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DUNE HIERARCHY AND MORPHOMETRIC CLASSES OF THE PARABOLIC SAND DUNE ASSOCIATION OF INNER SOMOGY, HUNGARY

Abstract: Inner Somogy in Southwest Hungary is covered by a complex system of parabolic dunes and elongated ridges formed by northerly winds. The aims of the research were to classify the positive aeolian forms based on their morphology, and to describe their spatial distribution. A small scale study area (No. 1) was chosen to classify the forms. By zooming out, the same evaluation was carried out on a larger area (No. 2). Finally, the same methodology was applied to all dunes of the whole region (No. 3).

Based on their hierarchy, the forms were divided into four levels. On No. 1 only one mega-form with three superimposed hierarchy levels appears. On No. 2 all four hierarchy levels appear only in the southeast, in an accumulation–transportational zone, while the northwestern part of the study area could be considered as an erosional–transportational zone. The region No. 3 is characterized by a transportational matrix and three accumulation zones.

Morphometric measurements were carried out, measuring the area (A), arc length (L_{arc}), chord length (L_{chord}), average width (A/L_{arc}) and curvature (L_{arc}/L_{chord}) of each positive, accumulation aeolian forms. Based on the parameters the dunes were grouped into seven classes. At test site No.1 the hierarchy levels and the morphometric classes are in agreement, but in study area No.2 and No.3 this statement is valid only for the accumulation zones where large dunes appear. The transportational zones of study areas No. 2–3 are characterized by medium-size and elongated dunes, but their hierarchy level is not in connection with their morphometry.

Key words: aeolian forms, dune morphometry, dune hierarchy, classification, parabolic dunes, Inner Somogy

INTRODUCTION

Up to date, most of the aeolian research focused on arid zone forms: their classification, development and their response to environmental changes (e.g. wind direction, sand supply, moisture availability); however, there is an increase in the number of investigations carried out in semi-arid and temperate sand areas.

Descriptive studies on aeolian dune types were carried out mainly in the deserts of Africa and North America (McKee 1979; Pye, Tsoar 1990; Cooke et al. 1993; Thomas 2011). Recently more and more researchers focus on the triggering factors of dune formation (Warren, Allison 1998; Wang et al. 2002; Dong et al. 2009; Hesse 2011; Barchyn, Hugenholtz 2012), and modeling dune development (Kocurek, Ewing 2005; Derickson et al. 2008).

Based on their geographic location, the semi-arid sand dune areas can be divided into two groups: coastal and inland sand areas. The primary coastal forms are foredunes (height: max. 30 m), which form on the beach from sandbars. Further inland higher (50–70 m) migrating backdunes develop, these can transform into a parabolic dune system (Thomas 2011). Several dune types are described within these systems, many are related to coalescence and different hierarchy levels: simple, compound, digitate and coalescent compound parabolic dunes, simple barchans, isolated barchanoid ridges, and coalescent compound barchanoid ridges (Tastet, Pontee 1998). Crescentic coastal dunes were formed by unimodal winds, while linear elongated ridges by bimodal ones (Chase, Thomas 2006), and as their width decreases their height increases (Labuz 2005). J. D. Girardi and D. M. Davis (2010) stated that fragmentation and reworking of dunes, apart from environmental elements, can also occur due to the effect of neighboring forms as off-axis blowouts cause off-axis growth and migration.

Inland semi-arid aeolian areas form on alluvial fans, floodplains and on the bottom of basins. In these areas the types and development of dunes were described (Cholnoky 1902; Kádár 1966; Borsy 1961, 1991), as well as their classification by sediment supply, dynamics, position of wings and symmetry were reported (Wolfe, David 1997; Lemmen et al. 1998; Hugenholtz et al. 2009; Kiss et al. 2009). The geomorphology of the inland aeolian regions is characterized by blowout–residual ridge–hummock form-assemblage (Cholnoky 1902; Kádár 1966), simple and compound parabolic dunes of several shapes (U–V forms, hemicyclic, lobate and elongate), and transverse dunes (Drenova 2006; Rebollal, Pérez-González 2008; Kiss et al. 2009; Kilibarda, Blockland 2011). It was determined that the simple dunes consist of material blown out from deflationary depressions, and the coalescence of these forms results in the formation of compound parabolic dunes, which indicates the active role of sparse vegetation (Rebollal, Pérez-González 2008). In accordance with elevation, compound parabolic dunes appearing on high surfaces gradually transform into transverse dunes, then into sand sheets as the surface becomes lower (Rawling et al. 2008). Markewich et al. (2009) argue that the winds building the elongated dunes were stronger or more stationary than those which accumulated crescentic dunes. In some areas sand sheets were found to be the most widespread aeolian forms (Gozdzik 2000; Drenova 2006; Rebollal, Pérez-González 2008) and their material was transported from a relatively large distance (Gozdzik 2000).

The correlation of dune types to aeolian activity periods, and therefore to Quaternary climate phases and human impacts can help understand the triggering factors of dune formation. The development of aeolian dunes is often related to cold and dry climate periods, changes in regional wind pattern and lake-level fluctuations (Arbogast et al. 2010). In populated and cultivated areas, formation of the sand dunes can be more influenced by human activity than by climate. Grazing, tillage, forest clearance and other disturbances of the vegetation can locally lead to destabilization of aeolian forms, inducing morphological alteration of the older dunes or development of new ones (Kuzucuoglu et al. 1998; Drenova 2006; Forman et al. 2009; Petric 2009; Kiss et al. 2009, 2012; Moskalewicz 2012).

According to Z. Borsy (1991), climate-induced aeolian activity in the Carpathian Basin occurred mainly during the Pleistocene, as since the Preboreal phase the surface has been stabilized by vegetation. In the largest Hungarian sand areas (Nyírség and Danube Tisza Interfluve), Holocene aeolian activity was dated by radiocarbon and OSL measurements (Lóki, Schweizer 2001; Ujházy et al. 2003; Kiss, Sipos 2007; Kiss et al. 2012). The data shows that in several areas the sand movements resulting from overgrazing, crop farming or forest clearance occurred mainly during the Subatlantic phase.

In the southwestern part of the Carpathian Basin, in Inner Somogy the development of alluvial fan terminated at the beginning of the Würm (Marosi 1970) or at the beginning of the Quaternary (Ruszkiczay-Rüdiger et al. 2011), thus aeolian activity could take place afterwards. As this region has almost the highest precipitation within Hungary, the dense vegetation could effectively impede the Late Pleistocene and Holocene aeolian activity (Marosi 1970). However, according to S. Marosi (1970) the superimposed dunes indicate several aeolian phases; and during the younger sand movements only the heads of dunes were reworked, thus older forms are always larger and at a lower elevation than younger ones. Consequently, the extension of sand movement must have decreased gradually, as the large dunes were divided and several dune generations (hierarchy levels) developed. According to S. Marosi (1970) and M. Pécsi (1962, 1997), periods of aeolian activity took place during the Pleistocene, because the iron-pan layers are of ice-wedge shape which was probably formed during glacials. Thus they concluded that the surface has been stable since the Pleistocene, and aeolian activity did not occur after the Late Glacial Maximum. However, the dunes are not eroded by run-off and only slightly developed soils formed under the closed forest, which suggests a relatively recent dune development and contradicts the earlier findings (Marosi 1970). Besides, the morphology described by J. Lóki (1981) does not refer precisely to hierarchy levels, as on his geomorphological maps the number of superimposed dunes is not visualized.

The aim of this study is to reconstruct the aeolian environment of the region by analyzing the spatial pattern of the positive (accumulation) aeolian forms. Our purpose is to determine the shape and size of the dunes, and to determine the original sand supply, wind direction and energy conditions of the environment during the dune formation. Further aim was to determine the possible number of main aeolian phases, based on the superimposition of dune generations (hierarchy levels). Therefore we intended to analyze the spatial distribution, agreement between hierarchy and morphometric classes of positive, accumulation aeolian forms in East Inner Somogy. Based on this study representative sampling sites for optically stimulated luminescence dating could be selected.

RESEARCH AREA

Inner Somogy is situated in the Carpathian Basin, in the southwestern part of Transdanubia, southwest from the Lake Balaton. Two joined sand areas are partly divided by the Marcali Ridge stretching from north to south (Fig. 1).

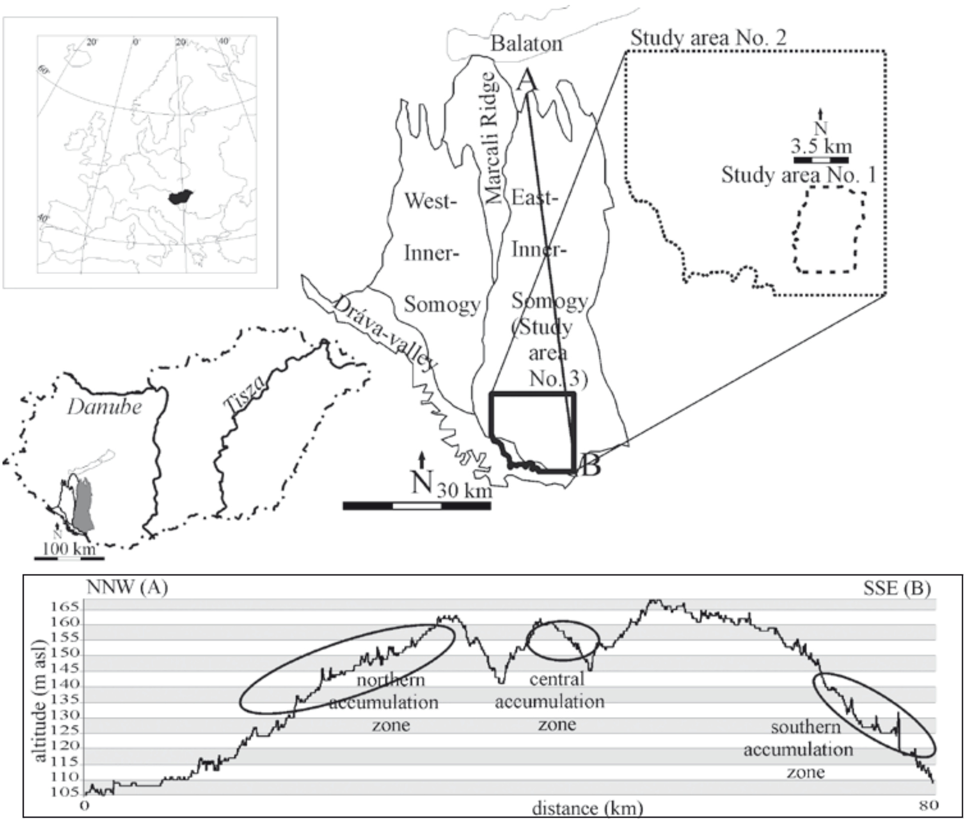

Fig. 1. Location of the study areas. The smallest is the study area No. 1 (21.4 km^2), larger is the study area No. 2 (245.4 km^2), but the whole region is covered by study area No. 3 (1610.1 km^2). The longitudinal section represents the elevation conditions of the region, and the spatial distribution of accumulation areas

The basement of the region consists of faulted, vertically shifted and eroded Variscan blocks (M a r o s i 1970), which were covered by sediments of various thickness from the Pannonian Sea and the Lake Pannon (S ü m e g h y 1953). The development of the area was described rather differently by different authors. According to L. Á d á m et al. (1981) during the Pliocene and Early Pleistocene the Danube and its tributaries filled up the area building an alluvial fan. After the Danube had changed its direction and abandoned the area smaller streams ran towards south in the meridional valleys. Aeolian activity became dominant during the Würm (M a r o s i 1970), when the prevailing northern winds eroded the fluvial sediment, and as the result of transportation the sand became finer towards the south (L ó k i 1981). During the Holocene formation of gullies and valleys was widespread (M a r o s i 1970). According to S. M a r o s i (1970) the meridional valleys are of tectonic origin, but L. F o d o r et al. (2005) could not detect either Neogene folding or signs of faulting in the substrate. On the contrary, E. T h a m ó - B o z s ó et al. (2010) found signs of Neogene tectonism in the Somogy Hills, but did not investigate them in Inner Somogy. K. S e b e et al. (2011) emphasized the importance of aeolian processes and described the whole geomorphology of the region as a yardang system, however, they did not study the development of sand dunes.

In the early twentieth century J. C h o l n o k y (n.d.) described a central deflation hollow in Inner Somogy, and an entangled accumulational area of hummocks in the south. S. M a r o s i (1967, 1970) mapped a blowout–residual ridge–hummock system, and described superimposed dune generations. J. L ó k i (1981) prepared a large-scale (1 : 100,000) geomorphologic map of Inner Somogy, indicating a complex system of dunes and ridges. He also described wind holes, oval-shaped and elongated hummocks, and asymmetric parabolic dunes. Based on OSL data the aeolian activity of the region was dated back to the Dryas stadials, to the Boreal phase and historical times (K i s s et al. 2012).

Today the mean annual temperature of the region is 10–11°C (T_{Jan}= –1°C, T_{Jul}= 20–21°C, Á d á m et al. 1981). The annual precipitation varies between 700 and 800 mm, which is 150–200 mm higher than in other Hungarian sand dune areas. The direction of the prevailing wind is northerly, however SW winds are also common. Typical wind velocity is 2.5–3.5 m/s, which is insufficient to initiate sand movement in the current environment (M a r o s i, S o m o g y i 1990). The potential natural vegetation of the region is dense hornbeam-oak forest with juniper (I v á n y i, L e h m a n n 2002). The region has been populated since the Iron Age, thus human impact dates back to that time (Z a t y k ó et al. 2007). The wetland areas were drained, artificial canals were built and fish-ponds were created. Lakes, marshes and alder-swamps remained in remote interdune depressions.

The research was carried out at three study sites (Fig. 1). The smallest is the study area No. 1 (21.4 km^2), which is located in the southern part of Inner Somogy, dominated by depositional (positive) forms. It represents an area of accumulation, where superimposition and dune hierarchy levels could be studied in detail. The study area No. 2 is larger by one order of magnitude (245.4 km^2) and includes area No. 1 and its surroundings. It represents the erosional-transportational and accumulation zones, and the dunes with different size and shape reflect the dynamism of the development of the area. Finally, the study area No. 3 covers the whole region of East Inner Somogy (1610.1 km^2) allowing detailed investigation of aeolian processes in a wider environment, where the spatial pattern of different zones could be studied. The central part of Eastern Inner Somogy is the highest (ca. 190 m a.s.l.), while surface descends to 100 m a.s.l. towards the Lake Balaton in the north and the Dráva River in the south (Fig. 1 — longitudinal section).

METHODS

The positive, accumulation aeolian forms were identified on 1 : 10,000 topographic maps using ArcGIS. Only the forms located entirely within the study site were evaluated. The superimposition of the dunes determined their hierarchy levels. The megaforms belong to the first hierarchy level, as they are the most complex landforms: they have deflation and accumulation parts, and they could be the combination of different dune types (complex dune), or coalescence of the same forms (compound dune). Dunes of the second hierarchy level build the megaforms, or form the basis of other dunes. The level 2 dunes are located on the heads, wings or blowouts of the megadunes. The third hierarchy level is superimposed on level 2, and level 4 is superimposed on some of them, but some level 3 dunes cannot be further dissected. None of the dunes in the hierarchy level 4 can be divided further and appear homogenous at the given scale. Simple dunes are not superimposed on other dunes, and no other dune was formed on them.

During the morphometric analysis the area (A), periphery (P), arc length (L_{arc} = length along the crest between the terminus of the wings), and chord length (L_{chord} = the shortest distance between the terminus of the wings) for each form were determined (Fig. 2). The curvature (L_{arc}/L_{chord}) refers to the shape of dunes (crescentic or elongated forms) and to the dune migration rate. Average width (A/L_{arc}) characterizes sediment availability during dune formation: dunes are filled if the sand supply is abundant, and with the decreasing amount of sand, partially filled or unfilled forms develop.

The dunes were classified based on the distribution curves of the morphometric parameters (Fig. 3). The first step of the classification was the identification of non-crescentic (linear) dunes, where the L_{chord} could not be defined. The rest of the dunes were classified based on their L_{arc} value, which indicates the dune size. Within these classes dunes were further divided based on their in-filling (A/L_{arc} ratio, Fig. 3) indicating sediment supply, however, the smallest crescentic forms (L_{arc} ≤160 m) were not classified further.

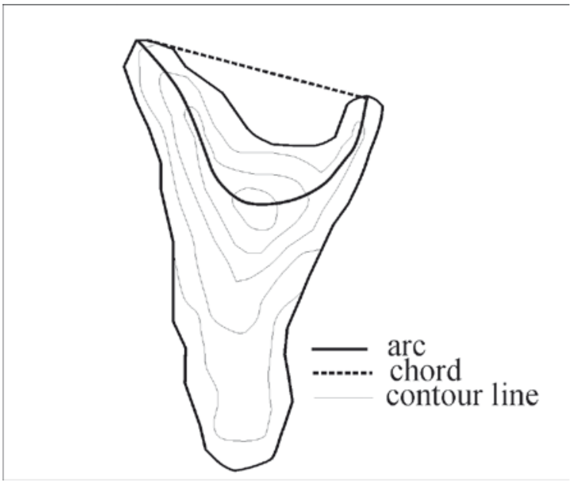

Fig. 2. Arc and chord of a parabolic dune

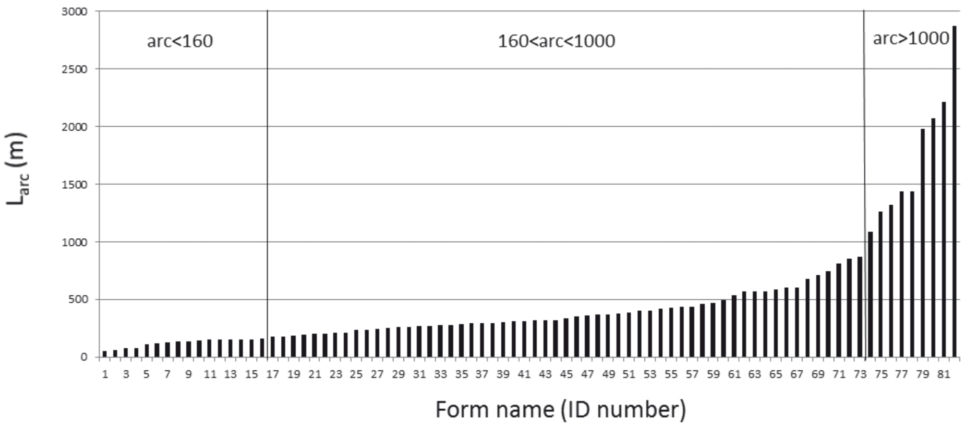

Fig. 3. Distribution curves of L_{arc} of the dunes in the study area No. 1

RESULTS

First, results of the hierarchy analysis are presented for the three study sites (zoom-out approach), then the results of the morphometric analysis are discussed, but only for the largest (No. 3) site.

DUNE HIERARCHY LEVELS

In the study area No. 1 the base of the dune system is a megadune (A = 6 km^2), which covers most of the site (Tab. 1). This megadune represents the hierarchy level 1, as superimposed dunes developed on it (Fig. 4). Dunes belonging to the hierarchy level 2 developed on the head or wings of the megadune, or they are

Table 1

Parameters for each hierarchy levels at particular study sites

	Study area No. 1				Study area No. 2				Study area No. 3			
Hierarchy level	Ratio (%)	A_{av} (km^2)	$L_{arc(av)}$ (m)	$L_{chord(av)}$ (m)	Ratio (%)	A_{av} (km^2)	$L_{arc(av)}$ (m)	$L_{chord(av)}$ (m)	Ratio (%)	A_{av} (km^2)	$L_{arc(av)}$ (m)	$L_{chord(av)}$ (m)
Level 1	1.18	6	10939	2315	0.84	5.8	10600	3200	0.18	4.94	8329	2429
Level 2	12.94	0.4	2191	819	40.93	0.2	1000	322	82.90	0.076	601	190
Level 3	69.41	0.03	377	151	52.32	0.03	345	97	15.28	0.025	307	96
Level 4	16.47	0.003	225	128	5.91	0.01	189	90	1.63	0.013	210	96

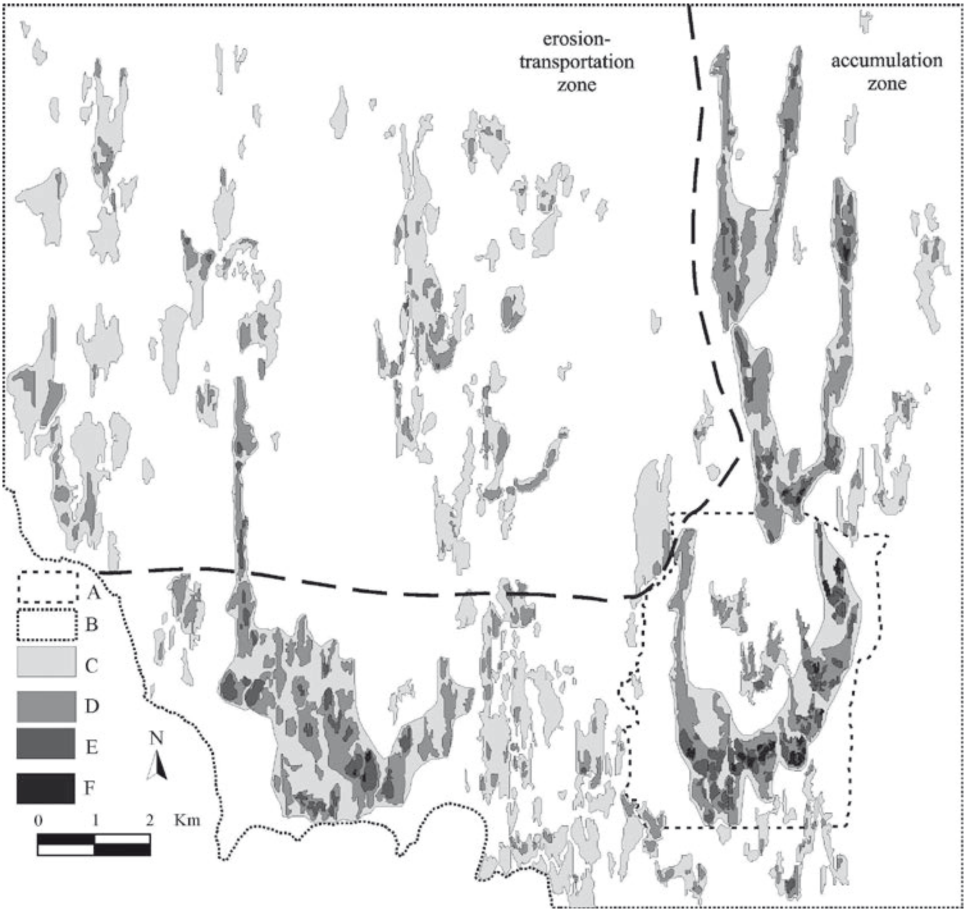

Fig. 4. Hierarchy levels of the dunes. A — study area No. 1, B — study area No. 2, C — hierarchy level 1, D — hierarchy level 2, E — hierarchy level 3, F — hierarchy level 4

located in its blowout. The average area of these dunes is one order of magnitude smaller (A_{av} = 0.4 km^2) than that of the megadune. These dunes are also complex: they are dissected by blowouts or smaller forms are superimposed on them. The average size of dunes in level 3 (A_{av}= 0.03 km^2) is also one order smaller than the size of the previous level, where level 3 is superimposed on the dune heads. The dunes of hierarchy level 4 are superimposed on the previous forms. These dunes are the smallest (A_{av} = 0.003 km^2), and morphologically homogeneous forms (Fig. 4), which appear in groups on the highest surfaces (heads) of larger dunes.

In the study area No. 2 the average area of the dune hierarchy levels also decreases by one order of magnitude (Tab. 1). In this area the dunes form four complex and compound megadunes in the southeast part of the area, where all four hierarchy levels appear. In the northwestern part of the area simple dunes are dominant, and some are superimposed, but they do not form a megadune (Fig. 4). The number of dunes in the southeast (325 dunes, representing 68.6% of all dunes) is significantly higher than in the northwest (149 dunes, 31.4% of all dunes). The area covered by dunes is also different, as it is 40.2% in the southeast and 15.4% in the northwest. Thus the southeastern part could be

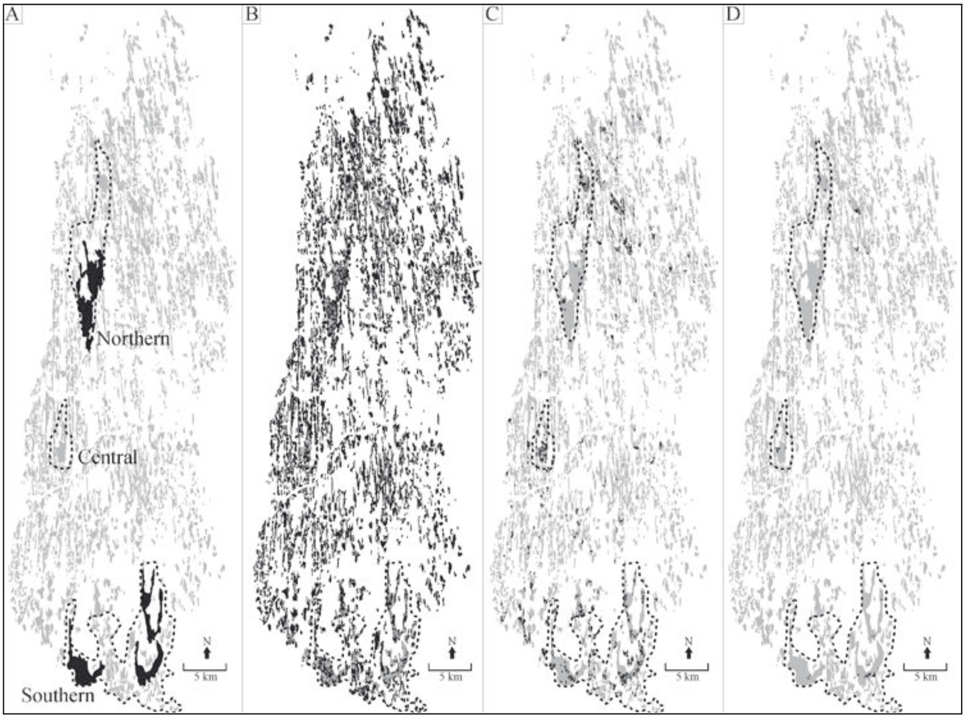

Fig. 5. Hierarchy levels of the dunes in the study area No. 3. A — hierarchy level 1, B — hierarchy level 2, C — hierarchy level 3, D — hierarchy level 4. (The accumulation areas are outlined by dashed lines, the rest of the dunes are indicated by grey colour)

Table 2

Proportion (%) of dune classes on different study areas

			Study area No. 1	Study area No. 2	Study area No. 3
Parabolic dune	large	partially filled	3.5	4.9	1.0
		unfilled	10.6	9.3	8.1
	medium	filled	11.8	14.3	20.2
		partially filled	25.9	17.1	22.0
		unfilled	22.4	9.9	11.3
Hummock			18.8	10.5	11.2
Wing fragment			7.0	34.0	26.2

considered as an accumulational zone, while the northwestern area is more of an erosional/transportational zone.

In the largest study area (No. 3) the average area of dunes still decreases by one order of magnitude with each level (Tab. 1). However, the dominance of simple dunes is typical, as ca. 75% of all dunes are simple with areas between 0.0006–0.96 km^2. The megaforms (hierarchy level 1) appear in three zones, in the northern, central and southern parts of the area (Fig. 5), where complex and compound parabolic dune systems are coalesced. Level 2 forms are the most common in study area No. 3 densely covering the region. Level 3 dunes do not appear on the edges and in the central, elevated part of the area (Fig. 5), while level 4 forms are limited to three zones and surrounding surfaces. These accumulation zones are relatively elevated above their surroundings (Fig. 1 — longitudinal section) and the average dune density here is 5.1 form/km^2 with 59% of the area covered by dunes. The rest of the study area is typified by the dune density of 2.5 form/km^2, and the simple forms cover only 16%.

MORPHOLOGICAL CLASSIFICATION

Based on the morphometric analysis seven classes were created, all of which are present in the largest study area No. 3 (Fig. 6).

The wing fragments are elongated, quasi-linear forms, thus the L_{arc}/L_{chord} ratio could not be defined. Their size varies considerably ($A = 0.58$ m^2–0.693 km^2; L_{arc} = 34–5630 m). Large numbers of forms belong to this class (26% of all dunes), but cover only 3.9% of the area. The wing fragments are spread all over the study area and they appear in hierarchy levels 2–4, indicating that they formed during repeated periods of the activity of aeolian processes.

The most typical forms of the study area, parabolic dunes, were classified based on their size and the degree of in-filling (sediment availability). The *large,*

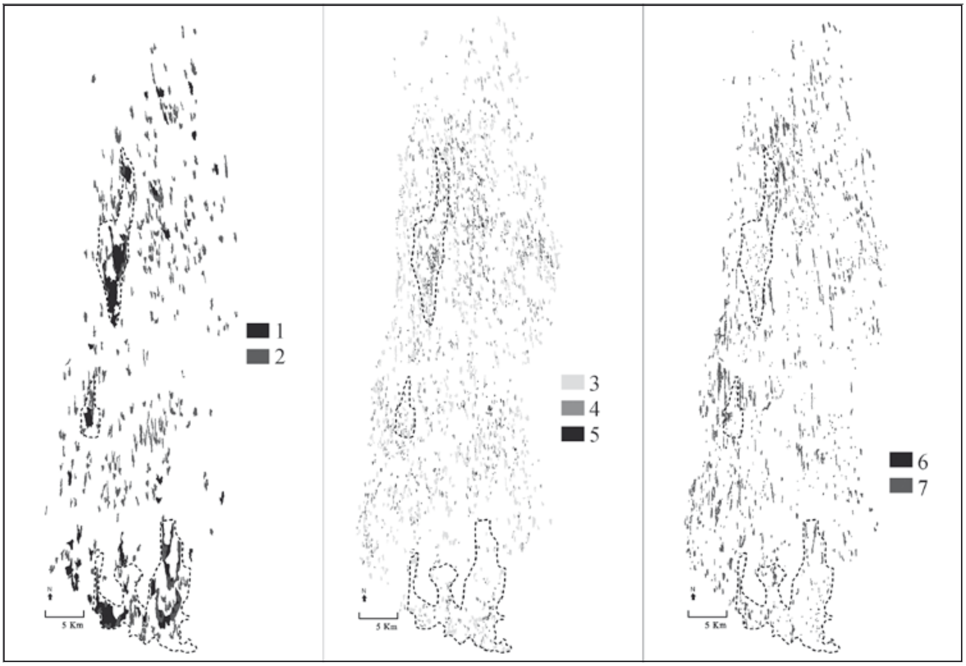

Fig. 6. Dune classes in the study area No. 3 (the accumulation areas are outlined by dashed lines). 1 — large, partially filled parabolic dunes 2 — large, unfilled parabolic dunes 3 — medium-size filled parabolic dunes 4 — medium-size partially filled parabolic dunes 5 — medium-size unfilled parabolic dunes 6 — hummocks 7 — wing fragments

partially filled parabolic dunes (L_{arc} = 1024–12 912 m, A/L_{arc} = 252.96–1245.88 m) indicate moderate sand supply. This dune type constitutes merely 0.95% of all dunes, but covers 4% of the study area. All the megaforms (level 1) belong to this class, but some of them belong to the hierarchy level 2 and 3. The large, partially filled parabolic dunes are widespread in the northern, central and southern accumulational zones.

The *large, unfilled parabolic dunes* (L_{arc} = 1002–6391 m, A/L_{arc} = 45.75–249.35 m) indicate limited sand supply during their formation. Almost 8% of all dunes belong to this class, but due to their unfilled shape, they cover only 4.9% of the study area. Almost all of them belong to hierarchy level 2, though in the area of megaforms, some members of this class appear in hierarchy level 3. The members of this class are scattered all over the study area, however they are somewhat more widespread in the accumulational zones.

The medium-size parabolic dunes (1000 m >L_{arc} >160 m) were further classified to three sub-classes based on the A/L_{arc} ratio. The *medium-size filled parabolic dunes* refer to abundant sand supply during their formation. Representing ca. 20% of all dunes, the members of this class have diverse size (L_{arc} = 161–997 m, A/L_{arc} = 110.32–1023.29 m) and occupy 4.7% of the study area. They are scattered all over the study area, some are located on the heads of large parabolic dunes, and some appear in rows perpendicular to wind direction, but the majority (ca. 90%) belong to hierarchy level 2.

The medium-size partially filled parabolic dunes (L_{arc} = 161–998 m, A/L_{arc}= 62.01–109.9 m) developed when the sand supply was moderate. They are the most abundant forms (22%), though due to the reduced amount of accumulated sediment, they cover only 2.3% of the study area. These dunes appear in hierarchy levels 2–4, though most of them (90%) belong to level 2. Many are found on the windward side of the accumulation zones.

Sediment supply was limited when the *medium-size unfilled parabolic dunes* (L_{arc} = 161–995 m, A/L_{arc} = 21.74–6198 m) formed. They represent only 11% of all forms and cover only 0.5% of the study area. The members of this class occur across the study area, but many are located in or upwind of the northern accumulation zone. They mostly belong to hierarchy level 2, but some appear in levels 3 and 4.

The smallest crescentic dunes are *hummocks* (L_{arc} = 28–159 m). They represent only 11% of the forms, and cover only 0.3% of the area. This class often appears in groups on the highest surfaces of larger dunes and mostly builds up the hierarchy level 4.

DISCUSSION

Comparison of the hierarchy levels and morphometric classes revealed that they are in very good agreement at study site No. 1. S. M a r o s i (1970) related hierarchy levels only to the blowout–residual ridge–hummock system. The present study proved the existence of a megadune (hierarchy level 1), which, morphologically, is a large, partially filled parabolic dune (L_{arc} = 10 km). Thus the base of the morphology is not a blowout–residual ridge–hummock system as S. M a r o s i (1970) suggested, but a parabolic form. As this form is the foundation of other dunes, it is probably the oldest form of the site. The head and blowout depression of the megadune are occupied by dunes belonging to the hierarchy level 2. These are mostly large, unfilled parabolic dunes, smaller in size (L_{arc} = 1–6 km) than the megadune, and indicating decreasing wind speed compared to the winds which formed the megadune. Still, the great size indicates strong winds at the time of their development, but their unfilled shape is a sign of limited sediment supply, related to wet conditions or denser vegetation. The medium-size parabolic dunes (L_{arc} = 0.16–0.86 km) belong to hierarchy level 3. Their medium size indicates lower energy wind conditions. Medium-size filled parabolic dunes are superimposed on the elevated heads of larger forms. At such locations the sand was always drier and more mobile, therefore there sand supply was sufficient for the development of these filled dunes. The medium-size partially-filled and unfilled parabolic dunes are mostly located on the wings of larger dunes. As their formation is in close connection with the density of vegetation and the limited sand supply, they indicate that the low–lying wings had less mobile surface than that of the heads, resulting in limited aeolian activity. It also points to the fact, that even within a small distance the vegetation and the moisture of the sand must have been uneven and patchy due to small height differences. The hierarchy level 4 mostly consists of groups of small hummocks superimposed on the heads of larger forms. Their small size indicates limited aeolian activity, and as they appear just on the highest surfaces, they point to aeolian activity in the periods when the lower (wetter) areas were already stabilized by vegetation. The small hummocks and all the members of hierarchy level 4 probably formed a few hundred years ago as a result of anthropogenic disturbance (e.g. overgrazing or forest clearance).

In study area No. 2 the hierarchy levels and morphometric classes are in agreement only in the southeastern part. Here, on the large, unfilled parabolic dunes (level 2), medium-size filled and partially filled parabolic dunes (level 3) are superimposed; their elevated heads were reworked by wind during a later aeolian phase creating hummocks (level 4). In the northwestern part of this study area the hierarchy of the dunes is less complex, superimposition is less characteristic as many isolated wing fragments and level 2 medium-size parabolic dunes with increasing degree of in-filling rate downwind are located here. Thus the northwestern part probably acted as a source area, the deflated material was transported southward (windward) to the southeast accumulation zone (Fig. 4). Therefore, by zooming out the erosional-transportational and accumulation-transportational areas could be identified.

Most of the study area No. 3 (89.7%) is interpreted as a transportational matrix (Fig. 5), which consists of hierarchy levels 2 and 3, with medium-sized partially filled parabolic dunes and wing fragments (Fig. 6). These forms cover only 16.4% of the area, thus most of the territory acted as a source area, similar to the erosional-transportational zone of study area No. 2. The deflated and migrating material was deposited southward, in three large, superimposed and coalescent dune systems (Fig. 1 – longitudinal section, Fig. 6). J. Lóki (1981) identified the dunes and the mentioned accumulation zones in Inner Somogy, but did not define relations between them or any hierarchy levels. In other temperate aeolian areas, similar dune generations were studied and described (Rebollal, Perez-Gonzalez 2008; Dong et al. 2009; Kilibarda, Blockland 2011), however, their investigations covered smaller areas at less detailed scales than our research. It enables us to reveal the spatial characteristics and to reconstruct the interactions of the aeolian environment considering a wider neighborhood of a sand dune area.

In these accumulation-transportational zones all four hierarchy levels appear. In the study area No. 3 three such zones were identified in the northern, central and southern parts (= study areas No. 1–2) (Fig. 1 – longitudinal section). These accumulation zones constitute only 10.3% of the area, but here the average dune density is 5.1 form/km^2, and dunes cover 59.1% of the area. The northern zone close to Lake Balaton has the highest dune density (8 features/km^2), and greatest dune cover (67.4%). The central zone is the smallest, but has a high dune density (5.6 features/km^2), and 55% of its area is covered by forms. The southern zone has the smallest dune density (3.7 features/km^2) though 54.7% of the area is covered by dunes almost the same as in the central accumulation zone. According to these data dune density and therefore the superimposition of dunes decreases downwind (southward).

Comparison of the location of accumulation zones with the hydrology of the area showed that downwind of each zone a stream or a river flows in an east-west valley (from north to south: Szabási Rinya, Lábodi Rinya and Dráva River). Probably the southward migrating dunes were stopped by these valleys: as their floors were always more humid and the vegetation was denser, thus the surface was less mobile. As the possibility of dune migration was impeded here, it resulted in the development of superimposed compound and complex forms. The central accumulation zone is the smallest, probably because the area available between the neighboring valleys was limited. In contrast, the southern zone is the largest, but the dunes are less superimposed (3.7 form/km^2), maybe because a larger vegetated area along the Dráva River stabilized the dunes further north.

Depending on the size of the study areas the erosional and accumulational zones show a different pattern. The study area No.1 represents a single but extremely complex megadune with several levels of superimposition. By zooming out, in the study area No. 2, the identification of an erosional-transportational zone was also possible, as in the northwestern part dune density and complexity were lower than in the southeastern accumulation area. In the whole studied region (area No. 3) three accumulational zones are embedded in a transportational matrix. This pattern is regularly repeated windward, thus some of the region may have acted as a sediment source and as a transportational area, while other areas accumulated the sand arriving from these nearby deflational areas. Based on electron-microscopy study (Lóki 1981), a short transport distance of the sand was determined, this finding is supported by the location of erosional-transportational zones identified in our work.

CONCLUSIONS

Altogether four hierarchy levels were identified in East Inner Somogy. The dunes within each level differ in their size (area), as there is one order of magnitude difference in the average extent of each hierarchy level. During the morphometric analysis four main classes (large and medium-size parabolic dunes, hummocks and wing fragments) were identified, and based on the degree of in-filling subclasses were determined referring to sediment supply. These groups are related to at least four aeolian development phases.

Formerly an OSL dating was carried out on dunes of the site No. 2, associated with four aeolian phases (Kiss et al. 2012). According to the ages, the large parabolic dunes (hierarchy level 1) were probably formed ca. 15–17 ka ago during the Oldest Dryas, when the open steppe vegetation expanded under cold and dry climate (Gábris, Nádor 2007). The following Bölling/Alleröd interstadials were mild and humid, thus closed deciduous forests could successfully stop the migration of dunes. Presumably during the cool and dry Younger Dryas, characterized by open steppe vegetation, the environmental conditions were favorable for the reactivation of dune development ca. 12–14 ka ago. At this time medium-size parabolic dunes (hierarchy level 2) developed partly of the reworked material of the older and bigger dunes. In the Early Holocene, during the dry Boreal phase (ca. 8 ka ago) another aeolian activity phase resulted in the development of medium-sized parabolic dunes (hierarchy level 3). Thereafter, the surface was stabilized for a long period of time, and the hummocks (hierarchy level 4) were formed in historical times ca. 200–300 years ago.

Aeolian areas often have a repeating pattern downwind. In Inner Somogy, accumulation zones appear in every 15–20 km, where migrating sand was deposited due to changes in energy conditions and probably also due to higher moisture content in relation with nearby valleys. Here dunes are superimposed in hierarchy levels. Their morphometry indicates stationary northerly winds, abundant sediment supply and an important role of scarce vegetation during their formation. To reconstruct the original sand supply and energy conditions during the formation of each hierarchy level, grain–size distribution analysis is needed.

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