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Baltica

BALTICA Volume 36 Number 1 June 2023: 79–88
https://doi.org/10.5200/baltica.2023.1.7

Diverse erosional indicators along a rapidly retreating Holocene strandplain margin, leeward Hiiumaa Island, Estonia

Ilya V. Buynevich, Hannes Tõnisson, Ülo Suursaar, Donatas Pupienis, Oleksiy V. Davydov, Are Kont, Valdeko Palginõmm, Oliver Koit, Katre Luik

Buynevich, I.V., Tõnisson, H., Suursaar, Ü., Pupienis, D., Davydov, O.V., Kont, A., Palginõmm, V., Koit, O., Luik, K. 2023. Diverse erosional indicators along a rapidly retreating Holocene strandplain margin, leeward Hiiumaa Island, Estonia. *Baltica, 36 (1)*, 79–88. Vilnius. ISSN 1648-858X.
Manuscript submitted 13 April 2023 / Accepted 9 June 2023 / Available online 22 June 2023

Abstract. A diverse suite of erosional features along the shoreline of Lehtma (Hiiumaa Island, Estonia) is used to assess their morphodynamic context and preservation potential. The Holocene strandplain along the east-facing (leeward) shoreline has experienced rapid retreat due to the anthropogenically induced sediment deficit. The study site is located just updrift of the erosional-depositional fulcrum segment, with southerly longshore transport resulting in the accumulation of eroded sand along a drift-aligned spit. The most prominent erosional indicators are mature pine trees in different stages of undercutting, toppling, fragmentation, and burial. Morphological features include scarps in paleo-beach/dune ridges (height: > 1 m), as well as modern berm scarps. Mineralogical indicators are exemplified by heavy-mineral concentrations (HMCs) of variable thickness (some > 2 cm) and concentration. Representative samples show a substantial increase in bulk low-field magnetic susceptibility ranging from < 10 μSI common to the nearby Holocene coastal lithosomes to > 8,000 μSI in second-cycle HMCs within berm enrichment zones. A conceptual morphosedimentary model describing the recent and current state of the system, as well as the preservation potential of specific structures and recognition in geological research (e.g., georadar signatures of buried trees and HMCs) is proposed. The approach presented in this study can be used to assess the distribution and preservation potential of erosional indicators along the Baltic Sea coast and mineralogically heterogeneous, forested sandy shorelines worldwide.

Keywords: *storm; scarp; foredune; heavy minerals; magnetic susceptibility; Baltic Sea*

*Ilya V. Buynevich** *(coast@temple.edu)*, *https://orcid.org/0000-0002-3840-0208*
Department of Earth and Environmental Science, Temple University, 1901 N. 13th Street, Philadelphia, PA 19122, USA;
Institute of Ecology, School of Natural Sciences and Health, Tallinn University, Narva mnt 25, 10120 Tallinn, Estonia

Hannes Tõnisson (annu@tlu.ee), *https://orcid.org/0000-0001-7949-5795*
Are Kont (are145@gmail.com)
Valdeko Palginõmm (valdeko.palginomm@gmail.com)
Oliver Koit (koliver@tlu.edu), *https://orcid.org/0000-0001-6146-9126*
Katre Luik (katre.luik@tlu.edu)
Institute of Ecology, School of Natural Sciences and Health, Tallinn University, Narva mnt 25, 10120 Tallinn, Estonia

Ülo Suursaar (ulo.suursaar@ut.ee), *https://orcid.org/0000-0002-3474-8151*
Estonian Marine Institute, University of Tartu, Mäealuse 14, 12618 Tallinn, Estonia

Donatas Pupienis *https://orcid.org/0000-0002-2811-7090*
Faculty of Chemistry and Geosciences, Vilnius University, 21/27 Ciurlionio St., LT-03101, Vilnius, Lithuania; Lithuanian Nature Research Centre, Akademijos St. 2, 08412 Vilnius, Lithuania

Oleksiy Davydov (svobodny.polet2012@gmail.com) *https://orcid.org/0000-0003-2144-9627*
Lithuanian Nature Research Centre, Akademijos St. 2, 08412 Vilnius, Lithuania;
Department of Geography and Ecology, Kherson State University, Ivano-Frankivsk, Ukraine;
Scientific department, National Nature Park "Biloberezhya Svyatoslava", Ochakiv, Ukraine

**Corresponding author*

INTRODUCTION

In many parts of the world, the coastal strandplains that experienced a net seaward accretion (progradation) during the Holocene, may enter a phase of erosion due to sediment deficit of variable origins. Such systems present a unique opportunity to investigate morphosedimentary signatures of hydroclimatic events (e.g., intense storms), /due to the juxtaposition of /by juxtaposing/ relict and recent landforms.

The coastline of Estonia, especially along its northern margin, represents ideal field sites for such a study due to the combination of: 1) the functionally non-tidal basin; 2) the recent isostatic uplift, and 3) the abundant sediment supply resulting in prograded strandplains of various orientations (Orviku *et al*. 2003; Kont *et al*. 2007; Tõnisson *et al*. 2011; Rosentau *et al*. 2013; Muru *et al*. 2018; Tõnisson *et al*. 2018; Suursaar *et al*. 2019, 2022; Rosentau *et al*. 2020; Soomere *et al*. 2020). The latter contain a rich archive of erosional signatures due to the net accretionary mode facilitated by uplift, which is often termed "forced regression". Whereas the term "regression" (as a noun) is better termed "progradation" (Buynevich, FitzGerald 2001; Tamura 2012), a regressive sequence of coastal ridges (upper berm/foredune) and intervening swales (berm/beachface) overlies marine deposits, which are often dominated by sand due to the paraglacial setting of this region.

Among the differently oriented strandplains in the northern Baltic Sea region, those sheltered from dominant and prevailing westerly winds are characterized by selective preservation of signatures of the most intense storms and minimal aeolian reactivation (e.g., reworking of paleo-ridge sand into parabolic dunes). The east-facing shoreline of Tahkuna peninsula (Hiiumaa Island) is one of such sites (Fig. 1). The recent anthropogenic activity (construction of harbor structures) has resulted in the several decades lasting rapid erosion along the margin of a/the Holocene strandplain (Anderson *et al*. 2012). The aims of this study are to assess the characteristics of erosional indicators and propose a conceptual morphosedimentary model of their formation, as well as preservation and recognition potential.

STUDY SITE

The Lehtma study site is located in the northern part of Hiiumaa Island, along the eastern coast of Tahkuna Peninsula (Fig. 1). With some of the highest historic uplift rates in Estonia that outpaced the Holocene eustatic sea-level rise (> 3 mm/yr; Vassiljev *et al*. 2015; Suursaar, Kall 2018; Vestøl *et al*. 2019; Rosentau *et al*. 2021), abundant sediment supply from marine and glacial depocenters has resulted in several large prograding strandplains (Fig. 1B). Along this leeward side of the island, significant wave heights typically range between 0.3–0.6 m (Suursaar 2013) but substantial storm impact still reaches this

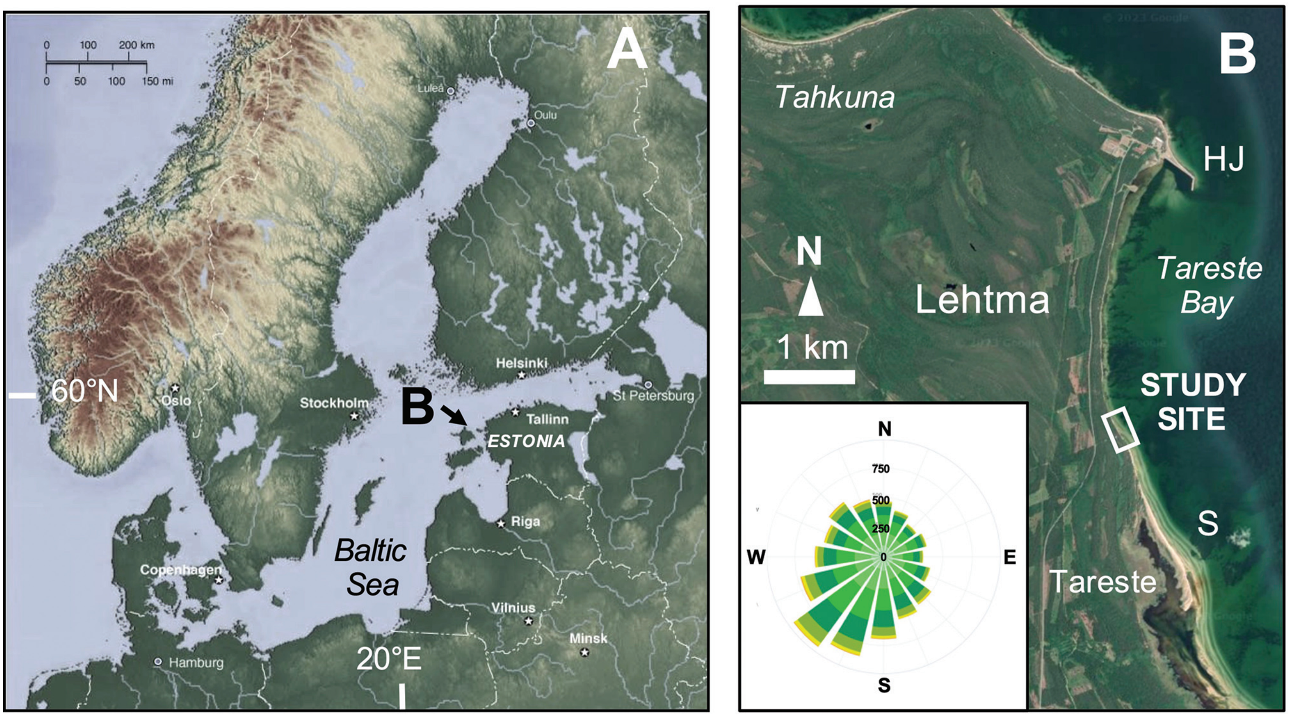

Fig. 1 Location of the study area: A) Hiiumaa Island, Estonia. B) Study site along the southern part of the Lehtma strandplain (HJ – harbor jetty; S – spit; image: 2019 GoogleEarth™). Inset – a wind rose showing a relatively low incidence of easterly winds along the Hiiumaa shoreline, with Tahkuna peninsula sheltering the site from the westerly wind and wave approach (source: Meteoblue)

part of the coast, although not as high in magnitude as northerly and westerly exposed margins of the Estonian archipelago and the mainland (Jaagus 2006; Suursaar, Kullas 2006; Orviku *et al*. 2009; Tõnisson *et al*. 2013). Changes in sea-ice cover produce seasonal and longer-term variations in incident wave impact, with land-fast ice acting as an agent of stabilization (freezing), transport, and erosion of sand (Jevrejeva *et al*. 2004; Sooäär, Jaagus 2007; Kont *et al*. 2011; Tõnisson *et al*. 2011; Jaagus, Suursaar 2013).

The Lehtma strandplain is an east-facing, slightly arcuate (swash-aligned) beach/dune ridge plain stretching for 3.5 km between the Lehtma Harbor in the north and the Tõrvanina Campground in the south. The prograded section consists of 2–3-m-high ridges and intervening swales, with isolated 5–10-m-high segments (Fig. 2). Vast tracts of Scots pine (*Pinus sylvestris*) and mountain pine (*P. mugo*) were planted in the 20th century to stabilize coastal sands (Anderson *et al*. 2012).

In recent decades, a sand deficit was caused along the Lehtma strandplain by the construction of the harbor jetty (quay) during 1960–80s, which hinders southerly longshore sediment and produces a zone of bypassing and retreat. Decadal mean rates of 2–3 m/yr have resulted in > 100 m of erosion since the 1970s (Fig. 2B, C; Anderson *et al*. 2012). The 2005 storm Gudrun is likely to have produced a substantial event-scale retreat (Suursaar *et al*. 2006; Tõnisson *et al*. 2008). The nearshore slope has a gentle gradient (0.4–0.7°) with an irregular, patchy seafloor (Figs 1 and 2). South of the study area, a depositional coastal cell (sediment sink) is represented by a 1.6–km-long drift-aligned recurved sand spit enclosing a small bay (Fig. 1B; Anderson *et al.* 2012). This downdrift depositional segment receives sand eroded from the study site and is fronted by several longshore sandbars (length: 200–500 m; width: 30–60 m). This study focused on the 0.5-km-long, NE-facing Tõrvanina-Paradiisiranna segment of the shoreline north of the transitional (fulcrum) point (Figs 1B and 2). This site is relatively sheltered from the prevailing westerly winds by the Tahkuna peninsula (Fig. 1B inset).

METHODS

The field surveys conducted in the fall of 2022 included ground observations (Fig. 3) of erosional features, shallow coring at upper beachface/berm sites (gas-powered augering with observations of extracted samples), and sampling of representative sand compositions: “background” and heavy-mineral concentrations (HMCs). As it is not feasible to collect thin layers enriched with heavy minerals (HMC–) in any other way than by applying an adhesive tape technique, representative sand samples were collect-

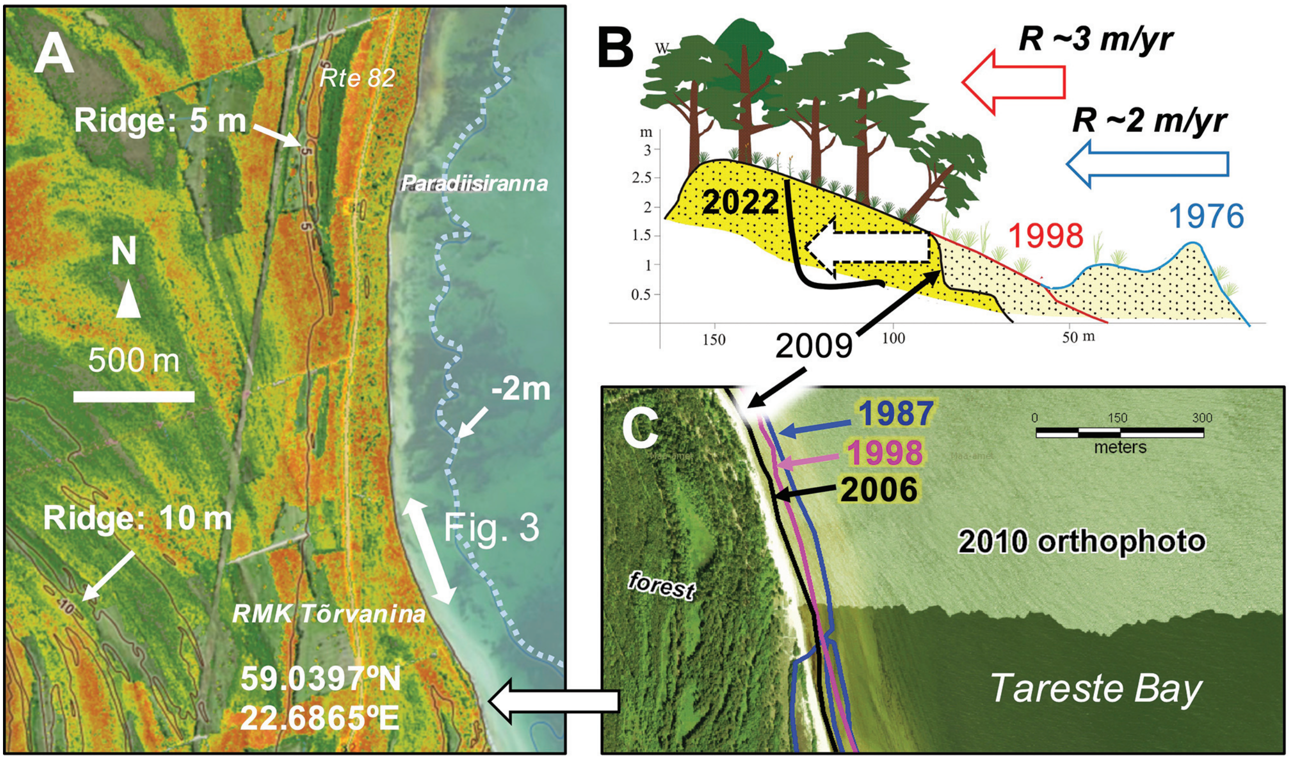

Fig. 2 A) The 2023 digital terrain model of the southern Lehtma strandplain showing preserved segments of 2–5-m-high Holocene ridge sets (yellow-orange) and intervening swales and cleared fields (green; source: Maa-Amet, X-GIS, Estonian Land Board). B) The sample shore-normal profile showing mean retreat rates between 1976 and 2009 (modified from Anderson *et al*. 2012). The projected shoreline position in 2022 (based on 3 m/yr retreat rate). C) The shoreline retreat over a 2010 orthophoto (from Anderson *et al*. 2012; following the color scheme of the authors)

ed based on visual assessment. Sample A, which is quartz-rich sand representing "background" composition, was collected from a freshly excavated scarp face, 10 cm below the paleo-ridge surface. Sample B is a ~ 1-cm-thick HMC located 20 cm below Sample A (Fig. 3C). Sample C represents a 3–4-cm-thick layer on top of a thin berm exposed by a berm scarp (Fig. 3E). Bulk low-field magnetic susceptibility (MS) was measured on hand samples using a Bartington MS3 meter with an MS2K sensor (0.93 KHz; see Buynevich *et al*. 2023 for methodology and recent comparative MS datasets from nearby strandplains).

RESULTS

Numerous pine trees are undercut or felled along the entire segment of the retreating shoreline (Fig. 3A, B). Along the beachface, segments of stumps protrude from the sand, with many large trunks scattered in various orientations. Podzol soil and roots of still living trees are exposed along steep scarps (Fig. 3B). Some older sections of trunks and large stumps protrude through berm, beachface, and even shallow nearshore areas (Fig. 3A, B).

Extensive scarps are cut into paleo-beach/dune

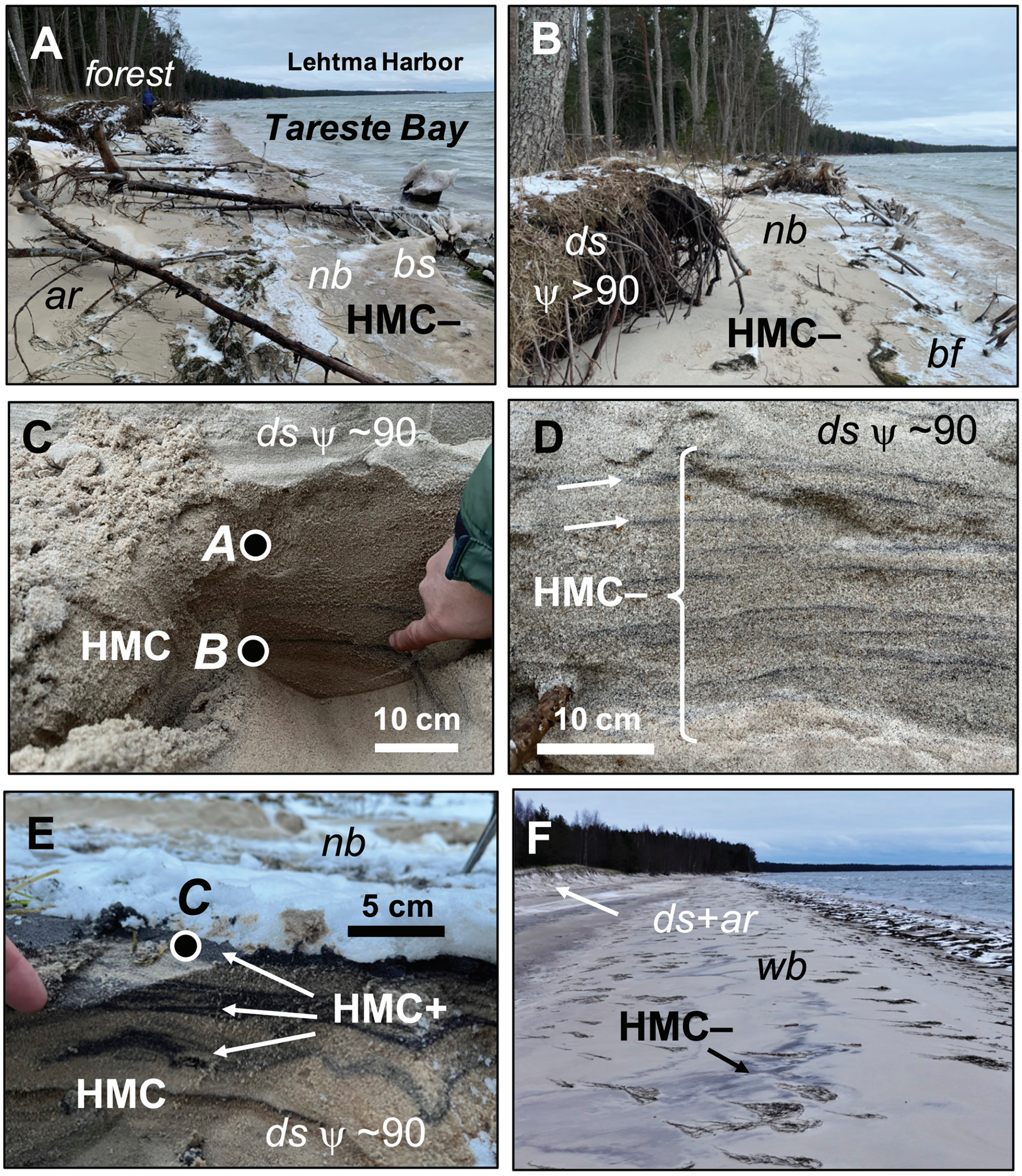

Fig. 3 Indicators of erosion: A) Multiple fallen trees over a narrow berm fronted by a low berm scarp. B) Undercut tree, with the root mass stabilizing an overhanging scarp (note stump remnants protruding through the berm and beachface). C) Section of a paleo-ridge scarp showing locations of samples A and B. D) Naturally exposed vertical scarp with numerous thin HMC layers. E) Upper section of a berm scarp with thick HMCs and location of sample C. F) Wide berm (nearly welded ridge) with thin HMCs fronting a paleo-ridge scarp. Field of view varies from north (A, B, F) to west (C, D, E). Key: ds – dune/beach ridge scarp; ar – aeolian ramp; bs – berm scarp; nb – narrow berm; wb – wide berm; bf – beachface; ψ – scarp gradient (degrees); heavy-mineral concentrations: HMC – = thin (< 0.5 cm), HMC = ~ 0.5–1.0 cm, HMC + = > 1.0 cm)

ridges, with face angles (ψ) varying between 70–90º (Fig. 3C, D). Overhangs (ψ > 90º) are typically supported by tree root masses (Fig. 3B). Scarps, which are partially healed by aeolian ramps, have substantially gentler gradients (Fig. 3A, F). Fresh scarp faces expose a diverse suite of aeolian and upper berm sedimentary structures, with variable fractions of heavy minerals ranging from sub-millimeter (HMC–; Fig. 3D) to ~ 1 mm in thickness (Fig. 3C). These are fronted by recent berms ranging from < 1 m to > 10 m in width and covered by HMCs of variable thickness and extent (Fig 3A, B, E, F). The berms have sections with steep active scarps (ψ ~ 90º) at the water line, exposing woody debris and buried HMCs (Fig. 3E).

The sand samples consisted of well-sorted medium-fine sand, with primarily ferrimagnetic (magnetite) finer fraction (> 50% by volume in Sample C; Fig. 4A). Bulk low-field magnetic susceptibility (MS) values for samples A, B, and C were 6.6, 365.7, and 8399.2 µSI, respectively (Fig. 4B). Coring through the upper beachface at several sites along the berm indicated that sand thickness is at least 2–3 m.

DISCUSSION

This study offers opportunity to examine a diverse suite of erosional indicators, which resulted from anthropogenically induced bypassing and erosion of the

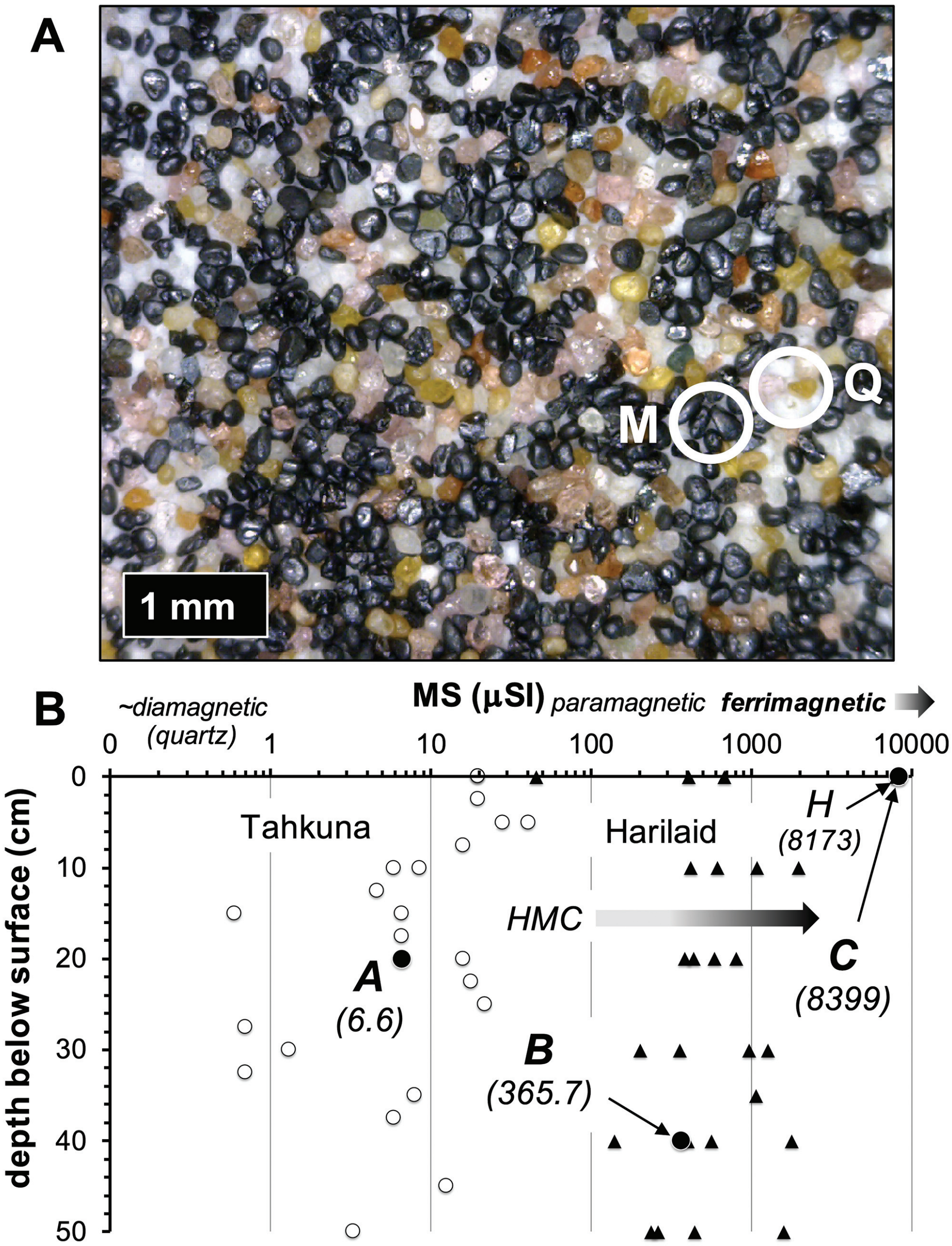

Fig. 4 Heavy-mineral concentrations: A) Photomicrograph of sample C showing abundant magnetite (M) in the finer fraction, with medium-grained sand dominated by quartz (Q). B) Magnetic susceptibility values of the three Lehtma samples A, B, and C (this study) compared to those from the nearby Tahkuna (circles; see Fig. 1B) and Harilaid (triangles; H = modern berm sample) strandplains (from Buynevich *et al*. 2023)

prograded coastal strandplain. The most prominent erosional indicators are mature pine trees in different stages of undercutting, toppling, fragmentation, and burial. Rapid erosion and retreat along the strandplains covered by mature forests results in a variety of attitudes (relative superposition), orientations, and preservation styles of tree trunks, stumps, and root masses. These produce a complex patchwork of roughness along the active beach and nearshore slope. Their impact ranges from stabilizing fresh scarps to producing areas of depositional shadows, and ultimately acting as erosional agents (ballistic impactors) when fragmented.

Two types of scarps present along the erosional re-entrant indicate the active process of the wave and, at times, sea ice impact on coastal morphology. Paleo-ridge scarps are primarily high (> 1m) vertical faces of paleo-beach/dune ridges, which are likely several centuries old (Fig. 3B, C, D, F; Ratas *et al.* 2011; Tõnisson *et al.* 2018; Buynevich *et al*. 2007a; 2023). These function as backshore dune scarps, although the relatively horizontal bedding (Fig. 3C, D) may be related to the upper berm accretion in the ridge section that experienced uplift. The current section may be part of a relatively low beach-dune ridge. Some older paleo-dune ridge sets exceed 2–3 m in height (Fig. 2A) and are not currently exposed along the eroding section.

Some undercut scarps still retain root masses of living or recently killed trees, so overhangs are common (Fig. 3B). In some areas, scarps are partially covered by aeolian ramps (Fig. 3A, F), which typically initiates the nucleation of a new ridge. Berm scarps are lower (~ 0.5 m) features that result from erosion and undercutting of relict swales or fresh (active) berms (Fig. 3E). The latter are identified by having parts of recently toppled trees protruding from freshly deposited sand (Fig. 3A, B), following ridge-and-runnel system migration during fairweather phases (Fig. 3F; Suursaar *et al*. 2013).

Heavy-mineral concentrations (HMCs) occurring both within relict beach/dune ridges (Fig. 3C) and within and on top of active berms (Fig. 3E) are the result of intense short-term (storm) or persistent long-term reworking (Komar, Wang 1984; Smith, Jackson 1990; Raukas *et al.* 1994; Buynevich *et al.* 2007b; Järvelill *et al*. 2015; Vilumaa *et al*. 2016; Pupienis *et al*. 2013, 2017). Besides thin (mm-scale) layers enriched with opaque minerals (primarily magnetite Fig. 3D), medium-to-thick (cm-scale) concentrations can be identified visually (Fig. 3C, E) and have high magnetic susceptibility values (Fig. 4).

Comparison to older sections of the nearby Tahkuna strandplain (Fig. 1B for location) and historic ridges at Harilaid (Saaremaa Island), shows similarity in MS values. The background relict ridge sand (Sample A) has very low values compared to the subjacent HMC (Sample B; Fig. 3C), which is similar to those at Harilaid (Fig. 4B; Buynevich *et al.* 2023). The most recent thick HMC (Sample C; Fig. 3E) is highly enriched with magnetite and has an MS value of > 8000 μSI similar to that of the berm deposit measure in 2019 at an eroded section of Harilaid (Sample H; Fig. 4B). Therefore, the recent berm HMCs can be considered as a second-cycle enrichment by persistent wave reworking in a regime of sediment deficit and longshore transport of lighter fraction (quartz, feldspar) in a southerly direction. These trends suggest regional patterns in MS values that can be used for reconstructing the relative degree of sediment reworking, as well as serve as strong reflections in geophysical (ground-penetrating radar [GPR]) images.

The results of field research and preliminary sediment analysis are integrated into a conceptual morphosedimentary model (Fig. 5). The original relict strandplain is in a regime of rapid erosion and retreat, with formation of scarps (exposing relict HMCs; Fig. 3C) and tree toppling onto a flattened profile with minor HMC formation (Fig. 5A). Continuing erosion generates sections of overhanging scarps (ψ > 90º) in areas stabilized by *in situ* root masses (Fig. 3B), with overtopping possible by storm wave runup or aeolian action (Fig. 5B). During fairweather stages that are common to this leeward coastal sector, sandbars (ridge-and-runnel systems) migrate onshore (Fig. 5B), eventually welding as berms of variable width (Figs 5C and 3F). Fresh berms temporarily bury remnants of tree trunks and stumps, with ongoing erosion producing fresh berm scarps (ψ ~ 90º) and second-cycle HMCs (Fig. 5C; 3E). In a hypothetical future phase, where a depositional front (fulcrum) may advance northward into the present study area, the active berm scarps may serve as nucleation sites for a new foredune ridge (Fig. 5D).

It is the leeward aspect of the study area that allows for intermittent periods of accretion to punctuate the ongoing trend of coastal retreat (Anderson *et al*. 2012). If the above scenario of net progradation replaces the current trend (e.g., Jaagus, Kull 2011), many relict and recent features observed in this study (Fig. 3) will be buried through vertical accretion by wave action (swash zone) and wind transport (aeolian ramps and secondary dunes). For example, buried trees may be identified in trenches or cores.

Furthermore, segments of trunks and stumps will produce distinct diffraction patterns in geophysical (GPR) images (van Heteren *et al*. 1998; Buynevich *et al*. 2017). The buried dune and berm scarps can be identified as truncations and disconformities in trenches and GPR images (Buynevich *et al*. 2004, 2007b, 2014; Dougherty *et al*. 2004; Vilumaa *et al*. 2016), especially where accentuated by heavy minerals. Seaward of these, second-cycle HMCs along the buried berms will similarly serve as distinct sedimentological and geophysical anomalies. Furthermore, their position and extent are important for an optical luminescence sampling strategy (Tamura *et al.* 2019; Buynevich *et al.* 2023).

Our study documents modern analogues of erosional indicators, which may be encountered in older sections of coastal strandplains along the Baltic Sea coast (Jarmalavičius *et al.* 2016; Muru *et al.* 2018; Tõnisson *et al.* 2018; Kelpšaite-Rimkiene *et al.* 2021) and similar forested shorelines worldwide that are now faced with the rising sea level and shifting storminess patterns (Bilj *et al.* 1999; FitzGerald *et al.* 2008; Clarke, Rendell 2009; Tamura *et al.* 2019).

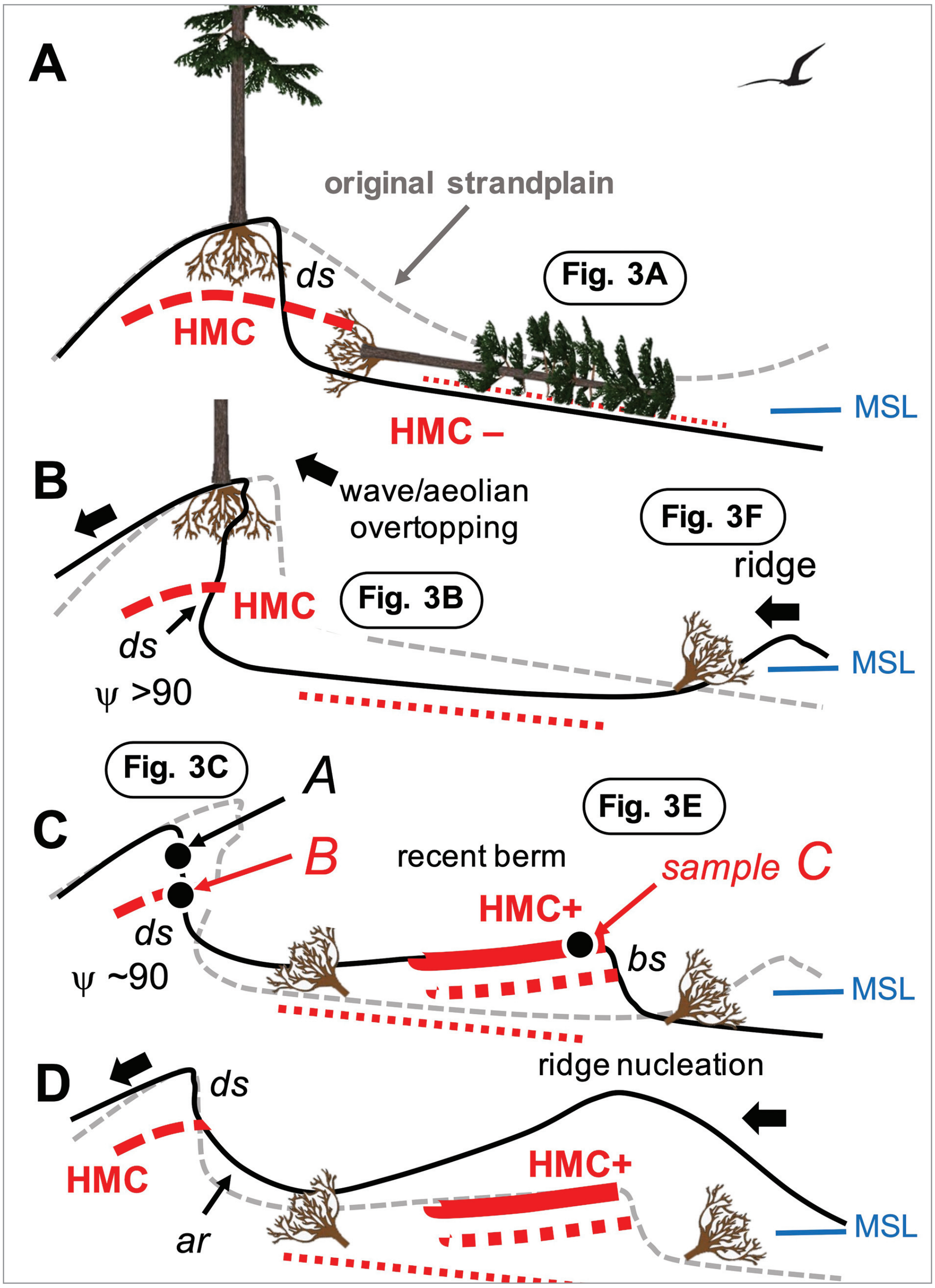

Fig. 5 Conceptual morphosedimentary model: A) Initial erosion and scarping of relict beach/dune ridge sets; B) Continuing erosion, HMC burial and sandbar approach (ridge-and-runnel migration); C) Persistent erosion and second-cycle enrichment (current condition); D) Burial and preservation of erosional indicators in a regime of progradation (a hypothetical scenario for the study site). Note that morphological (scarp disconformities), lithological (HMCs and /or gravel lag), and dendrological (tree trunks and stumps) indicators all produce specific subsurface anomalies that can be identified and mapped using trenches, multiple cores, or geophysical images. Dashed lines refer to the previous position of the shoreline or subsurface anomalies (HMCs) – (e.g., solid profile B is shown as a dashed line in C). MSL – mean sea level

CONCLUSIONS

Our study demonstrates the importance of field observations and sampling as a means of capturing the morphosedimentary aspects along a highly dynamic shoreline. The following conclusions have the potential for future studies along the coastal strandplains characterized by heterogeneous lithology and vegetation cover:

1) Erosion of heavily forested strandplains results in a diverse suite of preservation of tree trunks and stumps, which add complexity to erosional-depositional patterns along an active beach and nearshore areas.

2) The leeward position of the study site causes depositional fairweather phases to alternate with erosion caused by anthropogenically induced sediment deficit.

3) Lithological anomalies, such as heavy-mineral concentrations provide important information about the hydrodynamic conditions, as well as serve as visual and geophysical indicators.

4) Second-cycle lag formation (gravel and HMC enrichment) adjacent to relict HMCs results in compound paleo-surfaces, if buried by subsequent wave or wind action.

5) Magnetic susceptibility values of Lehtma samples vary from background concentration common to late Holocene sections of the nearby Tahkuna strandplain, to mineralogical anomalies similar to other sites (e.g., Harilaid, Saaremaa).

6) Interpretation of buried anomalies in trenches, cores, or geophysical (GPR) images must consider the erosional-depositional scenarios exemplified by the present study.

7) The present approach can be used to characterize the extent and preservation potential of erosional indicators along other parts of the Baltic Sea coast and forested sandy shorelines worldwide.

ACKNOWLEDGMENTS

This paper is dedicated to Kaarel Orviku, an intrepid explorer of Estonian coasts. We thank two anonymous reviewers for their suggestions that helped improve the manuscript. The study was funded by the Estonian Research Council Grant PRG1471 and a Fulbright U.S. Scholarship. We thank the people of Hiiumaa for their hospitality.

REFERENCES

Anderson, A., Ratas, U., Rivis, R., Palginõmm, V. 2012. Relationship between coastline changes and dynamics of coastal ecosystems of Tahkuna Peninsula, Estonia. *IEEE/OES Baltic International Symposium (BALTIC), Klaipeda, Lithuania*, 1–6, https://doi.org/10.1109/BALTIC.2012.6249189

Bijl, W., Flather, R., De Ronde, J.G., Schmith, T. 1999. Changing storminess? An analysis of long-term sea level data sets. *Climate Research 11*, 161–172.

Buynevich, I.V., FitzGerald, D.M. 2001. Styles of coastal progradation revealed in subsurface records of paraglacial barriers, New England, USA. *Journal of Coastal Research, Special Issue 34*, 94–208.

Buynevich, I.V., FitzGerald, D.M., van Heteren, S. 2004. Sedimentary records of intense storms in Holocene barrier sequences, Maine, USA. *Marine Geology 210*, 135–148.

Buynevich, I.V., Bitinas, A., Pupienis, D. 2007a. Lithological anomalies in a relict coastal dune: geophysical and paleoenvironmental markers. *Geophysical Research Letters 34*, L09707.

Buynevich, I.V., FitzGerald, D.M., Goble, R.J. 2007b. A 1,500-year record of North Atlantic storm activity based on optically dated relict beach scarps. *Geology 35*, 543–546.

Buynevich, I.V., Savarese, M., Kadurin, S.V., Larchenkov, E.P., Park Boush, L.E., Curran, A.H., Beal, I.A. 2014. Morphodynamics and geological legacy of berm scarps along non-tidal (Ukraine) and microtidal (the Bahamas) coasts. *Geology and Geography Bulletin, Odessa National University, Ukraine 19*, 177–187.

Buynevich, I.V., Savarese, M., Curran, H.A., Bitinas, A., Glumac, B., Pupienis, D., Kopcznski, K.A., Dobrotin, N., Gnivecki, P.L., Park Boush, L.E., Damušytė, A. 2017. Sand incursion into temperate (Lithuania) and tropical (the Bahamas) maritime vegetation: georadar visualization of target-rich aeolian lithosomes. *Estuarine, Coastal, and Shelf Science 195*, 69–75.

Buynevich, I.V., Tõnisson, H., Rosentau, A., Hang, T., Kont, A., Tamura, T., Suuroja, S., Palginõmm, V., Döring, S.F.S. 2023. Rapid magnetic susceptibility characterization of coastal morphosedimentary units at two insular strandplains in Estonia. *Journal of Marine Science and Engineering 11*, 232. https://doi.org/10.3390/jmse11020232

Clarke, M.L., Rendell, H.M. 2009. The impact of North Atlantic storminess on western European coasts: a review. *Quaternary International 195*, 31–41.

Dougherty, A.J., FitzGerald, D.M., Buynevich, I.V. 2004. Evidence for storm-dominated early progradation of Castle Neck Barrier, Massachusetts, USA. *Marine Geology 210*, 123–134.

FitzGerald, D.M., Fenster, M.S., Argow, B., Buynevich, I.V. 2008. Coastal impacts due to sea-level rise. *Annual Review of Earth and Planetary Sciences 36*, 601–647.

Jaagus, J. 2006. Trends in sea ice conditions on the Baltic Sea near the Estonian coast during the period 1949/50–2003/04 and their relationships to large-scale atmospheric circulation. *Boreal Environment Research 11*, 169–183.

Jaagus, J., Kull, A. 2011. Changes in surface wind directions in Estonia during 1966-2008 and their relationships with large-scale atmospheric circulation. *Estonian Journal of Earth Sciences 60*, 220–231.

Jaagus, J., Suursaar, Ü. 2013. Long-term storminess and sea level variations on the Estonian coast of the Baltic Sea in relation to large-scale atmospheric circulation. *Estonian Journal of Earth Sciences 62 (2)*, 73–92.

Jarmalavičius, D., Šmatas, V., Stankūnavičius, G., Pupienis, D., Žilinskas, G. 2016. Factors controlling coastal erosion during storm events. *Journal of Coastal Research, Special Issue 75*, 1112–1116.

Järvelill, J.-I., Kleesment, A., Raukas, A. 2015. Accumulation of heavy minerals in the eastern coast of the Gulf of Riga, south-western Estonia. *Bulletin of the Geological Society of Finland 87*, 67–78.

Jevrejeva, S., Drabkin, V.V., Kostjukov, J., Lebedev, A.A., Lepparanta, M., Mironov, Y.U., Schmelzer, N., Sztobryn, M. 2004. Baltic Sea ice seasons in the twentieth century. *Climate Research 25*, 217–227.

Kelpšaite-Rimkiene, L., Parnell, K.E., Žaromskis, R., Kondrat, V. 2021. Cross-shore profile evolution after an extreme erosion event, Palanga, Lithuania. *Journal of Marine Science and Engineering 9*, 38.

Komar, P.D., Wang, C. 1984. Processes of selective grain transport and the formation of placers on beaches. *Journal of Geology 92*, 637–655.

Kont, A., Endjärv, E. Jaagus, J., Lode, E., Orviku, K., Ratas, U., Rivis, R., Suursaar, Ü., Tõnisson, H. 2007. Impact of climate change on Estonian coastal and inland wetlands – a summary with new results. *Boreal Environment Research 12*, 653–671.

Kont, A., Jaagus, J., Orviku, K., Palginõmm, V., Ratas, U., Rivis, R., Suursaar, Ü., Tõnisson, H. 2011. Natural development and human activities on Saaremaa Island (Estonia) in the context of climate change and integrated coastal zone management. In: Schernewski, G., Hofstede, J., Neumann, T. (eds) *Global change and Baltic coastal zones*. Springer, 117–134.

Muru, M., Rosentau, A., Preusser, F., Plado, J., Sibul, I., Jõeleht, A., Bjursäter, S., Aunap, R, Kriiska, A. 2018. Reconstructing Holocene shore displacement and Stone Age palaeogeography from a foredune sequence on Ruhnu Island, Gulf of Riga, Baltic Sea. *Geomorphology 303*, 434–445.

Orviku, K., Jaagus, J., Kont, A., Ratas, U., Rivis, R. 2003. Increasing activity of coastal processes associated with climate change in Estonia. *Journal of Coastal Research 19*, 364–375.

Orviku, K., Suursaar, Ü., Tõnisson, H., Kullas, T., Rivis, R., Kont, A. 2009. Coastal changes in Saaremaa Island, Estonia, caused by winter storms in 1999, 2001, 2005 and 2007. *Journal of Coastal Research, Special Issue 56*, 1651–1655.

Pupienis, D., Buynevich, I.V., Jarmalavičius, D., Žilinskas, G., and Fedorovič, J. 2013. Regional distribution of heavy-mineral concentrations along the Curonian Spit coast of Lithuania. *Journal of Coastal Research, Special Issue 65*, 1844–1849.

Pupienis, D., Buynevich, I.V., Ryabchuk, D., Jarmalavičius, D., Žilinskas, G., Fedorovič, J., Kovaleva, O., Sergeev, A., and Cichoń-Pupienis, A. 2017. Spatial patterns in heavy-mineral concentrations along the Curonian Spit coast, southeastern Baltic Sea. *Estuarine, Coastal and Shelf Science 195*, 41–50.

Ratas, U., Rivis, R., Truus, L., Vilumaa, K., Multer, L., Anderson, A. 2011. The aeolian coastal ecosystems of Estonia and their changes. *Journal of Coastal Research, Special Issue 64*, 430–434.

Raukas, A., Bird, E., Orviku, K. 1994. The provenance of beaches on the Estonian islands of Hiiumaa and Saaremaa," *Proceedings of Estonian Academy of Sciences. Geology 43*, 81–92.

Rosentau, A., Jõeleht, A., Plado, J., Aunap, R., Muru, M., Eskola, K.O. 2013. Development of the Holocene foredune plain in the Narva-Jõesuu area, eastern Gulf of Finland. *Geological Quarterly 57*, 89–100.

Rosentau, A., Nirgi, T., Muru, M., Bjursäater, S., Hang, T., Preusser, F., Risberg, J., Sohar, K., Tõnisson, H., Kriiska, A. 2020. Holocene elative shore level changes and Stone Age hunter-gatherers in Hiiumaa Island, eastern Baltic Sea. *Boreas 49*, 783–798.

Rosentau, A. and 28 co-authors. 2021. A Holocene relative sea-level database for the Baltic Sea. *Quaternary Science Reviews 266*, 107071.

Smith, A.W., Jackson, L.A. 1990. Assessment of the past extent of cyclone beach erosion. *Journal of Coastal Research 6*, 73–86.

Sooäär, J., Jaagus, J. 2007. Long-term variability and changes in the sea ice regime in the Baltic Sea near the Estonian coast. *Proceedings of the Estonian Academy of Sciences, Engineering 13*, 189–200.

Soomere, T., Pindsoo, K., Kudryavtseva, N., Eelsalu, M. 2020. Variability of distributions of wave set-up heights along a shoreline with complicated geometry. *Ocean Science 16 (5)*, 1047–1065.

Suursaar, Ü. 2013. Locally calibrated wave hindcasts in the Estonian coastal sea in 1966–2011. *Estonian Journal of Earth Sciences 62 (1)*, 42–56.

Suursaar, Ü., Kullas, T. 2006. Influence of wind climate changes on the mean sea level and current regime in the coastal waters of west Estonia, Baltic Sea. *Oceanologia 48 (3)*, 361–383.

Suursaar, Ü., Kall, T. 2018. Decomposition of relative sea level variations at tide gauges using results from four Estonian precise levelings and uplift models. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 11 (6)*, 1966–1974.

Suursaar, Ü., Kullas, T., Otsmann, M., Saaremäe, I., Kuik, J., Merilain, M. 2006. Cyclone Gudrun in January 2005 and modelling its hydrodynamic consequences in the Estonian coastal waters. *Boreal Environment Research 11 (2)*, 143–159.

Suursaar, Ü., Tõnisson, H., Kont, A., Orviku, K. 2013. Analysis of relationships between near-shore hydrodynamics and sediment movement on Osmussaar Island, western Estonia. *Bulletin of the Geological Society of Finland 85 (1)*, 35–52.

Suursaar, Ü., Kall, T., Steffen, H., Tõnisson, H. 2019. Cyclicity in ridge patterns on the prograding coasts of Estonia. *Boreas 48 (4)*, 913−928.

Suursaar, Ü., Rosentau, A., Hang, T., Tõnisson, H., Tamura, T., Vaasma, T., Vandel, E., Vilumaa, K., Sugita, S. 2022. Climatically induced cyclicity recorded in the morphology of uplifting Tihu coastal ridgeplain, Hiiumaa Island, eastern Baltic Sea. *Geomorphology 404*, 108187.

Tamura, T. 2012. Beach ridges and prograded beach deposits as palaeoenvironment records. *Earth-Science Reviews 114*, 279–297.

Tamura, T., Cunningham, A.C., Oliver, T.S.N. 2019. Two-dimensional chronostratigraphic modelling of OSL ages from recent beach-ridge deposits, SE Australia. *Quaternary Geochronology 49*, 39–44.

Tõnisson, H., Orviku, K., Jaagus, J., Suursaar, Ü., Kont, A., Rivis, R. 2008. Coastal damages on Saaremaa Island, Estonia, caused by the extreme storm and flooding on January 9, 2005. *Journal of Coastal Research 24 (3)*, 602−614.

Tõnisson, H., Suursaar, Ü., Orviku, K., Jaagus, J., Kont, A., Willis, D.A., Rivis, R. 2011. Changes in coastal processes in relation to changes in large-scale atmospheric circulation, wave parameters and sea levels in Estonia. *Journal of Coastal Research, Special Issue 64*, 701–705.

Tõnisson, H., Suursaar, Ü., Rivis, R., Kont, A., Orviku, K. 2013. Observation and analysis of coastal changes in the West Estonian Archipelago caused by storm Ulli (Emil) in January 2012. *Journal of Coastal Research, Special Issue 65*, 832−837.

Tõnisson, H., Suursaar, Ü., Kont, A., Muru, M., Rivis, R., Rosentau, A., Tamura, T. Vilumaa, K. 2018. Rhythmic patterns of coastal formations as signs of past climate fluctuations on uplifting coasts of Estonia, the Baltic Sea. *Journal of Coastal Research, Special Issue 85*, 611–615.

van Heteren, S., FitzGerald, D.M., McKinlay, P.A., Buynevich, I.V. 1998. Radar facies of paraglacial barrier systems: coastal New England, USA. *Sedimentology 45*, 181–200.

Vassiljev, J., Saarse, L., Grudzinska, I., Heinsalu, A. 2015. Relative sea level changes and development of the Hiiumaa Island, Estonia, during the Holocene. *Geological Quarterly 59*, 517–530.

Vestøl, O., Ågren, J., Steffen, H., Kierulf, H., Tarasov, L. 2019. NKG2016LU: a new land uplift model for Fennoscandia and the Baltic region. *Journal of Geodesy 93*, 1759−1779.

Vilumaa, K., Tõnisson, H., Sugita, S., Buynevich, I.V., Kont, A., Muru, M., Preusser, F., Bjursäter, S., Vaasma, T., Vandel, E., Molodkov, A., Järvelill, J.I. 2016. Past extreme events recorded in the internal architecture of coastal formations in the Baltic Sea region. *Journal of Coastal Research, Special Issue 75*, 775–779.