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Past extreme events recorded in the internal architecture of coastal formations in the Baltic Sea Region

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ABSTRACT

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The postglacial uplift and transgressive-regressive phases of the Baltic Sea have affected the formation and displacement of sandy accumulation forms in the region. The dune-ridge complexes preserve a geological record of past sea-level fluctuations, coastal evolution, and extreme events, and offer insights into major driving mechanisms. This study aims to improve methodologies for identifying different storm signatures in coastal deposits using examples from Estonia and Latvia. The paleo-beach ridges are typically covered by aeolian sand, and the inter-ridge swales are mostly filled with organic sediments. Ground-penetrating radar surveys corroborate distinct textural patterns in sand layers underneath the ridges and swales. In the ridges, sharp seaward-dipping reflections represent storm scarps. The ridge sequences without dipping reflections suggest either aeolian origin or longshore transport; smaller sandy ridges, which are buried under peat layers, reflect prolonged, calmer phases. Compound dunes with ridges in their cores indicate major coastal events or shifts in atmospheric conditions that would have exposed wide sand areas to wind and facilitated dune development. This study demonstrates that the aeolian processes and changes in storminess have played an important role in the genesis of ridge-swale complexes in the Baltic Sea Region.

ADDITIONAL INDEX WORDS: *Beach ridges, dunes, heavy minerals, geophysical survey, luminescence.*

INTRODUCTION

Prograded coastal ridges and dunes are valuable archives of Holocene shorelines, past sea-level history, extreme events, paleo-storm morphostratigraphy, and medium-term variations in coastal processes (Björck and Clemmensen, 2004; Tamura, 2012; Bendixen *et al*., 2013; Hede *et al*., 2013; Dougherty, 2014; Nott *et al*., 2015). Beach ridge plains are found worldwide, where tropical cyclones or storm surges affect a spectrum of accumulation forms (Scheffers *et al*., 2012; Nott *et al*., 2015). These sandy shorelines are highly susceptible to erosion. Wave-eroded scarps in beach deposits are visible in subsurface ground-penetrating radar (GPR) records, indicating past high-energy events (Clemmensen and Nielsen, 2010; Nott *et al*., 2015). Heavy-minerals concentrations (HMCs) in dune scarps produce distinctive reflections in GPR images and are the evidence of erosional episodes in a long-term record of shoreline progradation (Buynevich *et al*., 2004; Dougherty, 2014).

Over the past 50 years, storminess has increased in northern Europe because of the changes in cyclonic activity. The number of cyclones moving over the area has increased in winter, shifting stormy season from autumn to winter (Suursaar *et al*., 2015). The Baltic Sea is essentially tideless, so that sea-level fluctuations are generally induced by wind direction and intense storms. Due to the isostatic uplift and sediment deficiency on the NE coast of the Baltic Sea, short-term relative sea-level changes (*e.g.* regressive and transgressive phases, extreme storms) are the main factor shaping regional coastal formations.

This study examines different storm signatures in beach deposits of Estonia and Latvia and discusses its relationships with the past changes in storminess. At an Estonian site, aeolian sand influx into peat sediments of a raised bog is used as a proxy for storminess.

METHODS

High-resolution topographic maps (LiDAR) were used for selecting the study areas and the locations of topographic transects. Field studies were conducted on two strandplains along the eastern Baltic Sea region (Figure 1). The Estonian study area is located at the northern end of Tahkuna Peninsula, Hiiumaa Island. The area is open to W and N winds. The shore-parallel ridges are fronted by a large dune belt containing relict blowouts and backed by lower foredunes. The aeolian processes have formed a large dune belt up to 17.5 m high. The GPR transect is >1 km long and traverses the ridges with altitudes of

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5.5-7.5 m a.s.l. The ridge system shows evidences of removal of several ridges in the past. The surface deposits include reworked sand comprising the ridges that formed during sea-level fall, and peat accumulating in swales. The ridge-swale landscape is covered by a pine (*Pinus sylvestris*) forest.

The Latvian study area of Siltere is located over 20 km SW from Cape Kolka, ~2.5 km from the shoreline (Figure 1). The study was carried out across a single relic dune at ~20 m a.s.l., which is backed by a bog-covered terrace. The dune is mostly composed of fine sand, whereas the terrace consists of a 1.5-m-thick sand layer on top of stiff clay. The length of the topographic/geophysical transect is ~100 m. There are no coastal formations in a landward direction. Seaward, several higher dune-ridge systems and low ridge sets occasionally separated by lakes, are the most characteristic physiographic features.

Shore-normal subsurface surveys have been collected with a digital GSSI SIR-3000 georadar with a 270 MHz antenna, with a range of 250 ns and trace spacing of 0.05 m for each site. The GPR data post-processing and analyses were performed using *Road Doctor* and *Radan* 7 software. The selection of the 270 MHz antenna favored deeper signal penetration (>10 m), while still providing dm-scale vertical resolution. The electromagnetic wave velocities were estimated using a depth-to-target method. Interpretation of GPR facies was based on hand auger and window sampler coring, which provided accurate depths of key stratigraphic boundaries and bounding surfaces.

Samples for luminescence dating of the Estonian study site were collected from the base of a large dune belt (Hiiu-2; 5 m a.s.l.; sampling depth 1.1 m) and a relict foredune ridge 270 m landward from it (Hiiu-1; 7 m a.s.l.; 1.3 m) using opaque plastic tubes. The material was composed of mixed medium-to-coarse grained sand, with the 200-250 µm fraction extracted by wet sieving and treated with HCl, H_2O_2, and $Na_4P_2O_4$. Potassium feldspar and quartz grains were enriched through heavy-liquid separation and quartz grains etched using HF. The measurements were performed on a Freiberg Instruments Lexsyg Research instrument (Richter *et al*., 2013). As quartz did not emit any detectable luminescence emissions, the subsequent analyses focused on feldspar. A modified protocol (Murray and Wintle, 2003) was used with adopted stimulation temperatures from Reimann and Tsukamoto (2012), relying on infrared light stimulation at 50°C (IRSL$_{50}$) and at 150°C (pIRIR$_{150}$). The central age model (Galbraith *et al*., 1999) was used to obtain a weighted average dose equivalence (D_e) value for each sample. Age calculations were performed in *Adele Software* using an assumed internal K content of 12.5±0.5% and alpha efficiency of 0.07±0.02. High-resolution gamma spectroscopy was used for the determination of dose rate of the relevant elements. IRSL dates for the Latvia site were analyzed in the Research Laboratory for Quaternary Geochronolgy (RLQG), Institute of Geology, Tallinn University of Technology (see Molodkov and Bitinas, 2006 for detailed methodology).

Peat sediments were collected from a small bog at the Estonian study site using Russian peat sampler. The core was described, documented, and photographed in the field, and packed into bisected PVC tubes. In the laboratory the core was subsampled continuously at 1 cm intervals. The chronology of the core was based on ten AMS ^{14}C dates using terrestrial plant macro-remains. All dates were obtained at Poznan Radiocarbon Laboratory, Poland, and calibrated using the IntCal13 curve (Reimer *et al*., 2013) with Clam ver. 2.2 (Blaauw, 2010). The standard lithological content was assessed using the thermogravimetric analysis (Precisa prepASH 340 Series). The content of dry matter in the sediment was determined by heating the samples at 105 °C to the constant weight. Loss-on-ignition (LOI) at 550 °C was used to establish the organic and mineral matter contents.

Boreholes were drilled and small pits were dug at the locations with strong subsurface reflections to calibrate GPR images and for textural analyses. Several HMC layers were analysed using immersion method with a polarized microscope.

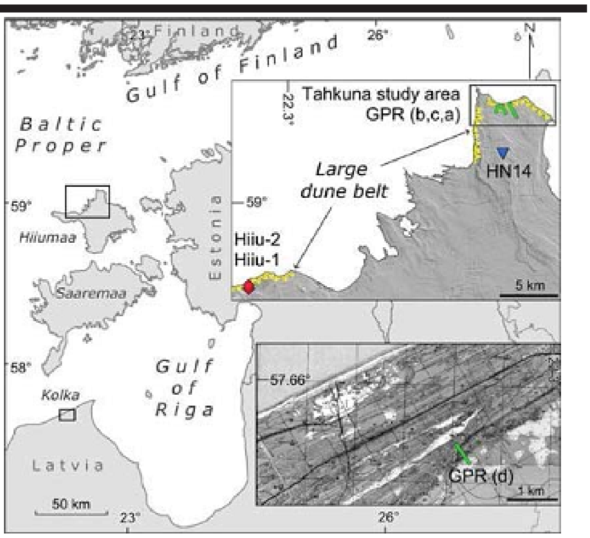

Figure 1. Location of study areas in the Baltic Sea region, LiDAR map (by Estonian Land Board) of Estonian study area with sampling sites of IRSL$_{50}$ (Hiiu-1, Hiiu-2) and peat core (HN14). And topographic map of the Latvian study area. a-d – locations of GPR profiles.

RESULTS

The results of geophysical and stratigraphic surveys, HMC analyses of sand and minerogenic fraction of peat, as well as ^{14}C and luminescence dates are summarized below.

Geophysical and sedimentological database

The morphology and internal patterns of the coastal formations were studied both in Estonia and Latvia. The Estonian profile was divided into three sections (Figure 2a-c) to ensure the quality of the data (parallel profiles in the locations where initial ridge-swale complexes were covered by dunes) and to avoid inaccessible sites (lakes, waterlogged bogs, streams).

The Estonian profile was divided into sections with different geomorphology and development history. The first section (Figure 2a1) includes the highest ridge in the profile. Similar ridges separated by former lagoons and filled with peat occurred landward of the profile. These ridges appear to be formed as spits as the result of longshore sediment transport (no seaward-dipping layers). This spit is followed by a 150-m-long section of large ridges (Figure 2a2). Extensive seaward-dipping reflections are clearly visible in GPR images. They are groundtruthed as

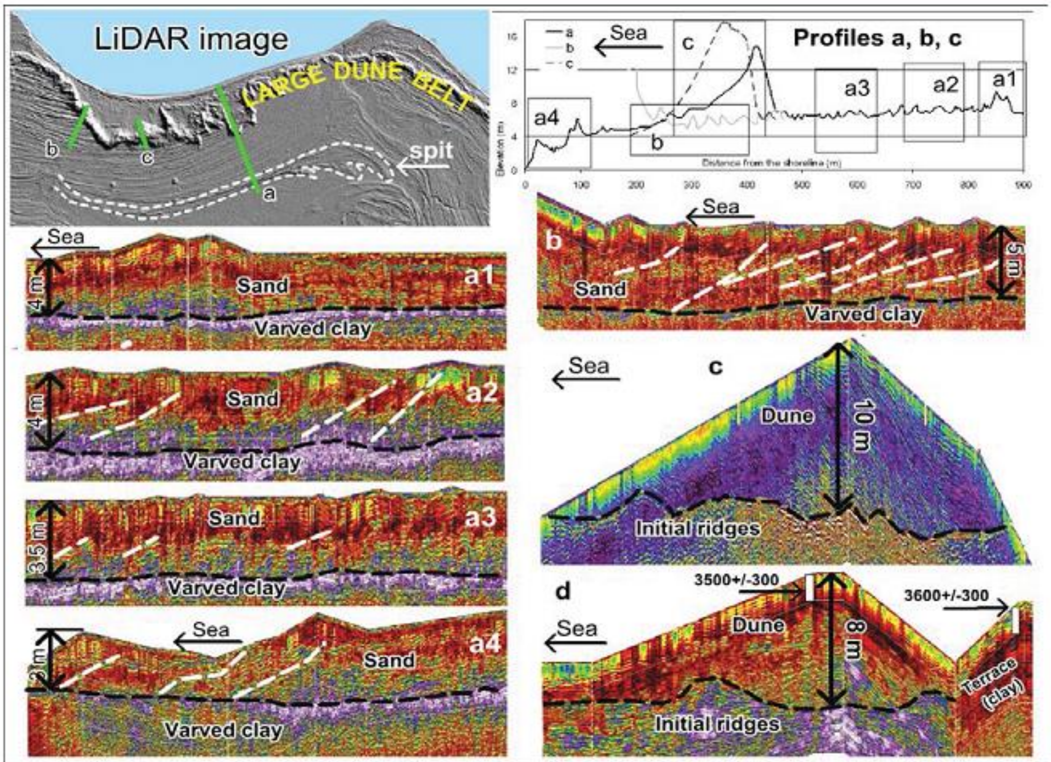

Figure 2. LiDAR image (by Estonian Land Board) and topography profiles (a-c) of Tahkuna study area, GPR images for profiles a-d. Dashed white lines – dipping layers with coarser sand or HMC. Two IRSL dates obtained in RLQG for the Latvian site shown in GPR image (d).

coarser-grained strata or those with higher HMC content. The next 250-m-long section (Figure 2a3) is characterized by low ridges with minor seaward-dipping layers. Most of the depressions between the ridges are filled by peat, resulting in almost flat topography. A parallel profile (Figure 2b) was used to establish a complete series of ridge-swale formation. The large ridges with long tilted layers have been formed in the result of cross-shore sediment accumulation. The final ridge in this section is covered by a large dune shown on another parallel profile (Figure 2c). The primary ridges are still visible under the 10-m-high dune. The landward tilted lamination on the leeward side of the dune is also clearly visible in the GPR image. As seen from the final section of the profile a (Figure 2a4), the seaward side of the large dune is flattened, probably due to dune migration and aeolian activity, until the last 100 m of the profile with two relatively large foredune ridges having seaward-dipping erosional surfaces.

At the Latvian study site typical, dune accretion mode is visible from the GPR reflection pattern (Figure 2d). According to the IRSL dating, this complex has been formed 3500 ± 300 years ago. The dates from the landward terrace and the seaward side of the dune fit the limits of calculated error indicating its rapid development.

$IRSL_{50}$ dates

The $IRSL_{50}$ ages are represented by lower and more clustered single aliquot D_e values compared to the $pIRIR_{150}$ ages, likely reflecting that the $IRSL_{50}$ signals were successfully bleached prior to deposition while the $pIRIR_{150}$ signals were only partially bleached. Preusser *et al*. (2014) have shown that samples for the region give $IRSL_{50}$ ages consistent with radiocarbon ages and hence the effect of anomalous fading on this signal is considered negligible. Furthermore, these provide a more plausible fit with the recent apparent land uplift rates in Estonia. Therefore, $IRSL_{50}$ ages are used to set the time of the formation of the ridge system in Tahkuna (Table 1) and the dune belt started to form 1210±80 years ago.

Peat core

The core in Tahkuna study area (coring site HN14) is 171-cm-long and records the entire thickness of the bog. The bog is located 3-4 km from the profiles and *ca* 2 km from the W-coast of Tahkuna Peninsula, 15 m a.s.l. The lowermost 6 cm is sand; the 165-68 cm section consists of highly decomposed peat with layers of wood (116-110; 97-94; 98-97; 89-88 cm) and some plant (mainly *Eriophorum vaginatum*) remains (110-100; 94-72 cm). The 72-68 cm section is reed peat, followed by 68 cm of well-preserved *Sphagnum* peat. The minerogenic matter content in the core is low in general with some exceptions (Figure 3). The highest concentration (54.9-99.4%) of mineral matter is at the bottom (171-165 cm - not shown on the Figure 3). The upper part of the core at 58 cm (*ca* 730 cal BP) and above contains 2.5-10.8% inorganic fraction. The mineral matter concentration before, during, and after the formation (2,200-1,100 cal BP;

107-73 cm) of the large dune belt is low (<2.4%) and monotonous.

HMC

HMC-rich layers coincide with prominent reflections GPR images as their electric susceptibility is much higher. Such layers suggest eroded slipfaces. We took several samples from the beach, dune and the ridges with similar properties along the Estonian coast. The fraction of heavy minerals on eroded beaches around Tahkuna Peninsula range between 13-18% (mostly ferromagnesian minerals and garnet), whereas the concentration on the top of the highest dune is only 1%. Several tests taken from similar ridges along the Estonian coast yield HMC content up to 4%. Therefore, we assume that the erosional slip-faces can be distinguished, because the HMC in these layers is many times higher than in aeolian deposits.

Table 1. *Feldspar measurement details: water content (WC), overdispersion value (OD), radionuclide concentration (Ra, Th, K), D_e, dose rate and inferred ages (before 2014). Number of accepted aliquots passing internal recycling ratio criteria (≤10%) was 12 in each case.*

Sam-ple	Proto-col	*WC* (%)	*OD* (%)	^{226}Ra (Bq kg^{-1})	^{232}Th (Bq kg^{-1})	^{40}K (Bq kg^{-1})	D_e (Gy)	Dose rate (Gy ka^{-1})	Age (ka)
Hiiu-	IRSL$_{50}$	20±5	6.9	14.3±0.4	20.1±1.3	274.6±6.7		4.80±0.1	2.18±0.14
2.20±0.14									
01	pIRIR$_{150}$		13.4					10.74±0.43	2.18±0.15
4.93±0.35									
Hiiu-	IRSL$_{50}$	8±4	9.8	14.6±0.6	23.1±1.1	439.0±6.9	3.49±0.11		2.88±0.19
1.21±0.08									
02	pIRIR$_{150}$		14.2					8.64±0.26	2.88±0.20
3.00±0.21									

DISCUSSION

The beginning of the Estonian section (Figure 2a1) was formed as a result of longshore sediment transport. Our previous studies have revealed that each increment of such drift-aligned recurved spits reflects changes in climatic and hydrodynamic conditions (Suursaar *et al*., 2015). Therefore, we hypothesize that each segment of the paleo-spit system reflects a climatic event in the past, possibly a major storm event or period.

Because the study region is experiencing sediment deficit, sea-level changes or extreme storms can create extensive ridges and dunes. A clear evidence of rapid formation of large dunes is the Latvian study area (Figure 2d). The first set of OSL dates indicates that the terrace behind the dune is almost of the same age, suggesting that the landform was created in a short time period or some re-deposition occurred during the Late Holocene The open sands are quickly covered by vegetation due to the influx of organic material from both seaward and landward sources (roots, seeds, *etc*.).

Stormy periods associated with high sea levels cause erosion of large volumes of coastal deposits from both erosional and accumulative sections. Our profiles were sited in the net accumulative sections of the shores where erosional bounding surfaces (truncations) archive the signatures of extreme events. These are often complemented with higher concentrations of heavy minerals (mineralogical lag; Smith and Jackson, 1990) and coarser fraction (textural lag). Most of the eroded material is accumulated either on shore or on the nearshore seabed. Therefore, the erosional layers are quickly buried by re-transported aeolian material from the exposed beach. These layers are clearly visible in the GPR images, with seaward-dipping layers in short succession indicating a longer stormy period. More extensive layers reflect stronger storm events with higher water levels. Large amounts of sand in nearshore zone contribute to the formation of larger ridges, their height being a function of aeolian aggradation, which seems to be characteristic for sections a2, b and a4 on the Estonian profile.

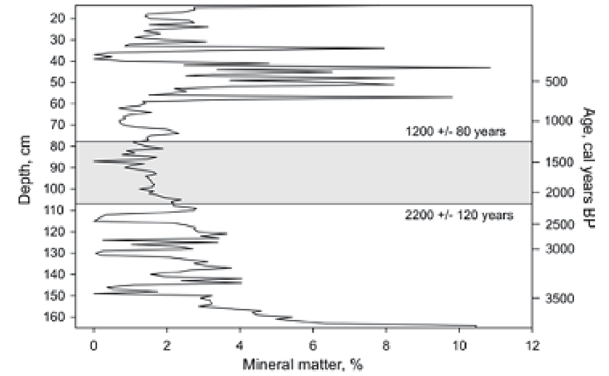

Figure 3. Concentration of mineral matter in the bog core from Tahkuna. The gray area represents the time period between two IRSL$_{50}$ samples.

The sections with small ridges with short tilted layers in deeper horizons are probably formed during relatively calm periods. Such short seaward tilted layers refer to low sea levels during their formation. Many ridges in this section are buried under peat layer today. Based on the GPR wave reflections, the section a3 was likely formed during a particularly calm period. Some slightly larger ridges in this section may have been formed as a result of a single stronger storm event.

The exceptionally high dune ridge, up to 17.5 m a.s.l., and extending across most of the northern coast of Hiiumaa Island, is an outstanding morphological feature in this region. Such high dunes are usually formed during periods of major sea-level fluctuations. However, the IRSL$_{50}$ dating confirmed, no sea-level fluctuations can be reported during the period of its formation. The formation of this dune cannot be connected with major storm events either, because this period is characterized by the lowest influx of mineral material into the bog a few km from the current shoreline (Figure 3). An alternative hypothesis is that this large dune was formed by an extreme event such as a tsunami about 1,200 years ago; however, historical documents or local folklores, referring to any such event, do not exist. On the contrary, the results of our current study suggest that this dune ridge was formed during a calm period with low cyclonic activity. Most of the Baltic Sea is covered by ice only in very cold and calm winters. If the sea ice cover breaks up during a NW storm, the sea ice may pile up on the shore. Sometimes such ice-ridges move hundreds of meters inland from the shoreline (Orviku *et al*., 2011), wiping out the vegetation and exposing wide areas of sand to wind activity. Thus, it is plausible to hypothesize that: (1) *ca* 1,200 years ago the winters were long and cold with less snow – a difficult condition for re-vegetating an open strandplain – and fewer major storms than usual, and (2) because of those situations, a background aeolian activity alone helped form such a large dune belt. Low content of mineral material in peat is also supporting the idea of calm and cold winters at that time.

CONCLUSIONS

High-resolution georadar profiles, in combination with drilling data, detailed LiDAR maps, radiocarbon and luminescence dating, HMC analysis of sand, as well as assessment of minerogenic fraction in peat, allow for a detailed reconstruction of past climatic conditions along sections of Estonian and Latvian coasts. Changes in storminess, including the character of storm periods, are reflected in the internal patterns of ancient coastal formations. Based on changes in topography and internal architecture of beach/dune lithosomes, we propose at least three periods with high cyclonic activity and two relatively calm periods punctuated by few intense storms.

Future studies will focus enhancing the chronology of coastal events to clarify the periodicity of storminess over the past two millennia in this part of the Baltic Sea. In addition, a comparative study of the erosional paleo-surfaces and recent storm monitoring data is necessary for a better understanding, and thus a better reconstruction, of the past storm parameters. Our findings are part of a valuable contribution to the forecasting of future scenarios in regional storm risk assessment by providing a deep-time perspective.

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