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GRAIN SIZE DISTRIBUTION OF STABILISED AEOLIAN DUNE SEDIMENTS IN INNER SOMOGY, HUNGARY

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Abstract
In Inner Somogy the former researches concluded that the grain size of stabilised aeolian dunes decreases from north to south fitting to grain size distribution of the alluvial fan the dunes were built of and to the prevailing wind. However, the trend is not so evident, if considering the dune types and sand moving periods. The aim of this paper is to analyse the grain size distribution trends from the point of view of (1) different dune classes, (2) OSL age and (3) general morphological characteristics of the region. During the analysis the grain size distribution of 345 samples from 17 cores (120-300 cm in depth) was determined, and 15 OSL samples were dated. According to the results, the material of simple forms and level 1 dunes (these are the lowest dunes on the surface of the alluvial fan) becomes finer southward, in accordance with the structure of the alluvial fan and prevailing wind direction. Similar trend applies for level 2 dunes (which were formed on the top of level 1 dunes), but it does not apply for level 3 dunes, which are situated on the top of other dunes. It seems that the grain size is inversely proportional to the size of a dune and its age, thus younger and smaller dunes have coarser and less well sorted material. The sediments of the oldest, large parabolic dunes are the finest, younger, medium size parabolic forms have fine material, and the youngest hummocks contain the coarsest sand. The decreasing grain size towards south is the most apparent along longitudinal residual ridges, while within parabolic dunes the wings contain finer material than their elevated head.

Keywords: Inner Somogy, grain size distribution, aeolian sediment, parabolic dunes, sorting process

INTRODUCTION

Grain size distribution analysis is one of the most commonly used methods in aeolian sand research (Bagnold, 1937; Lancaster, 1995; Zhu et al., 2014), therefore several techniques and scales were developed (Sahu, 1964; Wang et al., 2003; Blott and Pye, 2012). Aeolian sands are well sorted; the dominant grain size varies between 125-500 μm (Bagnold, 1937; Borsy, 1961). On dune heads, sediment is better sorted and finer than in interdune areas, the largest grains remain in deflation hollows (Zhu et al., 2014). On a sand area evolved by reworking an alluvial fan, the characteristics of the source material control the grain size, prevailing wind barely can modify it (Liu et al., 2014; Zhu et al., 2014); only sorting is improved through transportation (Zhu and Yu, 2014). Based on surface sediments from northern China, Nottebaum et al. (2014) determined that coarser aeolian grains appear more likely in lower elevations while finer sediments in higher elevations above sea level. Dunes of various ages in India show similar grain size distribution and consist mainly of fine sand (120-250 μm, Reddy et al., 2013).

Inner Somogy (southwest Hungary) was an alluvial fan of the Danube and its tributary, and the alluvial material was reworked by wind during the Neogene. Earlier researches investigated the grain size distribution of the alluvial sediments and aeolian sands too. Marosi (1970) separated fluvial and aeolian sands based on fauna remnants, cross-bedded sediment structure and surface characteristics of the single grains. According to his research, fluvial sediments of East Inner Somogy become finer from east to west and also from north to south (in accordance with the construction mechanism of alluvial fans). Thus, in the northern part 11% of the aeolian sediment is ≥1400 μm, while in the southern part its proportion is only around 2%. Also the distribution curve mode gradually shifted to the finer fractions towards the southern region (320-630 μm in north and 60-100 μm in south). Separating fluvial and aeolian sands applying electron microscope studies Lóki (1981) showed similar results. He noted that fluvial sediments of the northern region are coarser, as samples contain 50-60% of medium and coarse sand (>300-200 μm), and grains above 3000 μm were also found. In East Inner Somogy towards south, the proportion of the fine and very fine sand fraction (200-50 μm) gradually increases to 80%. The most common grain size is 320-100 μm, and 200-100 μm.

Increased proportion of fine particles towards south can also be detected in aeolian sands, as during the aeolian transport the sediment became sorted and refined (Marosi, 1970). In northern areas, the proportion of fine sand fraction (60-100 µm) decreased in the aeolian sediments compared to alluvial fan material, since wind presumably blown it southward. In south, loessy sediments (≤60 µm) accumulated, the predominant fraction remained 100-200 µm, its proportion even increased from approx. 30% to approx. 50% (Marosi, 1970). In East Inner Somogy in the sand dunes the proportion of fine sand is larger than of medium sand (Lóki, 1981). During a sedimentological research Marosi (1970) derived results from regional average values and did not investigate grain size distribution differences of dune types. Lóki (1981) did not study the grain size distribution differences between different aeolian forms, however he described dunes on the leeward side of Marcali Loess Ridge covered by loessy-sand (20-50 µm: 15-25%), and therefore, concluded that sand movement was not continuous.

This research aimed (1) to study the sedimentological characteristics of dune classes identified in the region by Györgyövics and Kiss (2013); (2) to evaluate the grain size distribution changes within the whole sand dune area and within a single dune, and (3) to analyse the connection between aeolian material and OSL age of dunes.

STUDY AREA

The most western sand dune area in the Carpathian Basin is Inner Somogy (3000 km2), situated on the south-western part of the basin between Lake Balaton and River Dráva (Fig. 1). During the Pliocene, the Danube and its tributaries flowed into the remnant of Pannonian Lake (Slavonian or Paludina Lake) and built an extensive alluvial fan (Ádám et al., 1981). Then as north of Inner Somogy, the Keszthely-Gleichenberg divide uplifted in the Late Pliocene (Pécsi, 1959) or Early Pleistocene (Ruszkiczay-Rüdiger et al., 2011), the Danube shifted northward and occupied its current west-east flow direction between Bratislava and Budapest (Borsy et al., 1969). Later even the smaller rivers abandoned the alluvial fan, thus aeolian processes reworked the surface during the Weichselian (Marosi, 1970). Throughout the more humid Holocene, sheetwash, gully and valley formation were widespread (Marosi, 1970). In the development of the area Sebe et al. (2010) emphasised the role of wind erosion and described the landscape as a complex yardang system, yet the age and process of sand dune formation and their possible Holocene modification was not studied in their work.

In the early twentieth century, Cholnoky (n.d.) described the area as a single, large blowout – residual ridge – hummock form. Later Marosi (1967, 1970) mapped several smaller blowout – residual ridge – hummock systems and identified superimposed dune generations. Lóki (1981) edited a large scale (1:100,000) geomorphologic map of the region, indicating complex dune systems, longitudinal ridges and blowouts. The latest research (Györgyövics and Kiss, 2013) identified large- and medium-size parabolic dunes with different degree of infilling, hummocks and wing fragments. The described forms occur as single dunes or as part of a three-level superimposed hierarchy system. From periglacial perturbation exposures inside the stabilised dunes, earlier researches (Pécsi, 1962; Marosi, 1870; Lóki, 1981) presumed widespread aeolian sand formation since Early Wechselian until Upper Pleniglacial. However, recent OSL measurements (Kiss et al., 2012) indicate to Late Glacial Dryas phases as the main active aeolian period, and local deflation events during the Preboreal and Boreal Phases, and human induced sand movements in the Subboreal Phase and in the 17^{th}-18^{th} centuries.

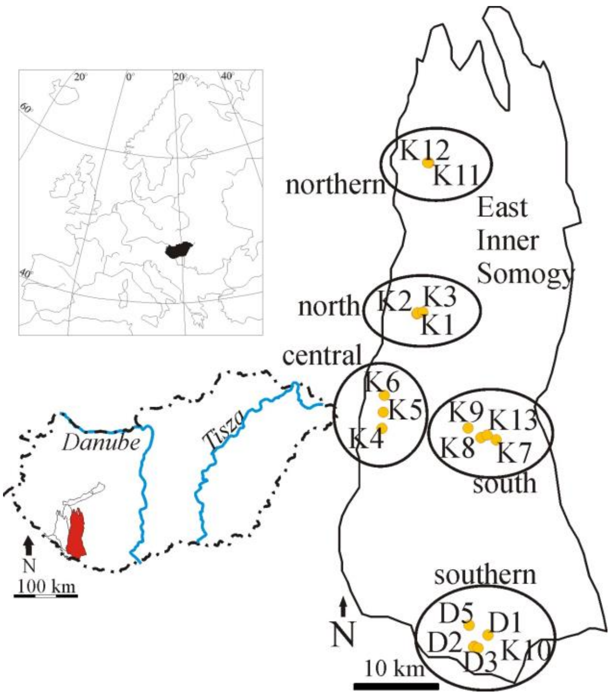

Fig. 1 The study area is located in southwest Hungary, in East Inner Somogy. The sampling sites (K and D) were grouped based on their location within the region.

Nowadays the mean annual temperature is 10-11°C (TJan= -1°C, TJul= 20-21°C, Dövényi, 2010). The annual precipitation is 700-800 mm, 150-200 mm higher than in the other large sand dune areas on the Great Hungarian Plain. Prevailing wind direction is northwardly, however, south-westerly winds are also abundant. The predominant wind speed is 2.5-3.5 m/s which is not sufficient to trigger recent aeolian activity (Marosi and Somogyi, 1990). Human impacts date back to the Iron Age since the area has been populated (Zatykó et al., 2007). The natural hydrography has been severely modified by draining swamps, building canals and constructing fish-ponds. Only remote depressions are occupied by interdune lakes, marshes and alder-swamps. The natural vegetation of the area is hornbeam-oak forests with juniper, however on large areas agricultural activity dates back to centuries (Iványi and Lehmann, 2002).

METHODS

Altogether 17 boreholes (120-300 cm deep) were drilled in Inner Somogy mainly on the heads of parabolic dunes. Samples were collected from every 10 cm for grain size distribution analysis. The sampling sites were chosen to include superimposed and simple dunes from each morphological class, and three boreholes from a single residual ridge. Meanwhile, to date the age of the aeolian forms samples were collected for optically stimulated luminescence (OSL) dating from the bottom of boreholes or at each 1.0 meter.

Grain size distribution analysis of the 345 collected samples was carried out by Analysette 22 MicroTec plus laser diffraction analyser. As the measurement range of the equipment is 0.008-2000 μm, particles larger than 2000 μm where removed by sieving, and percentage values were modified in accordance with fraction weight. Combined Udden-Wenthworth scale was used for classification (Blott and Pye, 2012). Profile figures were created in Tilia Graph where cluster analysis was also applied to facilitate the identification of zones and layers. The following statistical parameters were calculated according to the method of Folk and Ward (1957) in Gradistat (Blott and Pye, 2001):

- mode, which is the local maximum of the grain size distribution curve;
- mean (Mz), which is the arithmetic mean of the three thirds of the grain size distribution curve (Folk and Ward, 1957);
- grain size values at different cumulative percentages:
- d_{25} is the lower quartile of the grain size distribution curve, thus it is the diameter which separates the finer 25% of the grain population from the coarser 75%.
- d_{75} is upper quartile of the grain size distribution curve.
- d_{90} is the diameter size from which 90% of all sizes are smaller and 10% is larger.

Based on the difference of the values of d_{75} and d_{25}, the degree of sorting could be estimated. However, it is important to note, that this is not equal with sorting calculated as statistical standard deviation. In this case, the smaller difference between the values of lower and upper quartiles refers to better sorting.

In this research, grain size distribution variances of dunes in different hierarchy levels and morphometric classes were analysed. Based on mean (Mz) values the coarsest samples were chosen from each profile and only these were included in the regional comparison.

RESULTS

The studied borehole profiles were classified according to the morphometric class of the dune they were deepened in. The most typical profile of each class is presented here in details, first the largest thus the oldest dunes will be introduced, and then the smaller and younger forms.

Large parabolic dunes

These are the largest dunes of the region; therefore they form the base of the dune association. They are 1-10 km long along the crest, located in the accumulational zones and sometimes superimposed on each other. Based on the degree of infilling (sediment supply) unfilled and partially filled subclasses were identified. They consist of several different sediment layers which indicate that these dunes were formed during more than one aeolian period. For example in the profiles of dune heads (D3, K12, K13) a coarser sand layer is intercalated by two finer sand layers, while on the windward slope (K8) and wing (D5) the finest grain size is at the bottom of the profile, and the grain size distribution gradually becomes coarser towards the surface.

The profile D3 was made in a head of a large parabolic dune. The samples contain 77% sand in average (Fig. 2), within the sand fraction the predominant grain size class is fine sand (34-56%). Based on grain size variation three zones were identified. The bottom zone I. (210-155 cm) contains some coarse sand (0.5-1.1%), the proportion of medium sand gradually decreases (from 41% to 14%), while fine sand increases from 34% to 56% (d_{90mean} = 336 μm). Within this zone two layers of higher sand proportion were also defined. The grain size distribution of zone II. (155-65 cm) is relatively homogenous (d_{90mean} = 335 μm), a peak (38%) in medium sand proportion (85-95 cm) divides it to three layers. In zone III. (65-30 cm) probably due to soil development processes, the silt and clay content increased (32-36%, d_{90mean} = 280 μm), but well distinguishable layers were not found. Two OSL samples were dated from this profile. The age of the sample from 200-210 cm is 17.42±2.77 ka indicating Late Pleistocene sand movement when coarse grained sand was deposited (d_{90mean} = 349 μm). The age of the upper sample (100-110 cm: 13.43±2.08 ka) indicates Late Glacial aeolian activity. The finer layers (I/2-4) between the two dated samples are probably paleosols developed in the Bølling and/or Allerød interstadials between the two dated stadials. The upmost zone was deposited during a younger aeolian phase; its homogeneity refers to fast sedimentation within a short aeolian activity period. The grain size distribution of profile K13 is slightly different, as it was dissected to three zones: the middle zone (95-175 cm) contains the coarsest sand (d_{90mean} = 363 μm), the lower zone I. (d_{90mean} = 332 μm) and upper zone III. (d_{90mean} = 343 μm) are only slightly finer. This form is younger than the other dated large parabolic dunes, as its OSL age (K13/200-210 cm) indicates Preboreal aeolian activity (10.77±0.71 ka).

The D5 coring represents the material of the wing of a large parabolic dune. The sediment samples get coarser towards the surface (190 cm: d_{90} = 218 μm, 70 cm: d_{90} = 312 μm). OSL sample from 180-190 cm indicates 17.76±4.07 ka old sand movement, similar to the OSL sample of D3 profile at 200-210 cm. However this wing profile is much finer grained (D5/180-190 cm: d_{90} = 218 μm, D3/200-210 cm: $d_{90,}$ =

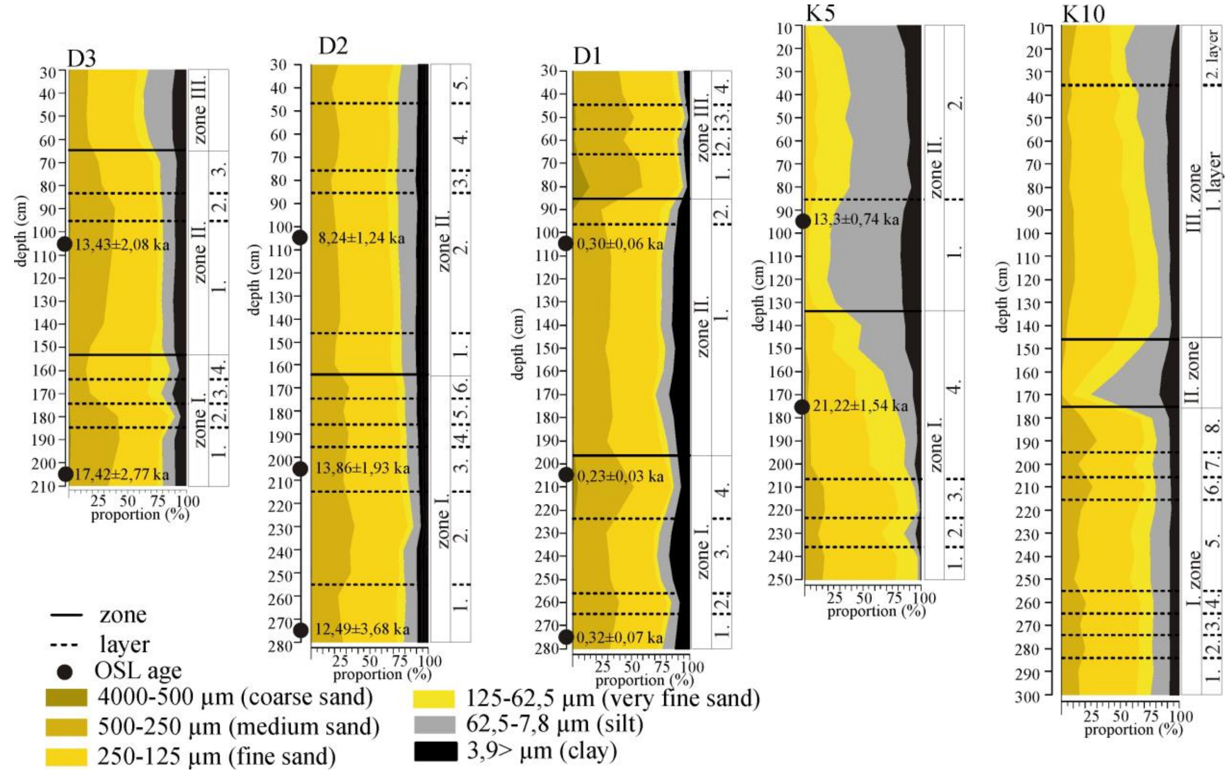

Fig. 2 Grain size distribution of profiles from each morphometric class, where D3 represents the head of a large parabolic dune, D2 represents a medium-size parabolic dune, D1 is a head of a hummock, K5 represents a residual ridge and K10 a deflation hollow

349 µm). The material of the windward slope of a large parabolic dune (profile K8) also becomes coarser towards the surface (zone I. d_{90mean} = 174 µm, zone II. d_{90mean} = 243µm), similarly to profile K12 where medium sand proportion in zone I. is 4-13%, but in zone II. it rises to 17-39%. However, here a significant sand peak was also defined.

Medium-size parabolic dunes

Medium-size parabolic dunes are an order of magnitude smaller than the large parabolic dunes, as the length of their crest varies between 1.0 and 0.16 km. Some are located in the accumulational zones superimposed on the heads of large parabolic dunes; others are in the transportational-erosional matrix and often form a row of dunes perpendicular to the prevailing wind direction. Their degree of infilling (filled, partially filled, unfilled) indicates various amount of sand supply during their formation. Their material is more homogenous, as the profiles show less variation than of the large parabolic dune profiles. The minor differences among the samples refer to repeated aeolian activity. The fine-grained layers of some profiles (K7 and K11) possibly refer to weathering caused by ground water or to soil development processes. These forms are simple dunes without large elevation differences, thus the lack of superimposition allowed the ground water variations to have an effect on sediments. However, similar weathering processes cannot be detected in the material of the superimposed level 2 or level 3 dunes (profiles D2, K1 and K2) located in the accumulational zones.

D2 coring deepened into a filled medium-size parabolic dune in hierarchy level 3. The sand proportion of the samples is over 70% (Fig. 2), where fine sand fraction is the predominant (≥ 40%). Based on the variations of fine and medium sand proportions, two zones were defined. In zone I. (280-165 cm) the samples contains 25-36% (d_{90mean} = 336 µm) medium sand fraction, while in zone II. (165-0 cm) only 17-25% (d_{90mean} = 302 µm). Within the two zones, finer and coarser layers can be found. Three OSL samples were dated from this profile. Samples from 270-280 cm and 200-210 cm date back to the Late Pleistocene (12.49±3.68 ka and 13.86±1.93 ka). As all along zone I. the grain size characteristics are similar, all layers were probably deposited during Late Glacial sand movements. The D3/100-110 cm OSL sample revealed similar age (13.43±2.08 ka). The grain size distributions of the dated samples of the two profiles are similar (D2/200-210 cm: d_{90} = 339 µm, D2/270-280 cm: d_{90} = 321 µm, and D3/200-210 cm / d_{90} = 349 µm), indicating identical wind regime and similar environmental conditions at the time of their formation. The uppermost OSL sample from D2 profile (D2/100-110 cm) refers to Boreal sand movement (8.24±1.24 ka). As this zone has relatively homogenous fine-grained samples, presumably all the 160 cm deep layer of the zone I. was deposited within a short period.

K1 drilling represents an unfilled medium-size parabolic dune from hierarchy level 3. All along the profile the sand content is higher (80-92%) than in profile D2. Here three zones were identified, as the sandy materials were intercalated by a fine-grain layer, where the silt and clay content increases 15-20%.

However, the profile of K2 was made in a filled medium-size parabolic dune in hierarchy level 2, it is similar to the material of the large parabolic dunes. The lower zone I. is finer grained (d_{90mean} = 316 μm) than zone II. (d_{90mean} = 362 μm). The proportion of the medium sand varies considerably therefore 8 and 7 layers were defined respectively. In I/6-8. layers the silt and clay content was high, indicating soil development processes, thus they refer to a possible paleo-surface. An OSL sample taken from K2/260-270 cm refers to Subboreal aeolian activity at 2.99±0.19 ka. From other blown sand territories of Hungary similar age of sand movement was identified (Danube Tisza Interfluve: Sipos et al., 2009; Kiss et al., 2008; and Nyírség: Kiss and Sipos, 2008), and related to Bronze Age anthropogenic activity.

Unlike earlier profiles presented here, the profile K7 is extremely rich in silt and clay. It was drilled in the head of a simple, partially filled medium-size parabolic dune. However, in zone I. sand content is relatively large (63-74%), then it is reduced to 44-67% in zone II., finally it increases to 69-81% in zone III. where silt-rich (32% and 43%) layers were intercalated between the sand layers. The Preboreal age (11.11±0.64 ka) of the OSL sample from K7/200-210 cm is very close to the age of profile K13/200-210 cm (10.77±0.71 ka).

Similarly to Profile K7, the middle zone of Profile K11 is also rich in silt (52-77%) framed by sandy lower and upper zones. K11 core was deppened in the head of a simple, filled medium-size dune. The increased silt and clay content might refer to soil development or caused by the effects of ground water variations.

Hummocks

Hummocks are the smallest crescentic forms (crest length is less than 160 m). They are generally elevated and located in groups superimposed on larger forms. Their material is relatively homogenous, thus it was probably accumulated within a short time. These dunes are very young, anthropogenic activity in historical times triggered their formation.

The D1 coring was made on the head of a hummock superimposed in hierarchy level 3. Its sand content is high (71-96%) with the predominance of medium and fine sand (24-51% and 32-50% respectively; Figure 2). The profile was dissected to three zones and within the zones 2-4 layers were identified. In zone I. (280-195 cm) the medium and fine sand grain size classes are the most common (d_{90mean} = 362 μm). This zone contains two coarser sand layers (sand proportion is 85% and 87%), and two finer grained layers (sand content is 75% and 71%). In the middle zone II (195-85 cm) the clay content slightly increases (from 4-9% to 7-10%), therefore the mean grain size is considerably finer (d_{90mean} = 342 μm). The bottom of the zone is nearly homogenous as sand proportions are between 71-76%, while in the upper part (105-95 cm) the proportion of sand abruptly rises to 83%. In the topmost zone III. (85-30 cm) the coarsest sandy layers were deposited (d_{90mean} = 425 μm). The largest grains were found in the lowermost layer (d_{90mean} = 504 μm), which was then covered by a finer (d_{90mean} = 386 μm), then a coarser (d_{90mean} = 412 μm), and another finer (d_{90mean} = 371 μm) layer. Three OSL samples were dated from this profile which all gave a very young age: 0.30±0.07 ka, 0.30±0.06 ka and 0.23±0.03 ka. North from the windward slope of the dune, a well-defined blowout is located. Presumably, this is the source area of the sediment deposited in the hummock. Probably the deflation was the result of human influence (grazing or bush burning). The three grain size zones refer to at least three deposition periods, but due to the measurement range and available error levels of OSL dating, the exact time of the sand movement phases cannot be specified. Three aeolian periods within approximately 130 years, during the 17^{th} and 18^{th} centuries can only be concluded.

Longitudinal form

Longitudinal ridges are elongated, quazi-linear forms which appear in various sizes (length: 35-5600 m). Numerous ridges are scattered all over the study area, some are simple dunes, but many are superimposed on large or medium-size parabolic dunes. Wing fragments or residual ridges could only be identified by their individual stratigraphic characteristics and age. On the western part of the region a longitudinal form stretching from north to south was sampled at three boreholes along the longitudinal axis. The studied form is covered by sandy silt and silty sand, and this sandy material becomes coarser and thinner downwind. The topmost layer of the sandy zones at the bottom of each profile has the coarsest grain size, referring to the existence of a paleo-surface where larger grains remained as the result of aeolian deflation. This stratigraphic characteristic is typical of residual ridges.

In the middle part of the residual ridge, at the K5 profile two sediment zones were identified. The lower zone contains high proportion of sand fraction, and it is divided by a sharp boundary from the upper, silt- and clay-rich zone (Fig. 2). In the bottom zone (250-135 cm) the proportion of sand fraction gradually decreases from 97% to 49%, meanwhile the medium-sized sand fraction completely disappears (d_{90mean} = 235 μm). The proportion of silt and clay abruptly increases to 14% at 235-225 cm, then decreases (3%) again, and only gradually rises up to 51%. These variations define four layers in zone I. In the upper zone II. (135-0 cm) the silt fraction dominates (53-73%, d_{90mean} = 110 μm), however, in the topmost layer the proportion of the sand fraction slightly increases (35-41%). For OSL dating the sandy I/4 layer (170-180 cm) and the loess-like II/1 layer (90-100 cm) were sampled. The sandy sample revealed the oldest age (21.22±1.54 ka) dated in the region. These data support our assumption that this form is a residual ridge formed during the deflation of the previously stable surface while in the central part of the region large parabolic dunes developed (e.g. D3: 17.76±4.07 ka). The age of the approximately 130 cm thick loess-like cover is 13.3±0.74 ka, determining the same age as D2/200-210 cm, D2/270-280 cm samples and D3/100-110 cm. It suggests that at time, when in the southern part of East Inner Somogy medium size parabolic dunes formed, simultaneously at the margins aeolian dust (loess) covered the residual ridge. Similar loess accumulation was also identified at the margins of other large aeolian areas in Hungary (Borsy, 1987).

Deflation hollows

Deflation hollows are located in the northern foreground of accumulational zones, which are the largest negative landforms here (area: >8 ha). They are built of alternating sandy and silty sedimentary layers. In the hollows after the aeolian activity the groundwater level increased, thus swamps and wetlands evolved, which were covered by varying thickness of sand during further aeolian phases. At the northern sampling site (K3) greater number of sandy and finer sediment layers was found than in south, while in the southern sampling site (K10) the sand layers are thicker.

Unlike previous profiles, at the K10 sampling site (Fig. 2) gray-coloured sand was found, which presumes dissimilar processes and the role of diverse post-sedimentation influences. The zone I. (300-175 cm) contains 75-81% sand (d_{90mean} = 287 μm), within the zone four sandy layers indicate repeated aeolian activity. In the zone II. (175-145 cm) fine grained layer was deposited (d_{90mean} = 166 μm) with high silt proportion (44-66%). In the topmost zone III. (145-0 cm) the proportion of fine and very fine sand is higher than in the bottom zone (d_{90mean} = 244 μm), while its silt proportion gradually increases towards the current surface (from 16% to 46%). Probably, the silty layers of zone II. and zone III/2 deposited in a swamp, where intensive weathering facilitated concentration of silt. The coarsest layers are I/6-8 which could represent the maximum deflation level. Later, a swamp was covered by blown sand layers which facilitated soil development and weathering processes took place. The only OSL samples collected at the bottom of the profile (280-290 cm) is currently under laboratory analysis.

DISCUSSION

Regional analysis

Earlier researches (Marosi, 1970, Lóki, 1981) found that the fluvial sediments of the alluvial fan and consequently the reworked aeolian material become finer southward. For the regional analysis the coarsest samples of each profile were chosen (based on mean values) and their d_{90} values were used. The samples were collected from five well recognisable regions, therefore they were examined in five (from northern to southern) location groups (Fig. 1). Besides the variance in these location groups, grain size distribution of hierarchy levels and morphometric classes were also studied.

On higher elevation the deposition of fine material is more common, while coarser sediments are more abundant on less elevated areas. However, data derived from the 17 study sites are not significantly different, as fine samples were also found in lower laying areas (Fig. 3).

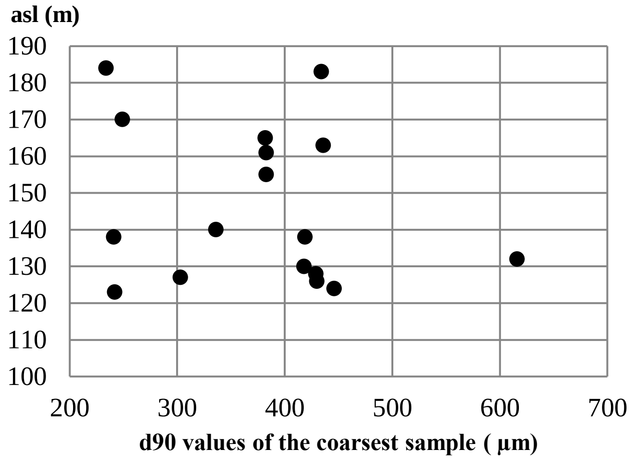

Fig.3 The d_{90} values of the coarsest samples from each profile plotted against elevation above sea level of the sampling site

Clear trend cannot be identified either by plotting the elevation of the coarsest samples against the first mode values of their grain size distribution curves (Fig. 4), however only six different first mode values are present. This presumes that the sediments deposited during at least six aeolian erosional-accumulational periods each characterised by different energy conditions.

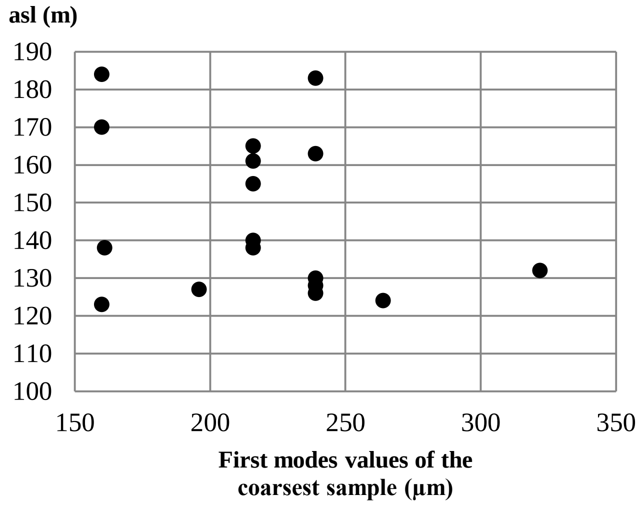

Fig. 4 The first modes of the grain size distribution curves of the coarsest samples from each sampling site plotted against elevation above sea level

As forms were grouped based on their hierarchy levels and morphometric classes, the grain size distribution analysis was also carried out on both classes. Within the accumulational zones grain size variation trends cannot be examined, because (1) most of the sampled dunes are in the southernmost part of each accumulational zones, and (2) the sampling sites are only 1-2 km apart, therefore a lack of representativity within each accumulational zone is a concern. Therefore only changes in the whole region and within single forms were analysed.

Considering the grain size distribution of the whole region (Fig. 5), the material in the northern part of the region is coarser (d_{90}=382-446 µm), then grain size decreases considerably towards the middle part (d_{90}=243-419 µm), while it rises again in the southernmost areas (d_{90}=242-616 µm). This contradicts the previous results, which described continuous refinement towards south. However, the coarse sandy material in south could be explained by the diverse ages and morphometric characteristics of the sampled forms. The southernmost accumulation zone is the highest containing the greatest amount of blown-out material, thus deeper layers were blown out, which were probably coarser due to the texture of alluvial fan sediments coarsening downward.

Within hierarchy levels, the grain size of simple dunes and level 1 forms become explicitly finer downwind. The d_{90} values of simple dunes decreases southward from 446 µm to 242 µm, while of hierarchy level 1 from 429 µm to 249 µm. This is probably the result of grain size trends in the original material, as fluvial sediments in the substrate also getting finer from north to south. In case of hierarchy level 2 dunes the d_{90} grain size values also decrease downwind (from 436 µm to 430 µm and then to 303 µm). However, the trend reverses in case of the elevated hierarchy level 3 dunes, where the d_{90} value in north is 382 µm, and it increases towards south to 616 µm. It could be explained by the development of hierarchy level 3 forms: they are mostly hummocks formed as the result of local deflation. The developed small blowouts acted as wind-tunnels where even the coarser sand fraction could be transported, and it became the building material of the hummocks. Also, these are the youngest dunes, therefore fine sediments of the surface were probably removed during earlier aeolian phases, thus the source of hierarchy level 3 dunes was the lower layers of the alluvial fan substrate, where coarser material was deposited.

Considering the average values of each hierarchy levels, the material of simple dunes is the finest (d_{90mean} = 313 µm), while of hierarchy level 1 dunes slightly coarser (d_{90mean} = 354 µm). The average values of hierarchy level 2 dunes become even coarser (d_{90mean} = 390 µm), and the coarsest forms are in hierarchy level 3 (d_{90mean} = 472 µm). So the more elevated a form is, the coarser d_{90} values is characteristic, as the source material was blown from deeper and deeper, thus coarser and coarser layers of the alluvial fan substrate. Thus, the aeolian deflation and accumulation reversed the original stratigraphy of the alluvial fan's surface.

Among the members of the large parabolic dune morphometric class, coarser and finer samples were both found, regardless of their spatial distribution (Fig. 1), thus downwind refinement cannot be determined in case of the oldest forms (Fig. 5). The material of medium-size parabolic dunes becomes finer southward, as their d_{90} values decrease from 446 µm to 246 µm. However, the southernmost sample does not fit into this trend (d_{90}= 418 µm). In case of the studied members of the hummock morphometric class, the material of the southern studied hummock is coarser than of the northern. During the formation of hummocks, the sediment was probably transported just for a very short distance, from the open sand

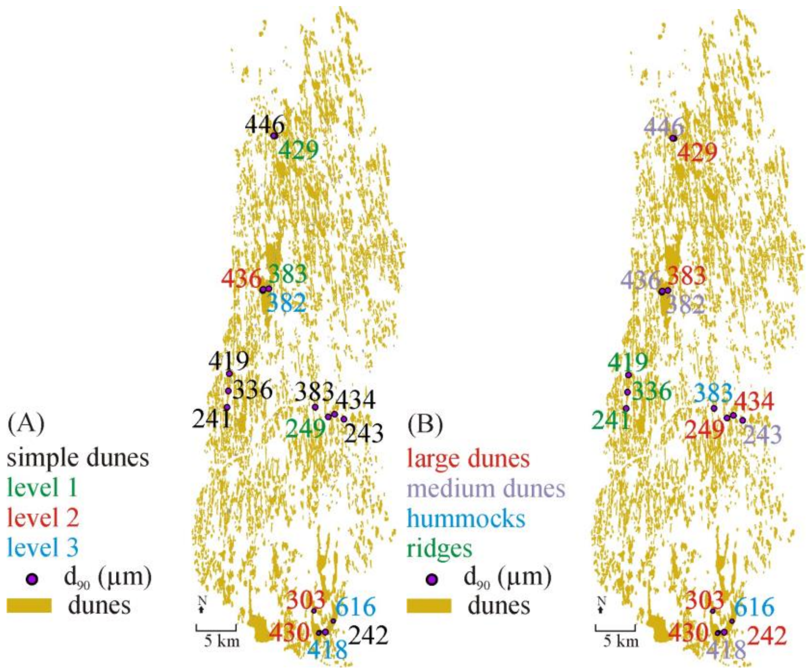

Fig. 5 The d_{90} values of the coarsest samples of the sampling sites according to the hierarchy level (A) and morphometric class (B) of the sampled dune

patches created by human disturbance, thus the source material of that location determined the grain size characteristics of the forms.

Average values of the morphometric classes become gradually coarser from the large parabolic dunes (d_{90mean} = 353 µm) through the medium-size ones (d_{90mean} = 385 µm) to the hummocks (d_{90mean} = 499 µm). Therefore as the size of the form decreases, their grain size increases, referring to limited sand supply and simultaneously denser vegetation, which restrict the spatial distribution of aeolian activity.

Within single forms, north to south refinement is the most emphasised in the sediments of the residual ridge sampled at three points, as here d_{90} values decrease from 419 µm to 336 µm and then to 241 µm. (Fig. 5). Considering the grain size distribution within a large parabolic dune it seems that finer material characterises the wings (d_{90}=303 µm) and coarser sand was found in the head (d_{90}=430 µm). It could be explained by the elevation of these sampling sites: the wing is lower, thus richer in moisture; therefore here the developed vegetation could act as effective sediment trap, resulting in finer sediment deposition due to the increased friction.

Correspondence of grain size analysis and OSL ages

Based on OSL ages and grain size distribution analysis data, grain size characteristics of the transported sediments during the different aeolian phases could be compared. Previous researches (Marosi, 1970, Lóki, 1981) argue that since Late Glacial wind velocity gradually declined, thus the extent of sand movement and also the grain size of deflated material decreased as well. In contrary, plotting OSL ages and d_{90} values of the samples (Fig. 6) shows that older forms are characterised by finer grain size distribution, however, the statistical relation of the two variables is not explicit (R2=0,198).

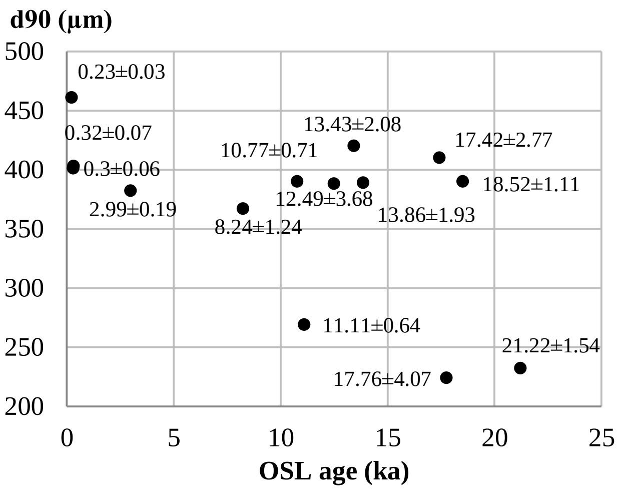

Fig. 6 Connection between OSL age and d_{90} values of grain size distribution curves of the same OSL samples

The youngest (0.23±0.03 ka, 0.30±0.06 ka and 0.32±0.07 ka) samples have very coarse grain size distribution (d_{90} values are 461 µm, 401 µm and 403 µm, respectively), thus these are even coarser than Late Glacial (17-18 ka old) sands. The formation of the 17th-18th c. hummocks is probably due to human activity. At the time of the first military mapping, the area was a pasture, therefore, possibly as a result of overgrazing the closed vegetation opened and the wind started to deflate the available sand. Probably, due to wind-tunnel effect the wind speed was high, thus coarse material could also be eroded and transported. However, it was transported only a very short distance and deposited soon forming hummocks.

It could be concluded, that if conditions are suitable – dry, open sand surface – the wind is capable of transporting the coarse fraction of sand, despite of the more humid climate since the Last Glacial that allowed the development of a dense vegetation cover (Járainé-Komlódi, 2000). However, in case of disappearing vegetation cover, coarse sand could be transported due to wind-tunnel effect.

The grain size of a sample could also be characterised by the mode of its grain size distribution curve. The plot of modes and OSL ages show a similar trend as d_{90} values and OSL age plots (Fig. 7). Modes of the grain size distribution curves of younger forms gradually increase from 150 µm to 300 µm, suggesting that the younger forms have higher first mode values. However, the statistical relation of the two variables is ambiguous, as correlation coefficient for the dataset is only R=-0.67. This is partly because samples with similar age show varying mode values as during an aeolian phase in different parts of the region sediments was deposited under different energy conditions and various sand availability.

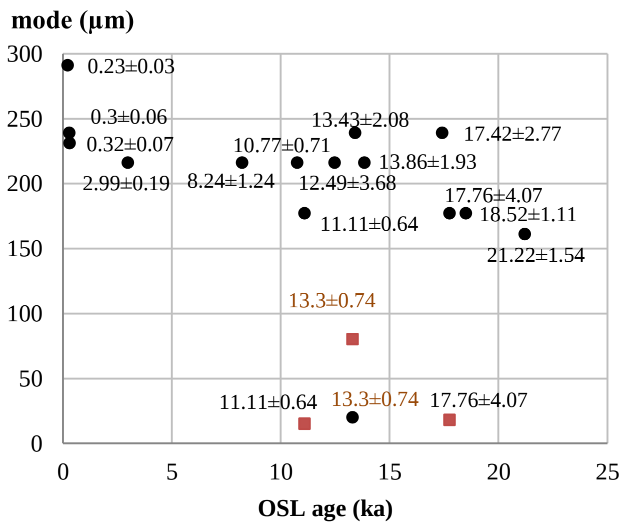

Fig. 7 Connection between OSL ages of the samples and their grain size distribution curve's mode values (black – first mode; red – second mode)

Second modes of the samples refer to secondary processes besides aeolian activity. For example on stabilised aeolian sand surfaces soils can develop, winnowed fine sand in dust can accumulate in leeward areas or variations in ground water level can locally concentrate fine particles and intensify weathering (Profile D5, K7 and K5).

Sorting of a sample was expressed by the difference of d_{75} and d_{25} values, where smaller sorting value refers to better sorted sediment. The correlation between OSL ages and sorting was also examined (R2=0.742, Fig. 8). The younger samples are less sorted than older ones. It refers to extensive and probably longer sand movement periods (Báldi, 1978) during older, climate induced aeolian activity phases. In contrary, during human induced, young sand movement periods the locally disturbance enabled just limited sorting process, as the material was transported within a very short distance which was not sufficient for sorting the sediment.

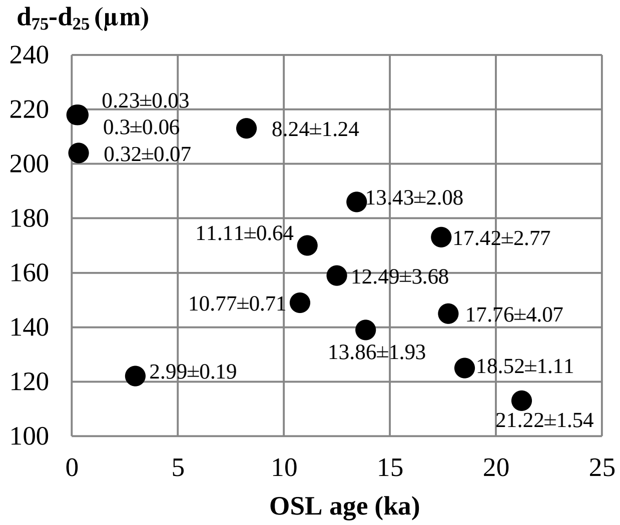

Fig. 8 Connection between OSL age and sorting value of the samples

CONCLUSIONS

In the studied profiles sandy and finer grained layers alternated. Probably during aeolian activity sandy material was deposited, whilst during humid phases finer material was formed due to increased weathering in swamps and soils. OSL data proved several sand movement periods when the finer layers were covered by sand.

The material of large parabolic dunes, simple dunes and hierarchy level 1 dunes is getting finer towards south, in accordance with the grain size changes of the alluvial fan. The grain size distribution of smaller, elevated and younger dunes is determined predominantly by local factors, such as grain size characteristics of source material and wind-tunnel effect. Similar results were found in North China, where the grain size distribution of sand dunes also became finer in the deposition direction of alluvial fan in the substrate (Zhu and Yu, 2014). Liu et al. (2014) and Zhu et al. (2014) concluded that sediment characteristics are predominantly determined by the source material, therefore sand reworked from deeper layers of the alluvial fan can form small in size but coarse in grain dunes. This phenomenon was also observed in Inner Somogy.

The d_{90} values show that the grain size is not finer in younger forms, as it was suggested in earlier studies (Marosi, 1970), on the contrary, it is coarser. Mode values of the grain size distribution curves also prove coarser sand in younger dunes. This can be a result of increased wind energy due to wind-tunnel effect, or of coarser source material. Similarly increasing grain size distribution was described in the Carpathian Basin on the Maros alluvial fan by Sümeghy (2014), where Pleistocene fluvial sands are finer grained than Holocene sediments, which is a result of increased energy of the river and therefore coarser sediment load. This indicates that during Holocene not only in fluvial, but also in aeolian environment the transport capacity increased. Moreover, in Inner Somogy based on d_{75}-d_{25} values, younger samples are poorly sorted, presuming short aeolian periods.

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