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AEOLIAN SAND DIFFERENTIATION ALONG THE CURONIAN SPIT COAST, BALTIC SEA, LITHUANIA

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Abstract: The comparison of sand texture from two subenvironments helps reconstruct the forcing mechanisms responsible for foredune formation, whereas mineralogical anomalies on the beach and dune ridge allow to assess the intensity of prevailing dynamic conditions, especially important when diagnostic textural variations are minimal. Based on 1993, 2011 and 2014 sampling periods, granulometry and heavy mineral concentration were used to characterize hydrodynamic processes along the Baltic Sea coast of the Lithuanian part of the Curonian Spit. Our findings revealed systematic differences in sand composition between beach and foredune.

Introduction

Sand composition of the foredune typically reflects the granulometric parameters along the adjacent beach and prevailing hydrometeorological regime (Harris 1958; Mason and Folk 1958; Shepard and Young 1961). Heavy-mineral concentrations (HMCs) have been recently applied to reconstruct regional hydrodynamic conditions and sand transport pathways (Buynevich et al. 2007; Buynevich 2011; Pupienis et al. 2011; Pupienis et al. 2013). Despite the general similarities of sand fraction characteristics on the beach and foredune, the two environments are formed and modified by varying dynamic factors, thereby generating important differences in sediment texture and composition. The comparison of sand texture from the two subenvironments helps reconstruct the forcing mechanisms responsible for foredune formation, whereas mineralogical anomalies on the beach and dune ridge allow to assess the intensity of prevailing dynamic conditions, especially important when diagnostic textural variations are minimal.

The main objectives of this paper are to evaluate the patterns in sand texture and HMC distribution in various coastal environments.

Study area and methods

Lithuanian section of the Curonian Spit stretches for 51 km from Nida settlement to Klaipėda port (Fig. 1). The Baltic Sea coast is fronted by 30–80-m-wide beaches are composed of fine and medium sand. The volume of beach sediment is 42–115 m^3/m and the foredune elevation varies from 6 m near Juodkrantė to 16 m at Smiltynė (Fig. 1). The recent abundance of sand in the northern part of the Curonian Spit is influenced by the Klaipėda port jetties, which block longshore sediment transport (Jarmalavičius et al. 2012). Dominant winds are from southwest (38.6%) and west (32.2%). Due to the fact that the Baltic Sea is non-tidal, the main beach-forming factor is wind-generated waves. The strongest winds are observed from September to February, whereas the lowest wind speeds are typical for March through August.

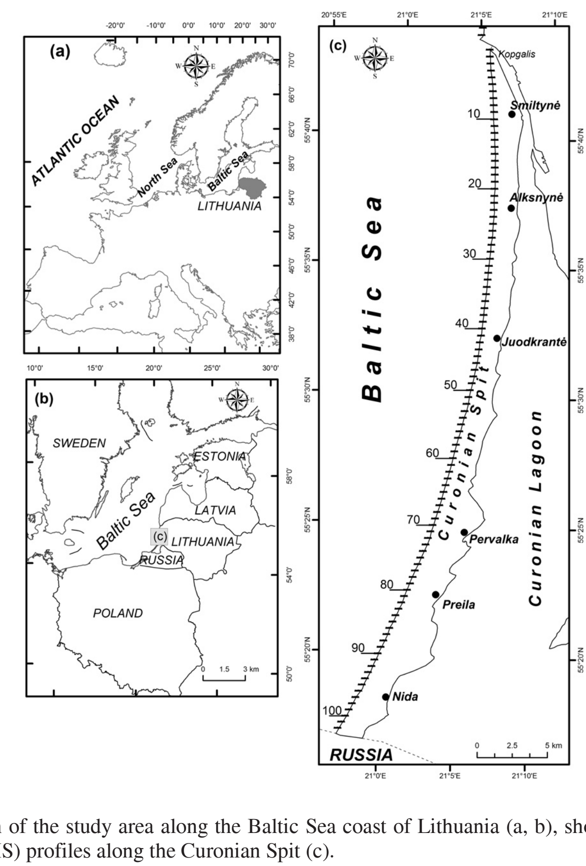

Fig. 1. Location of the study area along the Baltic Sea coast of Lithuania (a, b), showing magnetic susceptibility (MS) profiles along the Curonian Spit (c).

To assess sediment characteristics during sampling periods of 1993, 2011, and 2014, nearly 300 sand samples were collected at 500 m intervals across 101 profiles (Fig. 1c) from the middle of the beach (berm), foredune toe (seaward base), and stoss slope (seaward flank) of the foredune (Pupienis et al. 2013). The samples were mechanically sieved for granulometry, with heavy-mineral concentration assessed for 2011 and 2014 samples using bulk low-field magnetic susceptibility (MS) with a 0.565 kHz Bartington MS3 field scanning sensor (Shankar et al. 1996; Buynevich et al. 2007; Buynevich 2011; Pupienis et al. 2011; Pupienis et al. 2013).

Textural trends

Examination of the grain size parameters along cross-shore profiles revealed that the coarser fraction is concentrated on the beach, compared to the dune ridge. Mean particle diameter on the beach was 0.30–0.43 mm, foredune toe - 0.29–0.35 mm, and stoss slope of the foredune - 0.27–0.34 mm (Table 1).

Table 1. Parameters of mean grain size (mm) in 1993, 2011 and 2014 at the mid-beach, foredune toe, and stoss slope

Time Period		Mean, mm	Minimum, mm	Maximum, mm	Standard devation, mm
1993	Beach	0.37	0.18	0.90	0.14
	Toe	0.32	0.19	0.65	0.09
	Slope	0.29	0.19	0.56	0.06
2011	Beach	0.30	0.20	0.56	0.07
	Toe	0.29	0.19	0.53	0.06
	Slope	0.27	0.19	0.44	0.05
2014	Beach	0.43	0.23	1.01	0.17
	Toe	0.35	0.23	0.68	0.09
	Slope	0.34	0.21	0.63	0.08

Sand accumulated on the beach is not only coarser, but exhibits a wider size range during sampling periods. Mean diameter of sand particles on the beach ranged from 0.18 mm (1993) to 1.01 mm (2014), whereas on the dune ridge the this variation is lower, i.e. from 0.19 mm (1993 and 2011) to 0.63 mm (2014) (Table 1). Therefore, the sorting on the beach was worse (σ = 0.07–0.17) than on the dune ridge (σ = 0.06–0.08) (Table 1).

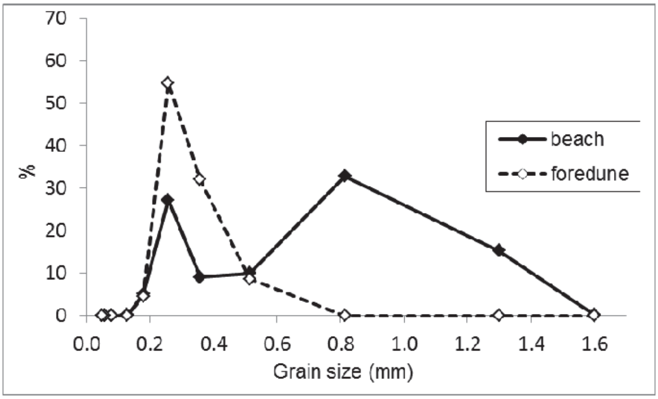

Fig. 2. Grain size distribution on beach and foredune 20 km south of Klaipėda port jetties.

Therefore, textural analyses suggest that a better sorting of the dune sand, may reflect its more stable regime both spatially (alongshore) and temporally. This was especially evident when considering coastal sections characterized by sand with variable texture. The coast near Juodkrantė, ~20 km southward from the Klaipėda port jetties, is dominated by coarsest sand on the Curonian spit. Beach sand is made up of mainly 0.4–1.0 mm fraction that represents 50% of sand volume (Fig. 2). On the dune ridge, this fraction comprises only about 5–10% of sand volume, with 0.200–0.315 mm fraction dominating the entire foredune ridge (protective dune) along the spit. A contrasting trend characterizes coastal sections dominated by fine fraction. Beaches located ~0.5 km south of the port jetties consist mainly of fine-grained sand (0.16–0.20 mm), which constitutes nearly 50% of sand volume (Fig. 3). Proportion of this sand fraction is lower on the dune ridge, i.e. on average 30–40%. As discussed in the previous example, 0.200–0.315 mm sand fraction is dominant in this coastal section. These trends show that despite a wide range of beach sand fractions, the mean grain size on the dune ridge is 0.200–0.315 mm. On the beach with prevailing 0.200–0.315 mm fraction, the difference in sand texture between the beach and dune ridge is not manifested, which could be explained by the fact that sand particles of this fraction are the most readily entrained into aeolian transport (Fig. 4). For both coarser and finer sand grains to be moved, a stronger wind velocity is required. Similar results have been described by other researchers (Fletcher 1979; Iversen and White 1982; Shao 2000).

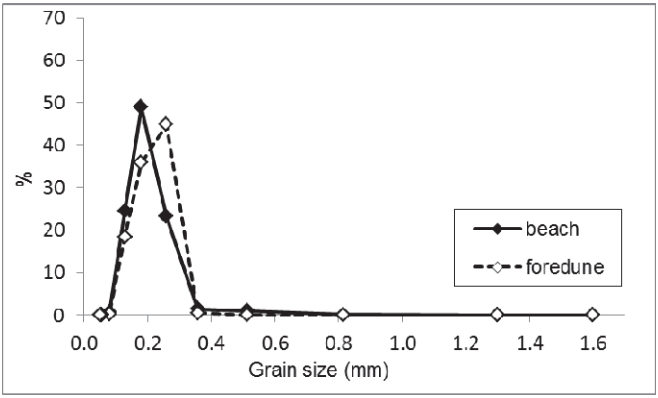

Fig. 3. Grain size distribution on beach and foredune 0.5 km south of Klaipėda port jetties.

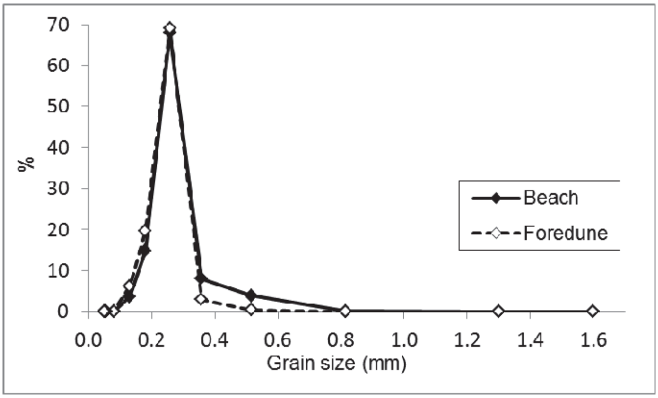

Fig. 4. Grain size distribution on beach and foredune ridge 10 km south of Klaipėda port jetties.

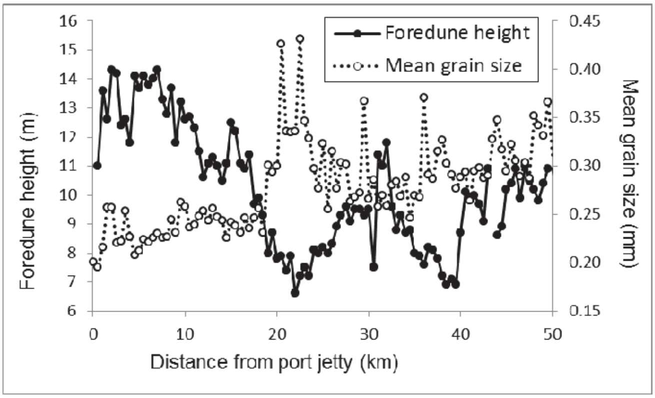

Fig. 5. Foredune height and mean grain size along the Curonian Spit coast of Lithuania.

The aforementioned patterns are important for dune ridge development. For example, the highest dune ridge (up to 16 m) was developed in in an area where the mean diameter of beach sand is 0.2–0.6 mm (Fig. 5) and dominant 0.200–0.315 mm sand fraction constitutes more than 50 % of sand volume. In contrast, the lowest dune ridge (< 6 m) was formed next to the beaches with mean grain size of 0.35–0.40 mm (Fig. 5), with dominant 0.63–1.00 mm sand fraction. Meanwhile, 0.200–0.315 mm sand fraction constitutes on average ~20% of sand volume. This inverse relationship, between dune ridge height and mean grain size, exhibits reasonable correlation (Fig. 6).

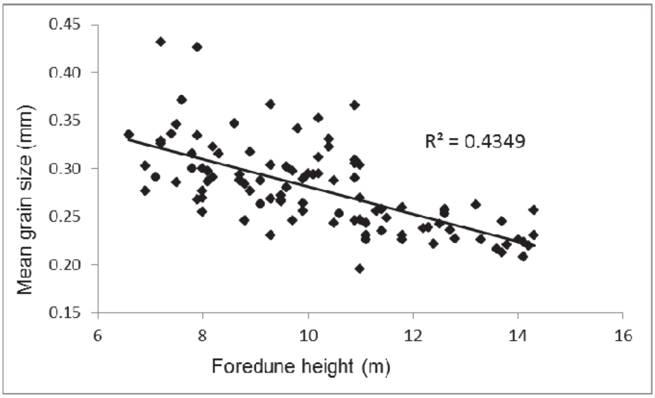

Fig. 6. Relationship between foredune height and mean grain size.

These patterns are controlled by the magnitude, frequency, and the type of transport mechanisms for various size fractions: 1) coarse sand particles typically transported by creep or reptation due to deceleration of wind speed near the foredune toe (Arens et al. 1995; Hesp et al. 2005) will preferentially accumulate at that morphologic boundary; 2) medium sand involved in aeolian saltation and grain collision (impact vs. fluid threshold) is accumulated on the dune ridge, and 3) the finest sand particles, which can be carried in suspension during strong near-surface winds, are transported over the foredune to the lee side.

Heavy minerals concentrations

The magnetic susceptibility (MS) values along cross-shore profiles were used as a proxy for heavy-mineral concentration (HMC), mainly magnetite content, along the Curonian spit coast (Table 2). The total range of MS values was κ=3.3–206.4 µSI. Despite relatively low difference in mean MS values between beach and dune ridge sands, the highest mean MS in 2011 and 2014 characterize beach sand, with foredune toe and stoss slope having lower values (Table 2).

However, this distribution is not uniform along the study region. Depending on hydrometeorological conditions, heavy minerals are unevenly distributed and are often exposed as ephemeral features.

Table 2. Parameters of MS value in 2011 and 2014 at mid-beach, foredune toe ,and stoss slope

Time Period		**Mean, μSI**	**Minimum, μSI**	**Maximum, μSI**	**Standard devation, μSI**
2011	Beach	38.6	11.9	116.4	20.9
	Toe	32.5	5.2	102.5	21.9
	Slope	26.9	5.9	124.9	16.3
2014	Beach	46.7	13.2	206.4	31.9
	Toe	31.8	6.0	125.1	23.3
	Slope	36.7	3.3	158.1	30.8

Therefore, susceptibility values are not stable along the cross-shore profile. The highest mean MS in 2011 were measured on the beach and foredune toe, with the lowest values on the stoss flank. In 2014, higher mean MS was recorded on the beach and stoss slope, whereas the lowest - on the foredune toe (Table 2). A comparison of 2011 and 2014 data demonstrates an increase along the stoss slope ($\Delta\kappa$=9.8 μSI) and on the beach ($\Delta\kappa$=8.1 μSI), whereas the foredune toe shows a decreasing trend ($\Delta\kappa$= – 0.8 μSI).

Heavy-mineral concentrations along cross-shore profiles are distributed according to specific patterns, which can be grouped into four types: 1) the highest HMC (i.e., MS maximum) in the middle of the beach with a decrease toward the foredune toe; 2) the lowest HMC is on the foredune toe and the higher – on the beach and stoss slope; 3) the maximum is on the foredune toe and the lower – on the beach and stoss slope, and 4) characterizes a situation when the lowest HMC content is on the middle of the beach and gradually increases toward the foredune toe (Fig. 7).

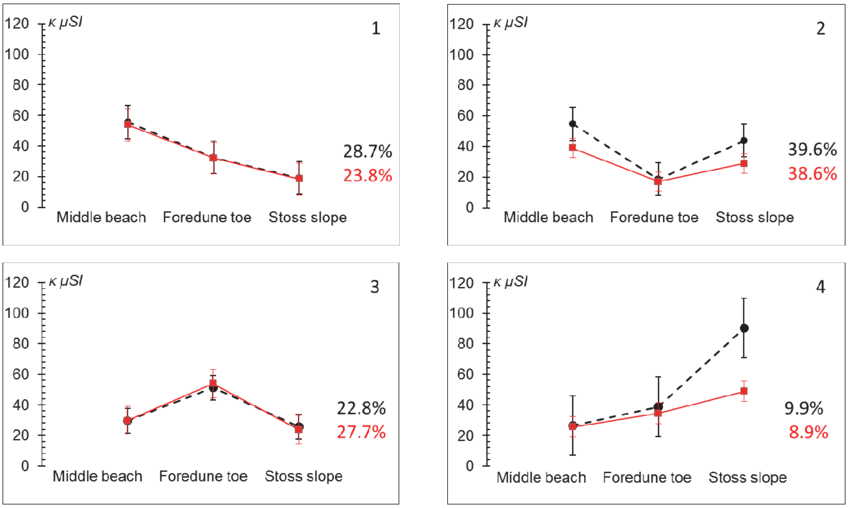

Fig 7. Magnetic susceptibility (MS) values of the surface sand layer are grouped into 4 types based on cross-shore trends. Trends are consistent for 2011 (solid red line) and 2014 (dotted black line), with corresponding frequency in percent.

These patterns in shore-normal HMC distribution are controlled by hydrometeorological conditions, namely aeolian and gravitational processes that result in exposure and lag formation (erosional mode) or burial by light-fraction sand particles (accretionary mode) (Pupienis et al. 2011; Pupienis et al. 2013). Thus, Type 1 likely reflects berm erosion followed by accumulation on the foredune toe and stoss slope. In the second type, erosion occurs on the beach, deflation and gravitational processes (grainflow) on the stoss slope, with accumulation on the fordune toe. Type 3 involves accumulation on the beach and stoss slope, and deflation of the foredune toe. The fourth type of HMC distribution reflects gravitational processes on the stoss slope and depocenters on the foredune toe and the berm.

The Curonian spit coast is dominated by HMC distribution Types 1-3, with Type 2 responsible for nearly 40% (Fig. 7). The fourth type is less common (<10%). These trends demonstrate that hydrodynamic and aeolian processes dominate over gravitational processes. It should be noted that HMC distribution remains stable along 36 of 101 profiles, and characterizes specific coastal sections: 15.0-16.5 (Type 1), 19.0- 20.5, 24.0-27.0 and 41.5-45.5 km (Type 2). In the first section, mean grain diameter reaches 0.24-0.25 mm on the beach and dune ridge, whereas along other sections sand particles of coarser diameter prevail: 0.38-0.43 mm on the beach and 0.29-0.33 mm on foredune. The fact that at 90% of the sites, heavy-minerals are concentrated to a greater degree along the berm than foredune ridge reflects the dominant onshore transport.

Conclusions

Spatial and temporal trends in textural and compositional parameters of surface sediment samples along the Baltic Sea shoreline of Curonian Spit, Lithuania reflect dominant processes along the berm and the adjacent foredune ridge. Our findings demonstrate that despite high degree of variability in sand granulometry on the beach, the 0.200 – 0.315 mm sand fraction is the main contributor to foredune accretion. An abundance of this fraction in beach sand generally determines a size of dune ridge, with the highest dune ridges developed in areas where this fraction is dominant. Four types of heavy-mineral concentration (HMC) help identify and distinguish dynamic processes occurring on the Curonian spit coast. In 2011, relatively low background surface HMCs on the beach and foredune are indicative of calm hydrometeorological conditions that favoured the onshore fine-to-medium sand transport. The higher HMC occurrence in 2014 reflects the effects of storminess that stimulated sand accumulation on the foredune toe.

Acknowledgements

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