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Parabolic dunes and soils of the Curonian Spit, south–eastern Baltic Sea coast

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Abstract Parabolic dunes, their soils, buried soils, and their ecological features, are still poorly understood in Lithuania. The dune sand massif here studied occupies several square kilometres of the Curonian Spit, in the vicinity of the Juodkrantė settlement, and is covered by old-growth forest. The massif of the parabolic dunes was formed as a result of active sand movement and vegetation interaction, which have influence to parabolic dunes formation. Four segments of parabolic dunes have been distinguished, each of them with a different morphology. The fourth, southern one is attributed to dunes of a new generation. The cross–sections of parabolic dunes and their branches identify dune slopes, tops, and steps. The grain–size distribution parameters show the character of aeolian dynamics, because the fine aeolian sand indicates areas where older sand dominates. Places where coarser sand has been deposited are younger. The existence of "steps" or secondary dunes in parabolic dunes is discussed. They were formed as a result of cover by new dunes generation sand. The type of dunes can be identified according to the soil pellicle moisture, which in contemporary and buried soils of the black dunes, is twice the amount of moisture found in the white dunes.

Keywords *Parabolic dunes • Buried soils • Sand grain–size • Pellicle water • Curonian Spit • Lithuania.*

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INTRODUCTION

The dunes of the Curonian Spit, on the south–eastern Baltic Sea coast, are part of the South Baltic sandy belt that is under constant threat of wind, surge, and anthropogenic impact. This research of the Juodkrantė dunes massif attempts to distinguish the areas of old generation sands and younger parabolic dunes with the same morphology. The Curonian Spit dunes were formed from deltaic and alluvial sand during the Yoldia Sea stage (11.2–10.3 kyr BP), and to a lesser extent, were supplied by erosion of the Paleogene sands cropping out at the Sambia Peninsula coasts (Gelumbauskaitė 2010; Gudelis, Klimavičienė, 1993). Sand deposition during pre–historical time extended into the lower reaches of the Nemunas River where some aeolian areas were formed in the western part of Lithuania (Fig. 1).

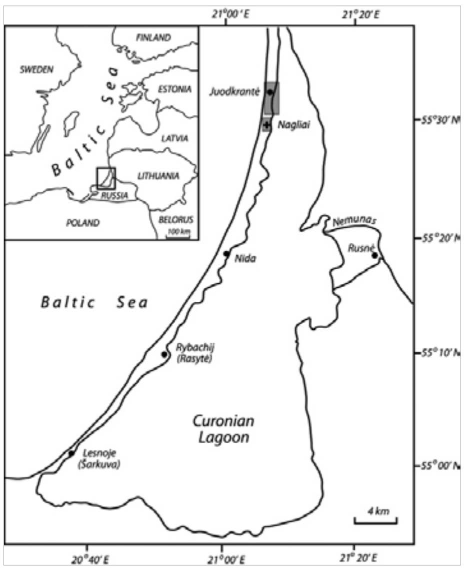

Fig. 1 A sketch of the studied area. Compiled by I. Baužienė, A. Česnulevičius 2011.

The devastation of natural plant life cover that caused the sand expansion on the Curonian Spit started with an invasion of cattle–breeders and has been accelerated by farming and intensive deforestation several hundred years ago (Moe *et al*. 2005). In the Middle Age many villages were buried by sand. The settlements that survived were Juodkrantė, Nida, and Šarkuva (now Lesnoje, Russia). Segments of pines forests in their surroundings acted as natural wind barriers, and helped the survival of these settlements. According to historic maps, the old-growth forest at the localities of Juodkrantė, Nida, and Šarkuva exist for more than 300 years (Gudelis 1989–1990; Paul 1944). However, the relict areas of the old-growth forest now are very small, occupying only a few square kilometres in the vicinity of the Juodkrantė settlement.

The old-growth forest grew on parabolic dunes, which emerged as a result of the interaction of drifting sand and vegetation. Some parabolic dune segments were formed on the Curonian Spit before the movement there of human activity. Later on, the stabilization of aeolian relief created favourable conditions for ecosystem succession, and the so-called black dunes were formed in the Juodkrantė area. These dunes have the morphogenetic features of parabolic dunes, whereas the so-called grey (stable) and white (active) dunes did not have these features (Fig. 2).

Danish, British, and Dutch researchers noticed and emphasised the influence of human activity on the ecological state of the aeolian relief and its degradation. There are some stages indicative of coastal dune formation and degradation (Allen 1982; Arens *et al.* 2004; Carter *et al.* 1990; Clemmensen *et al*. 2007; Jungerius 1990, 2008).

The aim of the present work is to determine the major properties (relief, sediments, and soil features) of parabolic dunes and to reveal the processes of dune massif formation from their morphological features and grain–size composition. Also, a description is given of some properties of soils, which determine the ecological state of the recent dunes. The limits between the old and new dune generations as well the differences of these dune generations are discussed. The main aspects of the history of dune formation that were pointed out by researchers are discussed in the article.

METHODS

A topographic map at a scale of 1:10 000 was used for the analysis of the parabolic dunes. Four cross–sections were chosen to study relevant morphological and morphometric characteristics of the dune massif. Quantitative parameters of the parabolic dunes were estimated from geodetic measurements using *Leica Smart Total Station*. The relief sections across the whole Curonian Spit define the most characteristic dunes with clearly distinguished slopes and tops. Digging sites were chosen on the basis of the dune relief cross–section and morphometric indices. The sand samples for grain–size analysis were taken from different morphological segments in the southern and central parts of the parabolic dunes, on the crests and on slopes of different exposition (Table 1, Fig. 3).

In some cases, the grain–size composition of the samples was compared with the composition of new generation sands. The sands differ in their origin, chemical and mineral composition. In terms of sedimentation, the size and morphological features of grains are of great importance, as they control transportation, accumulation and other processes (Trimonis 2005). The grain–size was determined using the classification of Wentworth (Krumbein, Sloss 1963), and Bezrukov and Lisitzin (1960) (Table 2). Quartiles Q_1, Q_2 and Q_3, a sorting coefficient (S_o), and asymmetry coefficient (S_k) were calculated from the same data (Gradzinski *et al.* 1980). The air–dried samples for precise grain–size determination were analysed using FRITSCH set of 12 sieves with a shaker. The following groups were distinguished according to the sorting results: excellent (1.0–1.23), good (1.23–1.41), medium (1.41–1.74), bad (1.74–2.0) and very bad (>2.0) (Rozhkov *et al.* 1973).

Fig. 2 White dunes sand massif in the Nagliai Reservation as seen from the eastern coast of the Curonian Lagoon. Photo by A.Česnulevičius, August 2010.

Two soil profiles were analysed from the old-growth forest in the parabolic dunes massif (Fig.4, S1, S2). The soil profile in the reforested

Table 1 Characterization of sampling sites. Compiled by R. Morkūnaitė.

Sample, No.	Slope	Dune	Depth, cm	Description
1	Western slope	Jonas (Witches) Hill	20	10 m below the top (50–55 m above sea level), greyish brownish sand
2	Western slope	Jonas (Witches) Hill	25	30 m below the top (30–35 m above sea level), yellowish brownish sand
3	South-west slope	Jonas (Witches) Hill	23	Top of northern arm (23–30 m above sea level), yellowish brownish sand
4	Eastern slope of parabolic dune	Jonas (Witches) Hill	25	20–25 m above sea level, whitish yellowish sand
5	Eastern slope of the southern arm parabolic dune	Ieva (Eva) Hill	37	10–15 m above sea level, whitish brownish sand
6	Eastern slope of hill top	Ieva (Eva) Hill	45	35–40 m above sea level, whitish greyish sand
7	Northern slope	Ieva (Eva) Hill	55	25–30 m above sea level, whitish brownish yellowish sand
8	Western slope	Ieva (Eva) Hill	57	20-25 m above sea level, whitish grey sand
9	Eastern slope	Unnamed hill to north of Jonas (Witches) Hill	27	10–15 m above sea level, brownish yellowish sand
10	Northern slope	Unnamed hill to north of Jonas (Witches) Hill	27	10–15 m above sea level, brownish yellowish sand
11	Western flat slope	Unnamed hill to north of Jonas (Witches) Hill	30	30–35 m above sea level, yellowish greyish sand

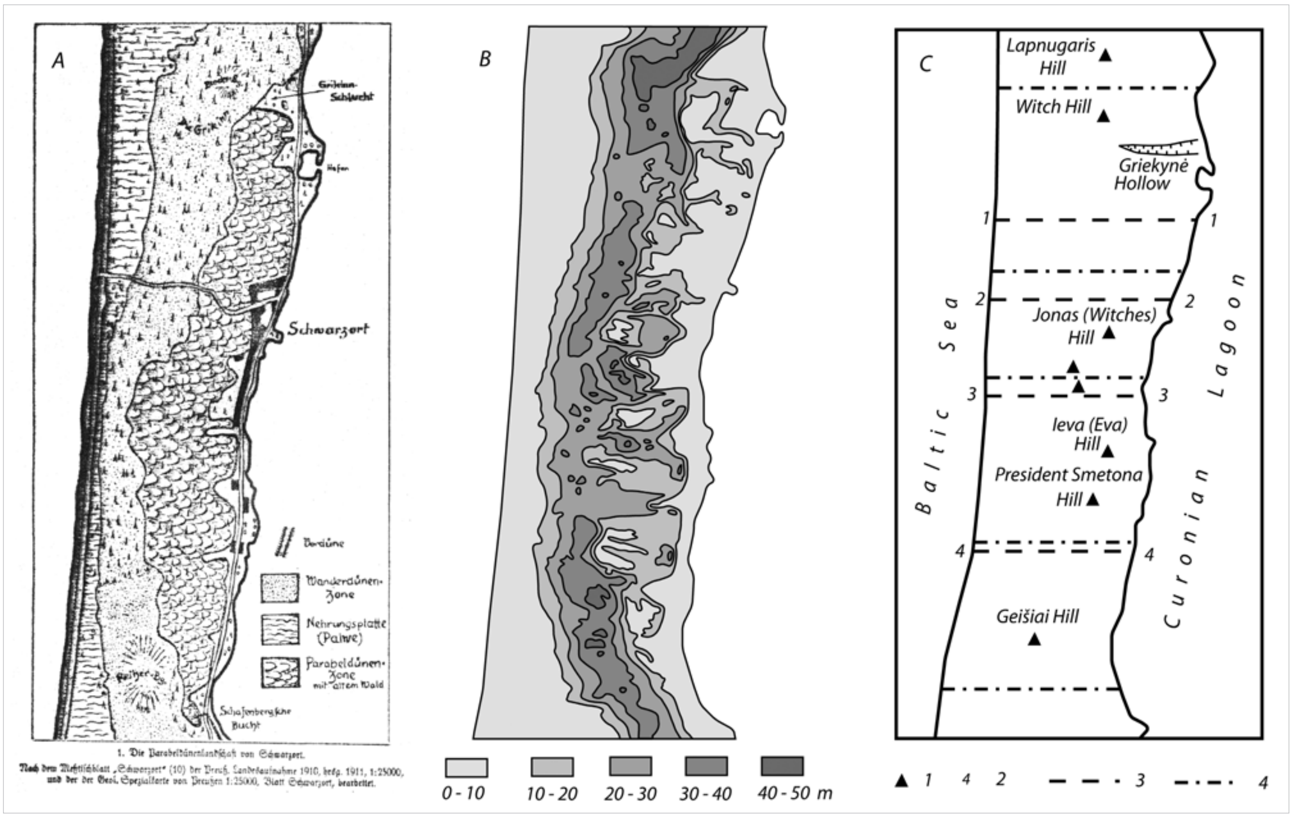

Fig. 3 Studied area: A – Juodkrantė environs with old-growth forest, foredunes, wandering sand and parabolic dunes in 1909; B – morphography of the parabolic dunes; C – cross–section locations and morphological segments. 1 – hills; 2 – numbers of cross–sections; 3 – direction of cross–sections; 4 – boundaries of different morphological segments. Compiled by I. Baužienė, A. Česnulevičius, 2011.

Table 2 Comparison of the grain–size classifications. Compiled by A. Česnulevičius (after M. Repečka *et al.* 1992).

Sediment size: mm	Sediment size: $\phi = -\log_2 mm$	Bezrukov, Lisitsin, 1960		Wentworth, 1922 (Krumbein, Sloss, 1963)	
		Boulders		Boulders	
	-8	Boulders		Cobble	
100	-7	Pebble	Coarse	Cobble	
50	-6	Pebble	Medium	Pebble	
25	-5	Pebble	Fine	Pebble	
	-4	Pebble	Fine	Pebble	
10	-3	Gravel	Coarse	Pebble	
5	-2	Gravel	Medium	Gravel	
2.5	-1	Gravel	Fine	Sand	Very coarse
1.0	0	Sand	Coarse	Sand	Coarse
0.5	+1	Sand	Medium	Sand	Medium
0.25	+2	Sand	Fine	Sand	Fine
0.10	+3	Aleurite	Coarse	Sand	Very fine
0.05	+4	Aleurite	Fine aleurite mud	Silt	Coarse
	+5	Aleurite	Fine aleurite mud	Silt	Medium
0.01	+6	Pelite	Aleuritic - pelitic mud	Silt	Fine
0.007	+7	Pelite	Pelitic mud	Silt	Very fine
	+8	Pelite	Pelitic mud	Clay	Coarse
	+9	Pelite	Pelitic mud	Clay	Medium
0.001	+10	Pelite	Pelitic mud	Clay	Fine
	+11	Pelite	Pelitic mud	Clay	Very fine
	+12	Pelite	Pelitic mud	Colloid	

dunes of the Nagliai Reservation was studied for comparison with the one known in the white and grey dunes southward of the Juodkrantė area. The active specific surface area of the solid phase of soil was determined. It is usually detected by gas adsorption analysis, but in this study, an expedited method was used (Kutilek, Nielsen 1994; Puri, Murari 1964). The soil samples were exposed to a 58% sulphur acid atmosphere until a steady mass was obtained. A continuous water pellicle forms on the surface in a 58% sulphur acid atmosphere. The active specific surface of a solid phase (m^2/g) was adjusted to the pellicle water content (mm) (Sapozhnikov, Shevchenko 1989).

OUTLINE OF PALAEOGEOGRAPHIC DATA

The Curonian Spit is the largest accumulative macroform existing on the southern coasts of the Baltic Sea. Four strips of parabolic dunes extend along the Curonian Lagoon shore, with a total length of 32.6 km. They represent the longest ridge of high (shifting) parabolic dunes in Europe (Povilanskas 2004). The Curonian Spit's present shape was assumed during the Holocene. Starting with the end of the Pleistocene (13.5 kyr BP), the geological history of the Curonian Spit is associated with the development of the Baltic Sea. Intensive erosion of Quaternary deposits followed after a few transgressions and the appearance of littoral drift along the south–eastern coast of the Baltic Sea. The extensive growth of the sandy spit that formed the lagoon took place during several stages of the Baltic Sea formation and at different rates. The process lasted for about 3,000 years (Gudelis 1998), but reached its peak intensity throughout and after the $Litorina_2$ transgression (5–6 m above the present sea level), i.e. the end of Atlantic to beginning of Sub–Boreal (6.0–3.0 kyr BP; Povilanskas 2004).

Studies devoted to the formation of the Curonian Spit and Curonian Lagoon stated that mainly glaciolacustrine and lacustrine processes during the Allerød to Boreal time (13.5–8.8 kyr BP) have formed entire sedimentary complexes. Moreover, fluvial processes were also significant for the development of the Curonian Lagoon. Thus, the palaeochannels incised along the traverses of Kintai–Preila, Dreverna–Juodkrantė, and Alksnynė, demonstrate the activity of fluvial processes during the Ancylus regression phases (Gelumbauskaitė 2010; Gelumbauskaitė, Šečkus 2005).

According to Kabailienė (1967, 2006), the deposits of the Ancylus Lake in the Juodkrantė area reached thickness of >10 m whereas in some other areas it was 3–10 m. This implies that at the time of 10.1–8.8 kyr BP, the studied area was submerged by water, but with a complex of freshwater diatoms. In some Juodkrantė boreholes, the maximal Litorina transgression deposits include re–deposited peat containing marine but also freshwater diatoms (Kabailienė 1967, 1990).

The studied massif of the Juodkrantė parabolic dunes begins in the northern part of the settlement Griekinė Hollow and extends for about four km to the south. The largest width reaches 700 m in the middle part. As is shown on the topographic map, the parabolic dunes of Juodkrantė comprise a rather complicated dune system (see Fig. 4). Three dune chains are composed of parabolic dunes with arms connecting at different angles. The real parabolic dunes of the Juodkrantė area are presented by only those parts of the massif which are covered by 300 year old-growth forest and have no cover of the new generation sand. Such sand occurs in the western and southern parts of the massif. New generation sand, which was blown up, renewed not only the deposits but also forms and, therefore, is considered as a new array of the parabolic dunes.

Thus, according to the data of stratigraphic subdivision (Bitinas *et al.* 2001; Moe *et al.* 2005; Rinterknecht *et al.* 2006), and the radiometric dating of the buried soils (4630–4035 ^{14}C yr BP; 3470–2960 ^{14}C yr BP; 1200–1040 ^{14}C yr BP; 500–280 ^{14}C yr BP) (Gaigalas *et al.* 1991), the aeolian sediments of the Lithuanian coast of the Baltic Sea were subdivided into two generations: an older one, formed at the end of the Atlantic time, and a younger one, formed during the Sub–Boreal period.

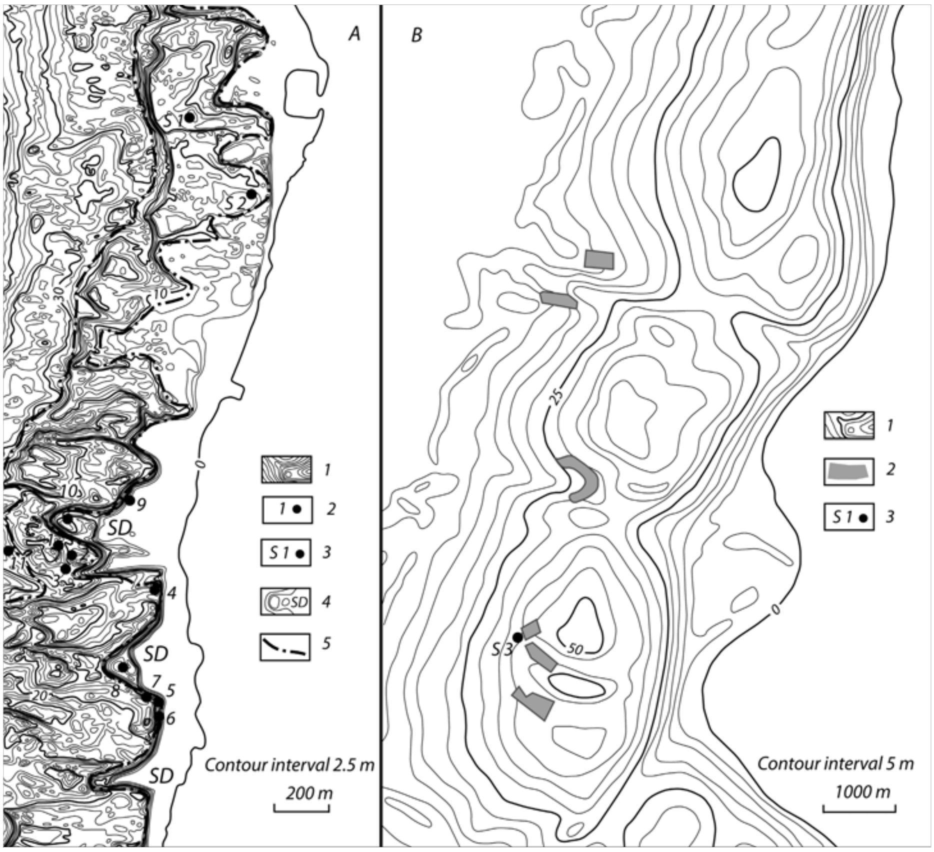

Fig. 4 Fragments of hypsometric maps: A – study area in the environs of the Juodkrantė parabolic dunes: 1 – contour lines; 2 – sand sampling points; 3 – soil profiles location; 4 – secondary dunes, or 'steps'; 5 – eastern and western boundary of old dunes. B – study area in the environs of the grey dunes: 1 – contour lines; 2 – soil outcrops; 3 – soil profile location. Compiled by I. Baužienė, A. Česnulevičius, 2011.

According to previous investigations, the massif of the Juodkrantė parabolic dunes has no buried soils (soil pits were dug to a depth of 2 m) (Gudelis, Michaliukaitė 1976). However, in this study buried soils were found on the walls of prospecting pits that supply the available research material with new facts.

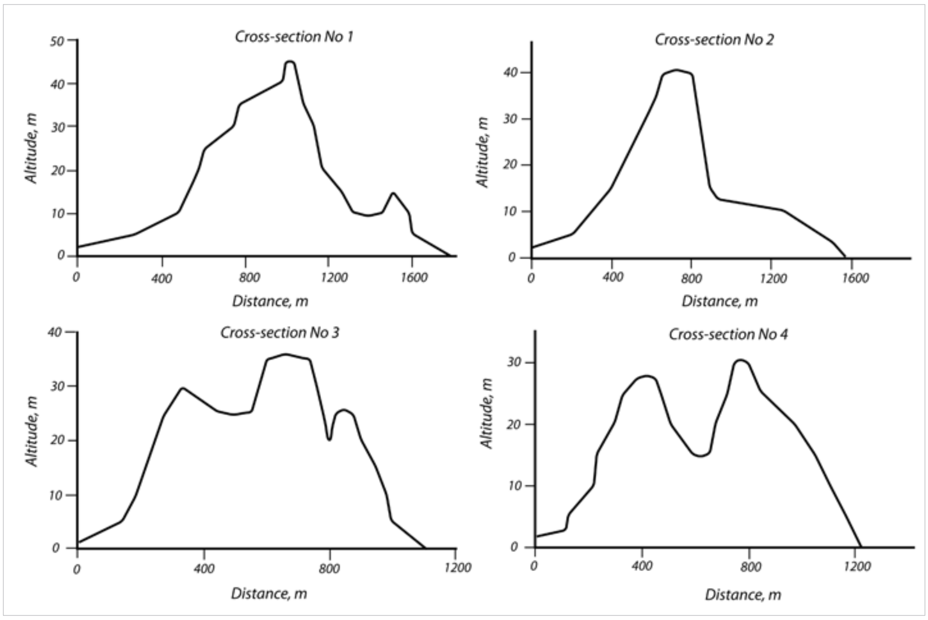

Fig. 5 Cross–sections of parabolic dunes: a) to the south from Witch Hill; b) in the middle of the Juodkrantė area; c) to the south from the Jonas (Witches) Hill; d) to the south from the Ieva (Eva) Hill. Compiled by R. Morkūnaitė, A. Česnulevičius, 2011.

MORPHOLOGY OF THE PARABOLIC DUNES

The morphological features of the dune massif were determined using the hypsometric map at a scale of 1:10 000 and geodetic measurements. The frontal ridge is best developed in the northern part of the massif (Witch Hill) where the absolute altitude of the dunes reaches 47–48 m. All contour lines in this area are slightly concave and curving to north–western direction (the length of this part of the ridge is about 1 km). The lowland is situated on the side of the lagoon. The windward western slope of the parabolic dune is steeper than its leeward slope (Fig. 5). According to the hypsography, the crest south of the frontal ridge (up to Witch Hill) at a height of 35 m is slanted from north–east to south–west. Its length is about 1 km. There are three depressions nearby and a wider arm with two summits. The profile indicates that the leeward side is even steeper towards the lagoon than in the first morphological sector of parabolic dunes.

The third morphological segment extends from the Jonas (Witches) to the President Smetona Hill for about one kilometre. This segment is composed of a complex of wings pointing towards the lagoon, with depressions at an absolute height of up to 5 m. The Ieva (Eva) Hill is situated in the middle of one of the wings. The cross profile of this morphological segment indicates that the height of the parabolic dunes is less than that of the first two segments, yet the step-like character becomes visible 5–10 m lower. The asymmetry of the windward and leeward slopes is not as evident as in the first two segments.

The fourth segment, which has a similar form as the second one, includes Geišiai Hill (45.5 m) and other hills in the southern part of the Juodkrantė massif. The wings pointing towards the lagoon are fewer. The crest of the segment is about 1 km long. The fourth segment shows two summits in cross profile. They are even lower than in the third segment, but the slopes are more asymmetric, and the arm is even higher. The old-growth forest characteristic of the fourth segment ends at the President Smetona Hill. The topographic map (scale 1:25 000) of 1910, that was used in the study (Paul 1944), has no old-growth forest plotted. Thus, the western summit of the profile under consideration might be interpreted as composed of the new generation sands.

A comparison of the quantitative characteristics of parabolic and recently active dunes is presented in Table 3. The identification of the distribution of parabolic dunes depends not only on their morphology, but also on the contents of the sands.

Table 3 Quantitative parameters of the Curonian Spit dunes. Compiled by A. Česnulevičius.

Parabolic dunes (Juodkrantė segment)					
Windward slope			Leeward slope		
height, m	length, m	inclination, degree	height, m	length, m	inclination, degree
17.5	102	9	22.5	36	32
12.5	88	8	12.5	32	21
25.0	86	16	27.5	44	32
15.0	63	13	17.5	31	29
25.0	74	18	27.5	52	29
Active dunes (Nagliai segment)					
Windward slope			Leeward slope		
height, m	length, m	inclination, degree	height, m	length, m	inclination, degree
10.2	110	5	14.2	31	24
42.4	240	10	27.8	62	24
16.2	320	3	26.8	59	24
39.3	390	6	36.2	74	26
30.2	640	3	29.9	68	23

GRAIN–SIZE OF SANDY SEDIMENTS

The differences in the mineral composition of the aeolian and marine sand are less important than those in their grain–size composition, which shows the specific qualities of what has been blown in and what has been blown around, as well as the relative age of the sand and complexity of the aeolian processes. Therefore, only grain–size analysis was conducted in this study.

Analysis of the average values of grain–size composition shows that a fine and a medium–size fraction (0.16–0.315 mm) predominate in the Juodkrantė parabolic dunes massif (Table 4). The western slope of Witches Hill has mostly a fine and medium–size sand (66.9%) and Ieva (Eva) Hill has a slightly smaller value (66.3%) (Fig. 6). Almost no difference is seen in the quantities of fine and medium–size fraction in the sand

Table 4 Average values of grain–size composition of the Juodkrantė dune sand. Compiled by R. Morkūnaitė.

Size terms		Fraction, mm (Krumbein, Sloss 1963)	Distribution of sand fraction, %
Silt	coarse	0.04–0.05	0.09
		0.05–0.063	0.06
Sand	very fine	0.063-0.1	0.3
	fine	0.1–0.16	3.7
		0.16–0.2	15.5
	medium	0.2–0.315	60.2
		0.315–0.4	6.2
	coarse	0.4–0.63	7.0
		0.63–1.0	2.5
	very coarse	1.0–1.6	0.76

of the old and new generations. A greater abundance of a coarse silt fraction (<0.04 mm) is characteristic of the old generation sand of Juodkrantė. This can be explained by faster wind speeds, which transport particles distinguished by inter-particle cohesion (Kuznecov, Glazunov 1985).

It was determined that there is sufficient amount of a very fine and fine–size fraction (0.063–0.16 mm) and a fine and medium–size fraction (0.16–0.315 mm) sand for a high, protective dune ridge to be formed on the seashore. If there is no fine and medium grain sand, a dune ridge may fail to form. Sand particles, which are finer than 0.15 mm, are not essential for the formation of a dune ridge (Žilinskas *et al*. 2001). Fine grain formations consist of bars, spits, and accumulation terraces (Kesel, Raukas 1967).

A bimodal distribution of the grain–size composition is characteristic for beach sand in the vicinity of Juodkrantė due to the deposition of abrasion products from the moraine sediments being uncovered on the shore's underwater slope (Jarmalavičius, Žilinskas 1996). The second most abundant sand fraction on the west slope of Ieva Hill is 0.63–0.4 mm (21.06%) (see Fig. 6). The samples were taken at a depth of 30 cm at a distance of 200 m from the sea.

The detailed grain–size analysis of the Curonian Spit beaches explained the distribution of the sand grains in the Juodkrantė parabolic dune massif. A parameter of the analysis, for example, is that the sand is better sorted (mean S_o = 1.2) on a protected dune

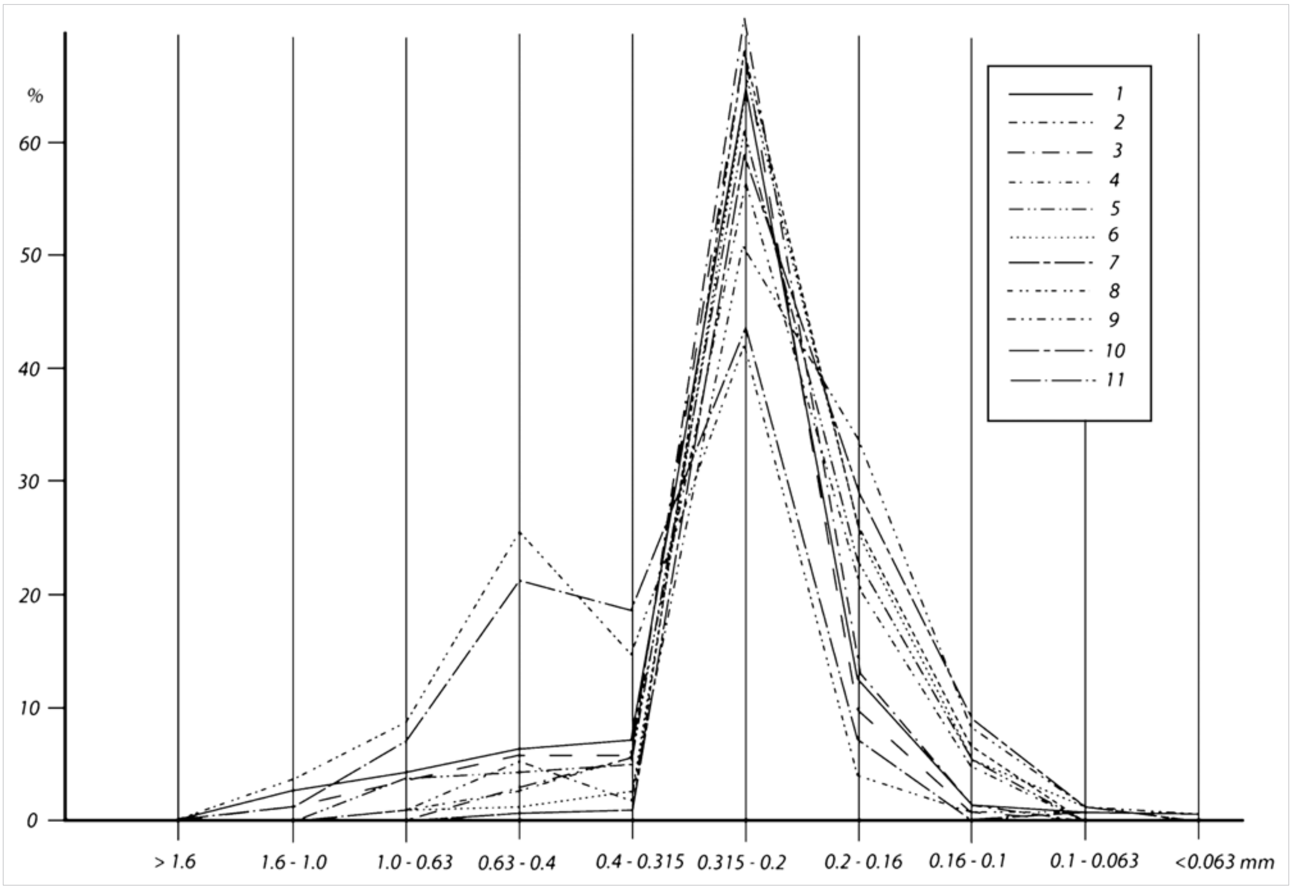

Fig. 6 Curves of grain–size composition of sand samples from the parabolic dunes of Juodkrantė. Prospect hole numbers and depths where the sand samples were taken are given in Table 1. Compiled by R. Morkūnaitė, A. Česnulevičius, 2011.

ridge than on the beach (S_o = 1.11–2.52) (Žilinskas *et al.* 2001). The sand is best sorted at two dune locations: on the leeward slope close to the crest and at the foot before it starts rising to the crest, where S_o = 1.4 and 1.58.

The grain–size analysis of the sand in the Juodkrantė parabolic dunes shows the same features for aeolian sand sorting as for the sand in the beaches. After calculating the sorting coefficient, it was discovered that the old parabolic dunes in the Juodkrantė massif are very well sorted (1.0–1.23), except for the western slopes of the dunes that are at the closest point to the sea: here the sand sorting is moderate to good (1.42; 1.36; 1.23) (Table 5). Sand sorting in recent active dunes is moderate (Česnulevičius, Morkūnaitė 1998).

According to V. Gudelis, it would be possible to explain the sorting differences that occur in the Juodkrantė massif by the fact that *the old parabolic dunes at Juodkrantė were ringed on the west by new generation dunes, which in the mid-19th century covered the aforementioned old dunes with a layer of sand that stabilised after a certain amount of time and were planted with trees* (Gudelis 1960). Thus, due to later sand deposits, the dunes that are furthest to the west of Juodkrantė are characterised by some features of young dunes, i.e. medium-grain–size and less sorted sand.

The sand sorting on Jonas (Witches) Hill is good and does not vary as much as the sand samples taken

Table 5 The statistical parameters of grain–size composition from the Juodkrantė parabolic dunes Compiled by R. Morkūnaitė.

Sample, No.	M_d (median diameter), mm	S_o (sorting)	S_k (asymmetry coefficient)
Jonas (Witches) Hill			
1	0.260	1.18	0.97
2	0.261	1.17	0.97
3	0.251	1.17	0.98
4	0.238	1.22	0.97
Ieva (Eva) Hill			
5	0.241	1.22	0.96
6	0.238	1.20	0.97
7	0.231	1.20	0.97
8	0.325	1.42	1.21
Unnamed hill to north of Jonas (Witches) Hill			
9	0.222	1.24	1.03
10	0.221	1.23	0.99
11	0.315	1.36	1.14

on Ieva (Eva) Hill (see Table 5). In the former case, the S_o is less than 1.2 both at the very top of the west slope and in the middle of the west slope. Analogous tests and their results are mentioned by other authors (Žilinskas *et al.* 2001). However, on the west slope of

Ieva (Eva) Hill, S_o is over 1.4 at a depth of 57 cm. The S_o in the middle of the east slope of Ieva (Eva) Hill is over 1.2 at a depth of 27 cm. The sorting worsens to 1.36 at a depth of 30 cm on the unnamed hill (to north of Jonas (Witches) Hill) gentle western slope that faces the sea.

The reason for this sorting distribution was revealed after using a map to analyse the geomorphologic situation of the sampling locations on these two hills. By comparing the geomorphologic situation of Jonas (Witches) Hill and Ieva (Eva) Hill, it is possible to understand the differences in the grain–size analysis of the aforementioned samples. There is an oblong closed depression on the west side opposite Jonas (Witches) Hill, while a small ravine, through which younger marine sand with coarser particles could be blown, runs from the sea towards Ieva (Eva) Hill. Both Ieva (Eva) Hill and Jonas (Witches) Hill have the same absolute height and are close to each other. Thus, the features of their formation are similar, only Jonas (Witches) Hill slopes more gently towards the lagoon.

Obtained data shows that the value of the asymmetric coefficient of the sand from the Juodkrantė dunes (see Table 5), which illustrates the nature of the process (Gradzinski *et al.* 1980), i.e., deflation or accumulation is greater than that in the east part of the crest of Ieva (Eva) Hill or in the southwest part of Jonas (Witches) Hill. It is possible to state that sand has accumulated here only because it was intensely accumulated during the period when the dunes were forming at the afore–mentioned locations.

The type and succession of vegetation have a great influence on aeolian dynamic processes that determine the possibility and intensity of deflation. Also, the type and succession of vegetation determines the morphology of dunes, especially its microforms.

SOILS AND VEGETATION

The soils of the Curonian Spit are classified on soil maps as *Haplic Arenosols* (Vaičys 2001), but in reality the soils of the parabolic dunes differ. The soils of the old parabolic dunes consist of eluvial and illuvial parts. The soil litter layer (0 horizon) is thick (15–16 cm, but sometimes it reaches 20 cm). The organic matter's content is higher in the B horizon than in A horizon. This is characteristic of *Typical Podzols* (Vaičys 2001). The exclusive feature of the Curonian Spit podzols is the prevalence of the humic acids related to calcium in the eluvial (E) horizon. The humic–calcium compounds are typical for surface horizons of soils under oak woods and rich in grass communities (Vaičys 1975, 2001).

The dominant soil profiles of the Curonian Spit were changed after fire events and affected by the aeolian processes. The aeolian dynamic processes were not as active in other areas of the Curonian Spit as they were in the parabolic dunes. The soil processes were most active in white and grey dunes where soil profiles were changed considerably. Soil profiles and some properties of the old-growth forest on the parabolic dunes (S1, S2) and deforested white–grey dunes (S3) in similar relief positions were investigated. Soil profile S1 is located in a trough between dunes of the old and new generation. Soil profile S2 is situated on an upwind slope on the black dunes landscape (Fig. 7).

The specific surface area (soil pellicle moisture) of the Juodkrantė podzols genetic horizons and buried soil horizons in white–grey dunes were compared. The specific surface area of soil particles is commonly used for the comparison of the ecological state of a soil (Kolli *et al.* 2004). The soil pellicle moisture of the Juodkrantė

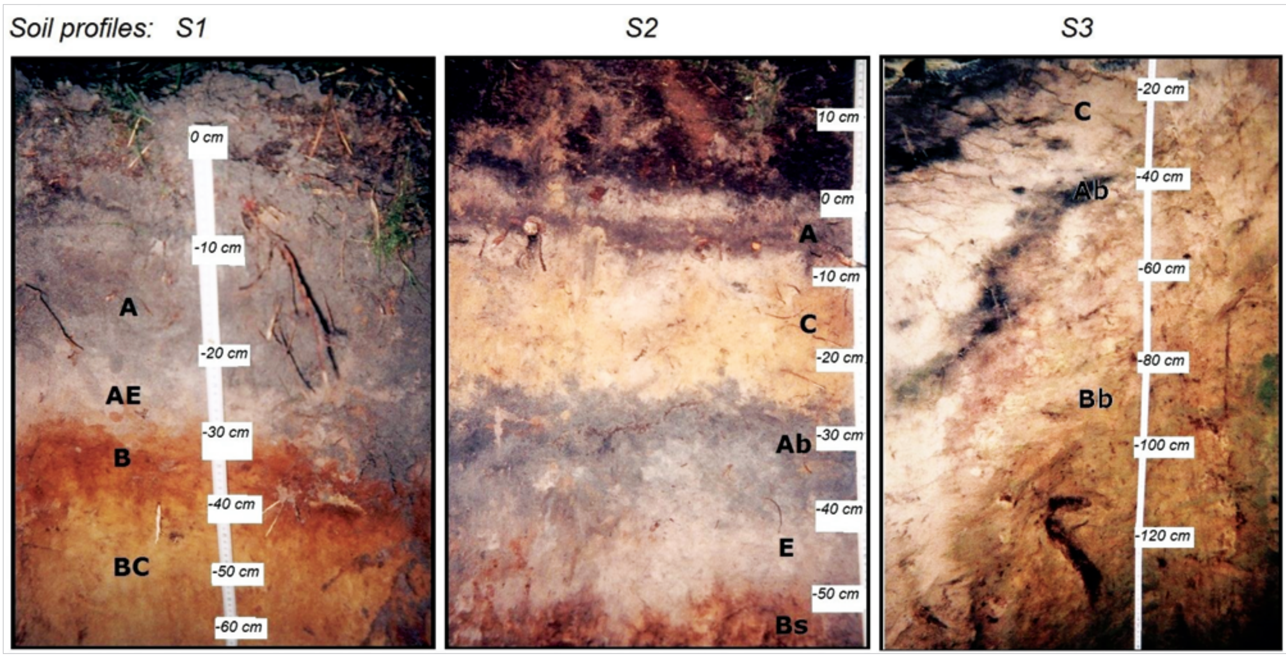

Fig. 7 Soil profiles in the Juodkrantė (S1, S2) and Nagliai (S3) environs. Compiled by I. Baužienė, 2011.

podzols was twice higher in parabolic (black) dunes compared with white–grey ones (Fig. 8).

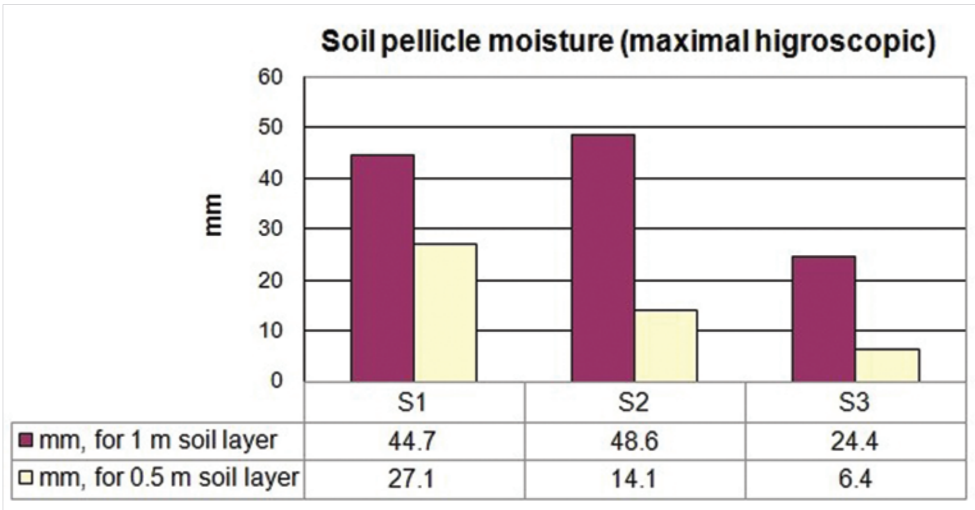

Fig. 8 Soil pellicle moisture of the Juodkrantė wooded parabolic black (S1, S2) and Nagliai white–grey dunes (S3). Compiled by I. Baužienė, 2011.

The vegetation type in the Juodkrantė area is old-growth forest, i.e. a climax plant habitat. Theoretically, the study area can be regarded as an area protected by the EU NATURA–2000 programme. It is close to the built-up areas of the Juodkrantė settlement and therefore an object of economic and private interests. Recently, politicians demanded that the territories of towns should be excluded from the list of protected zones.

DISCUSSION

On the basis of the morphological analysis of the relief, it was determined that the Juodkrantė dune massif experienced three–four formation stages. The Curonian Spit has been forming from the south to the north, thus the north segment is youngest. A single sand ridge with a wave shape that curves out and that is not yet distinguished by spurs and ravines can be seen on topographic maps at a scale of 1:10 000. The sand waves of the aging dunes did not retain their ridgeline and fragmented into individual parabolic dunes. In Juodkrantė, the length of each morphologic segment is about 1 km long. Such a long stretch of the segments support the presumption that the development of the separate segments began at different times. Lasting constant winds influenced the development of the relief microforms. On the other hand, the variability of wind directions (from northwest to southwest) could stimulate the transformation of the aeolian relief forms. Sand waves could change to low parabolic dunes where the conditions for sand accumulation were better. Parabolic dunes were growing and expanding, accumulating the sand brought from the seacoast.

Spurs and ravines are found in the second and third segments. The gullies and depressions are mostly in the third segment, which judging from the decomposition of the relief is the oldest. The fourth segment is marked by a young generation of dunes rejuvenated by newly deposited sand. A detailed map of the Juodkrantė vicinity in 1909, including Reizer (now Geišiai) Hill, shows that over half of the dune area had no continuous plant cover. The forest cover existed close to the settlement (Paul 1944). The wind carried marine sand from the west into the ravines and depressions. As a consequence, the ravine sand grain–size composition on the east side had a bimodal distribution.

Secondary dunes (or, steps in the dune's relief) formed at a height of 10–15 m above sea level in the Juodkrantė parabolic dune massif (see Fig. 3). The Vistula spit has 3–4 m high terraces created by water washing the bank (Mojski 2000; Rabek 1994; Miotk-Szpiganowicz, Uścinowicz 2008; Wróblewski 2003). Secondary dunes or steps are also visible when looking at the morphology of the Lake Peipus dunes (Raukas 1966). According to Martin (1986), lake dunes morphologically differ from the typical Holocene seashore dunes because they have a stepped structure, i.e., the majority of the younger dunes have been formed at the expense of the older ones. They are situated on an abrasion step on the slopes of old dunes. The creation of secondary superimposed aeolian forms occurs when the wave abrasion reaches a vegetation covered dune. The sand washed from the dunes, after drying, once again becomes aeolian and during strong winds once again covers the vegetation on the 'step' or ledge. These dunes are situated on the crests or slopes of old dunes and are morphologically diverse (Martin 1986).

It must be mentioned that Lake Ancylus did not leave such step dunes, although in the Curonian Lagoon, the morphology of the palaeosurface of the Lake Ancylus transgression–regression phases was most likely a smoothed plain dissected by inlets at the Dreverna–Juodkrantė traverse, and at Alksnynė. The palaeorelief starts from a depth of 5.5 m below sea level near the eastern lagoon coast and rises to 15.0 m below sea level near the western part of the Curonian Spit (Gelumbauskaitė 2010).

A palaeogeographical reconstructions of the Curonian barrier island, according to biostratigraphy and radiometric dating, show that aeolian forms appeared on the island during the Atlantic and beginning of the Sub–Boreal periods, when the Litorina$_2$ regression started (Kabailienė 1990; Grigelis, Gelumbauskaitė 2006). The so-called 'dunes' found in the Juodkrantė dune massif are also evidence of the deposition of a new generation of sand over an older generation. Research is needed to define the boundaries of the new and old parabolic dunes. However, we think that both old generation dunes and new generation dunes are not completely homogeneous, they are partly mixed.

The grain–size composition shows the heterogeneity of the main dune ridge of the Curonian Spit and the augmentation of the parabolic dunes in the old-growth forest with marine sand. In the Curonian Spit, 14 different shifting dune areas, which have become lower at various rates in the 20th century, are distinguished in the Great Dune Ridge (Povilanskas 2009). The diversity of the Great Dune Ridge shows the weak correlation among the morphometric parameters of the dunes (Paškauskas 2006).

The diversity of the relief forms and the grain–size of the sand, as well as the biodiversity dynamics of the Curonian Spit, are positive features. The increased number of flora and fauna species, but also the diversity of the environmental conditions, manifested themselves through distinct changes in the pedosphere. It was determined that the water retention capacity of the central ecosystem component, i.e., the mineral horizon of the soil, is over twofold greater in the black dunes than in the white-grey ones. During over two hundred years, since the burial of Nagliai village in AD 1733–1760, the soil water retention capacity degraded, probably, because the mineral and organic lamellae on top of the sand grains have been partly destroyed.

Research results indicate that almost a third of the area of the Juodkrantė parabolic dune massif is a result of binary formation. There are traces of old and new sand deposition generations. It has been suggested that the Juodkrantė parabolic dune massif is one of the more complicated aeolian relief complexes (Česnulevičius, Morkūnaitė 1998).

CONCLUSIONS

The Juodkrantė parabolic dune massif consists of four morphologically different segments, which presumably represent stages in the formation of the dunes. The first two segments are parabolic dunes, the third and fourth segments are an altered one that has been rejuvenated by the influx of new sand deposited on top of the parabolic dune.

On the basis of the sand grain–size composition it is possible to trace the boundary between old and new dune generations. The south segment (the Geišiai Hill dunes massif) is considered to be formed from old parabolic dunes as a young generation sand ridge. The 10–15 m high secondary dunes evidently show traces of a covering of a new generation of marine sand on top of the old generation.

The ancient forest soils in the Juodkrantė vicinity responded to natural geosystems; the forest minimized the problems caused by human error in managing the sensitive sandy landscape. People saved the forest around the settlements, which protected them from the expansion of the sand. Ancient and recent soil properties can survive and serve ecological purposes only if they are covered by forest vegetation.

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