. However, the present study has proven that aeolian sand transport could occur on the Nyírség alluvial fan due to human impact even if climatic conditions were not suitable.

Comparing the results with data from other sites, it seems clear that in the Holocene human impacts on vegetation had greater importance in inducing aeolian activity than climate change (Hilgers, 2007). As a consequence, the phases of aeolian activity differed spatially in both a worldwide and regional context. However, it seems that in the Neolithic period concerning Europe aeolian activity was widespread and was related to forest fires (Schlaak, 1999; Hilgers, 2007). Since the Bronze Age, however, the timing of aeolian activity was less uniform and its spatial and temporal variability increased (Schlaak, 1999; Böse and Brande, 2000; Hilgers, 2007). Between 1600 and 1800 AD another phase of general aeolian activity occurred, resulting in thick sand layers at several sites (Pelka-Gosciniak, 2000; Hilgers, 2007).

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