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TRIINE NIRGI

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Press

Department of Geology, Institute of Ecology and Earth Sciences,
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CONTENTS

LIST OF ORIGINAL PUBLICATIONS

The thesis is based on the following research papers, which are reprinted with the kind permission of the publishers:

Paper I **Nirgi, T.**, Rosentau, A., Habicht, H.-L., Hang, T., Jonuks, T., Jõeleht, A., Kihno, K., Kriiska, A., Mustasaar, M., Risberg, J., Suuroja, S., Talviste, P., Tõnisson, H. (2020) Holocene relative shore-level changes and Stone Age palaeogeography of the Pärnu Bay area, eastern Baltic Sea. *The Holocene* 30(1): 37–52.

Paper II Rosentau, A., **Nirgi, T.**, Muru, M., Bjursäter, S., Hang, T., Preusser, F., Risberg, J., Sohar, K., Tõnisson, H., Kriiska, A. (2020). Holocene relative shore level changes and Stone Age hunter-gatherers in Hiiumaa Island, eastern Baltic Sea. *Boreas*, doi.org/10.1111/bor.12452.

Paper III **Nirgi, T.**, Rosentau, A., Ots, M., Vahur, S., Kriiska, A. (2017). Buried amber finds in the coastal deposits of Saaremaa Island, eastern Baltic Sea – their sedimentary environment and possible use by Bronze Age islanders. *Boreas* 46: 725–736.

Paper IV **Nirgi, T**., Grudzinska, I., Kalińska, E., Konsa, M., Jõeleht, A., Alexanderson, H., Hang, T. Rosentau, A. (manuscript). Late Holocene relative shore-level changes and palaeoenvironment of the Pre-Viking Age ship burials in Salme, Saaremaa Island, eastern Baltic Sea.

Author's contribution:

Paper I The author participated in the data collection, is responsible for sedimentological analyses and interpretations, prepared samples for radiocarbon dating, created age-depth model, compiled RSL database and led the writing of the manuscript.

Paper II The author participated in the fieldworks and collecting samples, performed sedimentological and terrain analyses, prepared samples for radiocarbon dating, created age-depth model and compiled RSL database. The author contributed to the interpretation of results, writing and editing of the manuscript.

Paper III The author participated in the fieldworks, data collection and analyses, is responsible for the sedimentological interpretations, created GIS-based paleo-environmental reconstructions and led the writing of the manuscript.

Paper IV The author participated in the data collection, is responsible for sedimentological analyses and interpretations, prepared samples for radiocarbon dating, created age-depth model, compiled RSL database and led the writing of the manuscript.

ABBREVIATIONS

a.s.l.	above the present sea level
AL	Ancylus Lake
AMS	Accelerator Mass Spectrometry
b.s.l.	below the present sea level
BIL	Baltic Ice Lake
BSB	the Baltic Sea basin
cal. ka BP	calibrated 14C years before present (AD 1950)
DEM	digital elevation model
GIA	glacial isostatic adjustment
GIS	Geographic Information System
GPR	ground-penetrating radar
GPS	Global Positioning System
ILS	Initial Litorina Sea
IPCC	the Intergovernmental Panel for Climate Change
IRSL	infrared stimulated luminescence
ML	lower (marine/lake) limiting data point
MSL	mean sea level
LGM	Last Glacial Maximum
LIA	Little Ice Age
LiDAR	light detection and ranging
LS	Litorina Sea
LOI	loss-on-ignition
OSL	optically stimulated luminescence
PLS	Post-Litorina Sea
RSL	relative shore level
RTK	real-time kinematic
SLIP	sea-level index point
TL	upper (terrestrial) limiting data point
YS	Yoldia Sea

1. INTRODUCTION

Comprehending sea-level fluctuations and the local, regional, and global effects of this on human populations during the Holocene period (last 11 700 years) requires an interdisciplinary methodology for high-resolution sea-level reconstructions and detailed data on palaeo-sea-level variation. The melting of large ice caps during the Last Termination caused a global sea-level rise and left the deglaciated areas under the influence of glacial isostatic adjustment (GIA) which, in coastal areas, led to significant changes in coastline location and configuration. These processes are also relevant today, as global warming is expected to accelerate the melting of polar ice caps. Sea-level rise represents one of the most immediate societal threats associated with present-day and future climate change (Rosentau et al., 2017; Horton et al., 2018; Steffen et al., 2018; Khan et al., 2019). Studying instrumental data series that have been gathered during the past few hundred years does not provide exhaustive knowledge about relative shore-level (RSL) change mechanisms, which is essential for predicting and preparing for sea-level change in the future. Therefore, for the future of ocean, climate, and hazard research, it is important to obtain data regarding analogous processes from the past, such as in terms of studying the interaction between GIA and sea-level change (Church et al., 2013; IPCC, 2014; BACC, 2015).

The Baltic Sea basin (BSB; Figure 1) with high potential of available sea-level data serves as one of the best places in the world in which to study interactions between sea-level change, postglacial land uplift and prehistoric human adaptations during the Holocene (Risberg et al., 1991; Jussila and Kriiska, 2004; Zillén et al., 2008; Bērziņš et al., 2016; Muru, 2017). The damming and drainage of the basin has caused significant RSL fluctuations, which has varied greatly along the coastline of the BSB mainly due to the uneven land uplift. Thanks to this process, prehistoric coastal landscapes and settlement sites along the southern Baltic Sea have been submerged (Fischer, 2011; Jöns, 2011), while in the northern Baltic Sea areas they have been uplifted and situated successively at different altitudes (Hedenström and Risberg, 2003; Lindén et al., 2006; Vaneeckhout, 2008; Rosentau et al., 2011). In the peripheral area of the Fennoscandian uplift zone, as in Estonia and southern Sweden, prehistoric people had to adjust to transgressions and regressions of the shifting coastline owing to competition between glacio-isostatic land uplift and eustatic sea-level rise (Rosentau et al., 2011). Here, the terrestrial landscapes and associated coastal settlements have been inundated by the Ancylus Lake or Litorina Sea transgressions (ca. 10.7–10.2 and 8.5–7.3 cal. ka BP, respectively), and occur both below (Hansson et al., 2018 a, b; 2019) and above (Rosentau et al., 2011; 2013; Muru et al., 2018) present-day sea level. The discovery of submerged landscapes in areas with similar postglacial land uplift rates to that of south-western Estonia raises the question of whether any submerged prehistoric landscapes or settlements may also exist in Estonian coastal waters. Further RSL research in this regard with a focus on the Holocene RSL lowstand periods is required in order to improve previous RSL models and predict the potential locations of submerged prehistoric settlements.

The recently-compiled Holocene sea-level database for the BSB and its comparison with major GIA models (ICE 5G, ICE 6G) has indicated a large level of disparity (in the order of tens of metres) between models and available sea-level records along the periphery of the Fennoscandian uplift region (Klemann et al., 2018), which certainly affects the reliability of future sea-level predictions. These differences are due to the scarcity of detailed sea-level data in areas which have a complex and dramatic history of sea-level fluctuation during the Early to Mid-Holocene. RSL studies in these areas are therefore necessary to make it possible to improve existing GIA models by providing new data about sea-level changes, especially for the poorly-known low water-level phases that preceded the Ancylus Lake and the Litorina Sea transgressions.

The study areas for current PhD theses (Figure 1a) were selected from coastal western Estonia, where the lowest and highest land uplift rates have been documented and where, beside valuable geological sea-level data, numerous prehistoric shore-connected settlement sites are known. The variations in the uplift rates (presently ca. 1.7–3.3 mm/yr) have led to remarkable differences in the RSL history throughout the study areas. Refining and comparing the timing and patterns of RSL changes in these areas helps to clarify the effect of land uplift in terms of the amplitudes and synchronicity of the RSL fluctuations. Due to flat, slightly undulating terrain, the study areas have experienced significant shore displacement. Transgressive shorelines are marked by ancient coastal landform systems, which often surround former lagoons (present-day wetlands), a preferred landscape for prehistoric settlers. Widely-known terrestrial organic sediments, which have been buried under younger coastal sediments, have not only proven to be valuable archives of sea-level and palaeoenvironmental data (e.g. biostratigraphic proxies), but also contain traces of prehistoric settlements.

Combining archaeological and geological data allows to use a geoarchaeological approach, which is useful for understanding the connection between palaeoenvironmental changes and prehistoric settlement patterns (Butzer, 2008; Astrup, 2018). Analysing shore-level changes at different temporal and spatial scales helps us to understand how these changes influenced prehistoric people in coastal regions. Furthermore, archaeologists support palaeogeographical and palaeoecological studies with additional chronological data from their archives, while geoscientific methods contribute with the palaeoecological, RSL, and shore displacement reconstructions. The latter are composed using a geographic information system (GIS), which is a great tool for placing data from several research disciplines into spatio-temporal relations in order to be able to draw up new interdisciplinary conclusions (Muru, 2017).

RSL reconstructions are compiled using sea-level indicators, which formed in relations to the historical position of the shoreline and include sedimentary, geomorphic, archaeological, and fixed biological proxies (Khan et al., 2019). RSL indicators have been used during the last few decades for estimating future sea-level changes by establishing long-term background rates for vertical land motion (e.g., Engelhart et al., 2009) and in improving GIA models (e.g. Lambeck et al., 1998; Peltier et al., 2002). Regional variations in past RSL provide valuable data for archaeological, ice-sheet dynamics, and Earth rheological studies. The high density of sea-level traces has given the coastal areas of western Estonia great potential for sea-level studies.

One of the main outcomes of shore-level studies is composing RSL curves, which show the water level in relation to the land in a certain area at a certain time. A comparison of the Holocene RSL curves which were compiled for various areas reveals the differences in the timing and amplitudes of the transgressions and regressions and allows to study sea-level fingerprints (Kendall et al., 2008; Mitrovica et al., 2011; Khan et al., 2019) in order to assess the impact of local events, such as the ice melting and lake drainage, upon global sea-level changes. Although numerous studies exist in regard to RSL changes in Estonia covering the first half of the Holocene (e.g. Ramsay, 1929; Kessel and Raukas, 1967; Königsson et al., 1998; Saarse et al., 2003; Rosentau et al., 2011), data is sparse where it concerns the Late Holocene regression period (Grudzinska, 2015). Late Holocene RSL data is necessary when it comes to constructing complete RSL curves, but it is also essential when predicting future RSL evolution, which must be based on a solid understanding of RSL history.

The main goal of current thesis is to reconstruct Holocene RSL fluctuations in western Estonia and to determine its relations with changes in prehistoric settlement pattern. The specific objectives of this dissertation are as follows:

- compiling new RSL reconstructions that are based on critically reviewed sea-level indicators in order to estimate the water-level amplitude and timing of Early- to Mid-Holocene regression and transgression episodes;
- quantifying Holocene RSL lowstands and testing hypotheses in regard to the possible existence and preservation of submerged landscapes in western Estonia;
- refining the timing and possible diachronicity of the Mid-Holocene RSL highstand in Estonia, and comparing the timing and pattern of RSL changes in areas of slightly different uplift rates in the periphery of the Fennoscandian uplift zone in order to clarify the causes of the RSL change;
- reconstructing Late Holocene RSL variability and its relation to present-day land-uplift, and evaluating the spatio-temporal accuracy of RSL change;
- specifying interactions between RSL changes and the displacement of prehistoric settlements in western Estonia through palaeogeographical methods in order to assess the direction of movement, settlement sensitivity to the position of the coastline, and its variability over time;
- implementing geoarchaeological approaches in terms of providing new palaeoenvironmental reconstructions of prehistoric coastal settlement sites in western Estonia.

This study comprises data from four scientific papers that address the Holocene RSL changes and geoarchaeology of the prehistoric sites in western Estonia, which are summarized in the following section.

PAPER I

Nirgi, T., Rosentau, A., Habicht, H.-L., Hang, T., Jonuks, T., Jõeleht, A., Kihno, K., Kriiska, A., Mustasaar, M., Risberg, J., Suuroja, S., Talviste, P., Tõnisson, H. (2020) Holocene relative shore-level changes and Stone Age palaeogeography of the Pärnu Bay area, eastern Baltic Sea. The Holocene 30: 37–52.

A buried river channel with up to 4.2-m-thick organic-rich infill was discovered and mapped in the Pärnu study area (Figure 1a). The channel sediments were studied on the coastal lowland and on the shallow seabed with several methods in order to reconstruct the local environment at the time of deposition and the Holocene RSL changes. The channel cuts through the glaciolacustrine varved clays to the glacial till surface and is covered by ca. 7-m-thick Litorina Sea sand deposit. Based on the sedimentary, diatom and pollen evidence, the sediments of the valley infill displayed three lithological units, which reflect the development of the river from an active period to a stable abandoned channel stage. The radiocarbon dates indicate an active river channel period between 10.76 and 10.57 cal. ka BP, followed by a gradual closing about 9.7–9.0 cal. ka BP and an abandoned phase between 9.0 and 8.1 cal. ka BP. The seismo-acoustic mapping of the shallow seafloor of the Pärnu Bay indicates the continuation of the initial channel of the River Pärnu on seabed up to ca. 5 km offshore and up to the water depth ca. 5.5 m.

The new data combined with previously published RSL records from Pärnu area show a rise of the Ancylus Lake (10.7–10.2 cal. ka BP) water level of about 18 m at an average rate of 35 mm/yr and rise of the Litorina Sea (8.5–7.3 cal. ka BP) about 14 m at an average rate of 12 mm/yr. The data suggests that RSL dropped at least down to –5.5 m a.s.l. before the AL transgression and at least to –4 m a.s.l. before the LS transgression.

PAPER II

Rosentau, A., Nirgi, T., Muru, M., Bjursäter, S., Hang, T., Preusser, F., Risberg, J., Sohar, K., Tõnisson, H., Kriiska, A. (2020) Holocene relative shore level changes and Stone Age hunter-gatherers in Hiiumaa Island, eastern Baltic Sea. Boreas, doi.org/10.1111/bor.12452.

A coastal landform system and Holocene organic sediments in present-day Kõivasoo Bog were investigated in the Kõpu Peninsula in the western part of Hiiumaa Island in order to reconstruct Stone Age palaeogeography of Hiiumaa and to clarify Holocene RSL changes since the Ancylus Lake transgression.

Kõpu coastal formations, which are surrounding the Kõivasoo Bog, can be divided into two sets. The first developed during the Ancylus Lake regression period ca. 10.0–9.9 ka and the second set during the Litorina Sea regression at ca. 6.4–3.9 ka. These two sets of landforms are separated by an unconformity related to the Litorina Sea transgression episode. During the Ancylus Lake regression, a freshwater mesotrophic Kõivasoo palaeolagoon formed between the sandy coastal formations in the Kõpu area with the accumulation of calcareous gyttja containing cold water ostracods and large lake diatoms typical to Ancylus Lake and Initial Litorina Sea. Due to the uplift of the basin above the threshold elevation, the lagoon was isolated from the BSB and turned into a coastal lake around 8.8 cal. ka BP. According to the age-depth model, the calcareous silt started to accumulate around 10.5 cal. ka BP and the overlying calcareous gyttja was deposited between 10.1 and 8.2 cal. ka BP. Then, after ca. 500-year-long hiatus the accumulation of gyttja begun, which was replaced by peat accumulation ca. 6.9 cal. ka BP. The reconstructed RSL curve reveals a 20 m drainage of Ancylus Lake followed by a land-uplift-driven 3-m regression during the Initial Litorina Sea period. The Litorina Sea transgression was less than 4 m in this area. During the 7.4–6.0 cal. ka BP, RSL fall was about 4.3 mm/yr and about 1 mm/yr less during the last 6000 years suggesting deceleration in the isostatic rebound.

Hiiumaa was first inhabited ca. 7.6–7.5 cal. ka BP, probably by hunter-gatherers from the Saaremaa Island. Palaeogeographic reconstructions show that the earliest campsites were established at shores of the Kõpu palaeobay successively at lower elevations following the shoreline retreat of the Litorina Sea, but Corded Ware and younger sites were not shore-connected.

PAPER III

Nirgi, T., Rosentau, A., Ots, M., Vahur, S., Kriiska, A. (2017) Buried amber finds in the coastal deposits of Saaremaa Island, eastern Baltic Sea – their sedimentary environment and possible use by Bronze Age islanders. Boreas 46: 725–736.

A layer of buried organic matter, sandwiched between sandy coastal deposits and containing pieces of natural amber, was discovered in the Holocene coastal plain in SW Saaremaa Island where amber is not known in sedimentary successions but is common in Stone Age and Bronze Age archaeological sites. The aim of the study was to clarify the origin of the amber findings in the village of Vintri and to describe their depositional environment using a multi-proxy approach combining sediment stratigraphy, geochemical analyses of amber finds and RSL reconstruction.

Infrared spectra and isotopic composition of the amber indicate that it is Baltic amber, also known as succinite, which is common in the SE coast of the Baltic Sea. The amber-bearing organic layer was well preserved probably due to its quick burial in the coastal zone and by favourable moisture conditions below the local groundwater table. According to the radiocarbon dates this layer was deposited during the Late Bronze Age, about 2.7–2.5 cal. ka BP. A palaeogeographical reconstruction shows that the study area was separated from the Saaremaa mainland by two narrow straits. The amber was probably transported to Saaremaa within organic matter along the main SW–NE orientated current flows from the southern Baltic where Paleogene and Quaternary amber deposits are known to exist widely.

The study shows that during the Late Bronze Age natural amber accumulated in the coastal zone of Saaremaa Island and that the islanders had the possibility of collecting it.

PAPER IV

Nirgi, T., Grudzinska, I., Kalińska, E., Konsa, M., Jõeleht, A., Alexanderson, H., Hang, T. Rosentau, A. (manuscript). Late Holocene relative shore-level changes and palaeoenvironment of the Pre-Viking Age ship burials in Salme, Saaremaa Island, eastern Baltic Sea.

Two unique Pre-Viking Age ship burials were found from Salme village, Estonia, containing the remains of seven men in the smaller and 34 men in the larger ship. According to the archaeological interpretations, these ships belonged to a Viking crew possibly from the Stockholm-Mälaren region. Geoarchaeological research was conducted to reconstruct Late Holocene RSL changes and palaeogeography of Saaremaa and Salme area to provide a palaeoenvironmental background to the burials. Another aim was to test the hypothesis of the possible existence of the Salme palaeostrait and to reconstruct its configuration during the Vendel Period. Thus, the sediments of the Salme coastal landforms and former strait were studied by combining geological and archaeological proxies together with AMS radiocarbon and OSL dating methods.

Late-Holocene RSL curve for the last ca. 3000 shows almost linear RSL fall from the 5.5 m a.s.l. to present-day level with an average rate of 2 mm/yr and a slight slowdown in regression after 1300 AD.

Salme I and II ships were buried around 700–750 AD into the sandy-gravelly coastal deposits which accumulated in the open coastal zone about 710–450 years earlier, around 60–320 AD. Reconstructions show that the burials were located about 2–2.5 m above coeval sea-level and at 130–170 m from the coastline. Thus, it is likely that both ships were moved from the shore to the higher ground for burial. Palaeogeographic reconstructions display up to 2.8-m-deep semi-enclosed strait at 750 AD with 80–100 m wide eastern part. About 170 years after the burial of the Salme ships the strait began to fill with laminated silty gyttja. Sedimentological evidence and diatom data refer to the following closing of Salme palaeostrait between 1270–1300 AD.

2. BACKGROUND

2.1 Post-glacial development of the Baltic Sea

The development history of the modern Baltic Sea dates back to the end of Late Weichselian glaciation, about 20–19 cal. ka BP, when after ca. 7 ka-long period of low global sea level (Lambeck and Chappell, 2001; Peltier and Fairbanks, 2006; Clark et al., 2009; Lambeck et al., 2014) the Scandinavian Ice Sheet started to retreat at its southern margin (Hughes et al., 2016; Stroeven et al., 2016). Release of significant volume of meltwater from the retreating ice sheet and ice margins blocking the natural drainage caused the formation of proglacial lakes along the glacier margin. Thus, deep freshwater **Baltic Ice Lake** (BIL) developed along the southern margin of Scandinavian Ice Sheet, in the Baltic Sea basin, at ca. 16.0 cal. ka BP (Andrén et al., 2011). Its size and water level varied considerably depending upon the position of the retreating ice margin, isostatic rebound and the location of outlets.

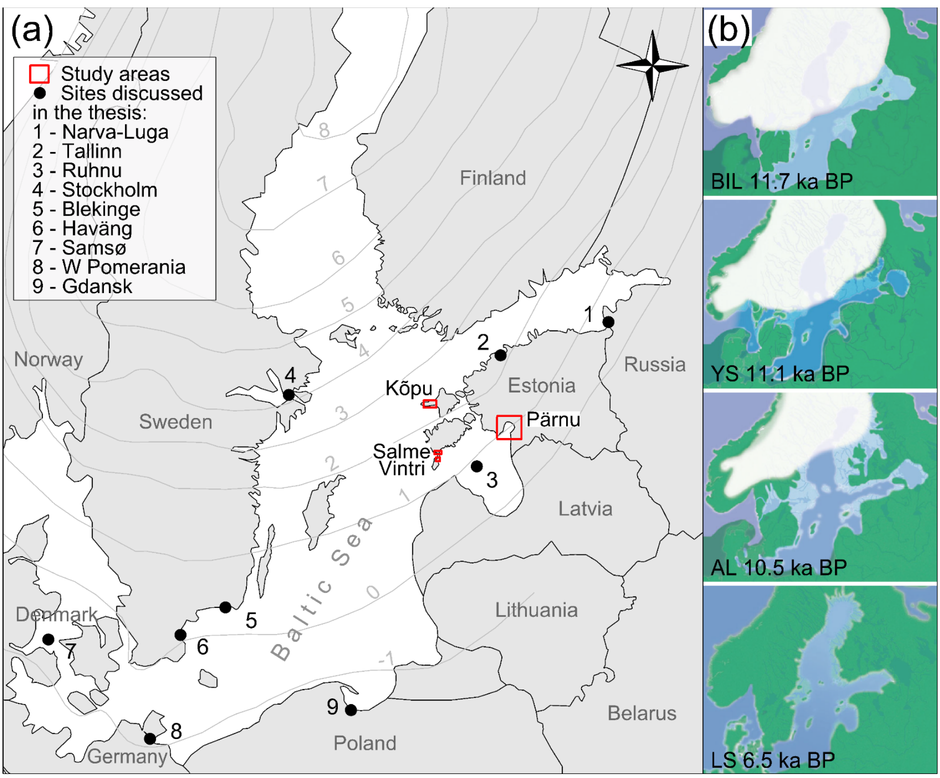

Figure 1. a) An overview map of the BSB with present-day apparent land uplift isobases (mm/yr, Ekman, 1996), the locations of the study areas and sites discussed in the thesis. **b)** Late and postglacial development of the BSB (Andren et al., 2011)

During the initial stage of the BIL (Figure 1b), it was most likely at level with the sea, but as the isostatic rebound was greater than the sea-level rise, the BIL rose above the sea level (Andrén et al., 2011). Therefore, the BIL advanced and retreated several times before final drainage to the ocean through central Sweden in the Billingen area at ca. 11.7 cal. ka BP (Björck, 1995; Bodén et al., 1997; Andrén et al., 2011). The drainage lasted ca. 1–2 years and resulted in ca. 25 m drop in water level (Björck et al., 1996; Mäkinen and Räsänen, 2003), which is the reason, why coastal landforms of the BIL are now far inland in Estonia. The final drainage of the BIL, which coincides with the start of the Holocene Epoch, marks the beginning of the **Yoldia Sea** (YS; Figure 1b) in the history of the Baltic Sea.

Even though the water level of the BSB was low enough to allow water-exchange with the Atlantic Ocean through the straits of the south-central Swedish lowland and Lake Vänern (Andrén et al., 2002), the first ca. 300 years of the YS was characterized by freshwater conditions (Svensson, 1989; Wastegård et al., 1995; Heinsalu and Veski, 2007). Later, as the meltwater input from the receding ice decreased in relation with the Preboreal Oscillation and water-exchange with the ocean increased (Björck et al., 1996, 1997), the YS became gradually brackish (Andrén et al., 2002). Brackish conditions have been indicated by the diatom record in sediment sequences of YS age from several parts of the BSB, e.g. from the eastern Gotland Basin (Andrén et al., 2000) the Landsort Deep (Lepland et al., 1999), the Bornholm basin (Andrén et al., 2000), the Gdansk Bay offshore of the Lithuanian coast (Kabailiené, 1995) and from the Gulf of Finland (Heinsalu and Veski, 2007). However, after up to 350 years of brackish period, the high land uplift rate caused the shallowing of the straits and increased outflow from the BSB, which, in turn, prevented the inflow of saline water to the BSB and turned the YS into a freshwater basin again (Andrén et al., 2000). At the end of YS, most of present BSB was deglaciated, except for the Bothnian Bay (Andrén et al., 2011).

Closing of the straits in central Sweden, that decreased the water exchange with the ocean in tandem with glacial meltwater inflow, led to a rapid water-level rise in the BSB (Andrén et al., 2000, 2011). This marks the end of the YS and the beginning of the freshwater **Ancylus Lake** (AL) at around 10.7 cal. ka BP (Björck, 1995). The AL transgression was a rapid and uninterrupted event (Kessel and Raukas, 1979; Björck, 1995; Saarse et al., 1997, 2006; Berglund et al., 2001; Veski et al., 2005). While the northern areas of the BSB experienced a more or less slowing regression at that time, the extent of the transgression in the central and southern part varied largely due to isostatic rising or submerging (Andrén et al., 2011). According to numerous ^{14}C dates of peat and tree remains buried under the beach deposits around the BSB, the time span for AL transgression has been estimated to ca. 500 years (Andrén et al., 2011). In Estonia AL transgression culminated at around 10.2 cal. ka BP (Veski et al., 2005; Rosentau et al., 2013) leaving behind clearly defined raised beaches. The water level in the up-dammed AL (Figure 1b) was ca. 10 m above the global sea level (Björck et al., 2008) before it started to lower again.

AL regression history has been a subject of debate for many years (von Post, 1929; Björck, 1995; Bennike et al., 1998; Lemke et al., 1999, 2001; Björck et al., 2008 etc.). It has been mostly disputed whether the drainage was rather sudden or calm until Lemke et al. (2001) showed that it could not have been rapid but may have caused an initial lowering of the AL about 5 m through the river system in the German-Danish area (Björck et al., 2008). When the sea level in Kattegat had reached the level of the AL, it became possible for saltwater to flow through the river system into the Baltic again (Andren et al., 2011). The water-level lowering together with the first signs of marine influence about 9.8 cal. ka BP has been considered to mark the end of the AL and the onset of the **Initial Litorina Sea** (ILS) (Berglund et al., 2005; Andren et al., 2011).

In Estonia the ILS, earlier described also as Mastogloia Sea, can be characterized as a long and stable period with relatively low water level, thus organic-rich deposits from that period are significantly more expressive compared to the pre-AL deposits. Due to the lack of clear biostratigraphic evidence of salinity change with almost balance between eustasy and isostatic rebound along the Estonian coast, this transitional period has been inconsistently addressed in the history of the Baltic Sea research in Estonia and has been linked to the subsequent Litorina Sea in numerous studies.

About 8.5 cal. ka BP the water level in the BSB started to rise again, marking the end of the ILS and the beginning of the brackish **Litorina Sea** (LS) (Andren et al., 2011), also called Littorina Sea (after a mollusc *Littorina littorea*) in the literature of S and W parts of the Baltic Sea. The main mechanism behind the onset of the LS is believed to be the rising sea level due to melting of the Laurentide and Antarctic ice sheets, which caused ca. 30-m rise in the absolute sea level (Lambeck and Chappell, 2001). The LS transgression in Estonia culminated at ca. 7.3 cal. ka BP (Veski et al., 2005, Saarse et al., 2009; Rosentau et al., 2013) and since then the RSL in Estonia has been regressive. So-called LS transgressions (Berglund, 1964; Berglund et al., 2001, 2005; Mörner, 1970; Seppä et al., 2000; Christensen and Nielsen, 2008), caused by eustatic sea-level fluctuations due to episodic melting events of large ice sheets, have not been recognized in Estonian RSL records. The initially high rates of the RSL rise culminated in the establishment of a highstand with the highest shoreline reaching 7–27 m a.s.l. (Saarse et al., 2003). Afterwards, the RSL lowering started, evidenced by coastal formations (Rosentau et al., 2013) and isolated lake basins (Grudzinska et al., 2013) found on gradually lower elevations along the coastal areas.

Due to the slowdown in global sea-level rise around 7.0 cal. ka BP (Lambeck et al., 2014), the isostatic land-uplift started to dominate along the Fennoscandian uplift periphery and gave rise to regressive shore displacement and paludification between the highest LS and the present-day coastline (Rosentau et al., 2011). Still, minor sea-level fluctuations lasted between 7.3–3.7 cal. ka BP (Christensen, 1995; Clemmensen et al., 2012). Mollusc fauna, isotopic composition of shells and diatom stratigraphy of offshore sediments demonstrate the maximum post-glacial salinities in the Baltic basin around 6.0 cal. ka BP (Hyvärinen et al., 1988;

Westman and Sohlenius, 1999). Due to the decrease of the outlet area through Danish straits coupled with the increase in climate-driven fresh-water discharge (Gustafsson and Westman, 2002; Zillén et al., 2008) the salinity in the Baltic Sea basin gradually declined since around 4.5 cal. ka BP (Grudzinska, 2015) which is proposed to mark the boundary between LS and subsequent **Post-Litorina Sea (PLS)** which in Baltic Sea research in Estonia and Finland is consistently addressed as **Limnea Sea**. Since then the RSL in Estonia has been regressive due to the continuous glacial isostatic adjustment outpacing the declining rates of post-glacial absolute sea-level rise in the Mid-Atlantic period (Lambeck et al., 1998).

2.2 RSL and settlement history of eastern Baltic Sea

Shore displacement in the Baltic Sea basin has been caused by interactions between (global) changes of eustatic sea level, (local) postglacial isostatic adjustment processes and periodic up-damming and drainage of the basin. **Eustatic** changes are primarily governed by water being added to or subtracted from the ocean through exchange with ice held in the polar ice caps (Lambeck, 1990). For example, expanding of ice sheets during the LGM caused ca. 130 m fall in global sea level (Lambeck and Chappell, 2001; Clark et al., 2009; Lambeck et al., 2014; Peltier et al., 2015). However, eustatic sea-level rise may also be reduced or even reversed by the progradation or in other words, by coastal sediment-transport and accumulation (van der Noort, 2013). **GIA** describes the response of the Earth's surface to the build-up and decay of glaciers. The most known component of GIA, so-called „postglacial rebound", relates to the uplift of the land surface due to the melting of a glacier. The uplift was most rapid at the beginning of deglaciation and although the ice retreated from the Baltic Sea basin about 10 cal. ka BP (Lambeck et al., 2010; Andrén et al., 2011) and the uplift rate has been gradually slowing, the Earth is still readjusting due to the viscoelastic nature of the mantle (Påsse, 2001; Steffen and Wu, 2011; Whitehouse, 2018; Olsson et al., 2019). The GIA rate depends upon the thickness of the ice sheet in a specific area, thus, the greatest and the most rapid uplift is characteristic to the regions with the thickest ice sheet, such as the northern part of Bothnian Bay, ca. 1 cm/yr (Steffen and Wu, 2011). If the isostatic uplift rate in a certain area during a given period exceeds the eustatic rate, the resulting situation is defined as regression (RSL lowering). The opposite case results as a transgression (RSL rise).

Variations in GIA rates have caused significant differences between RSL changes in different parts of the BSB (Figure 2). For example, since the onset of the Litorina transgression at about 8.0 cal. ka BP the areas with higher GIA rates in the NW parts of the BSB have been dominated by continuous regression, whereas in the areas with lower uplift rates the RSL has been transgressive (Rosentau et al., 2017; Muru, 2017).

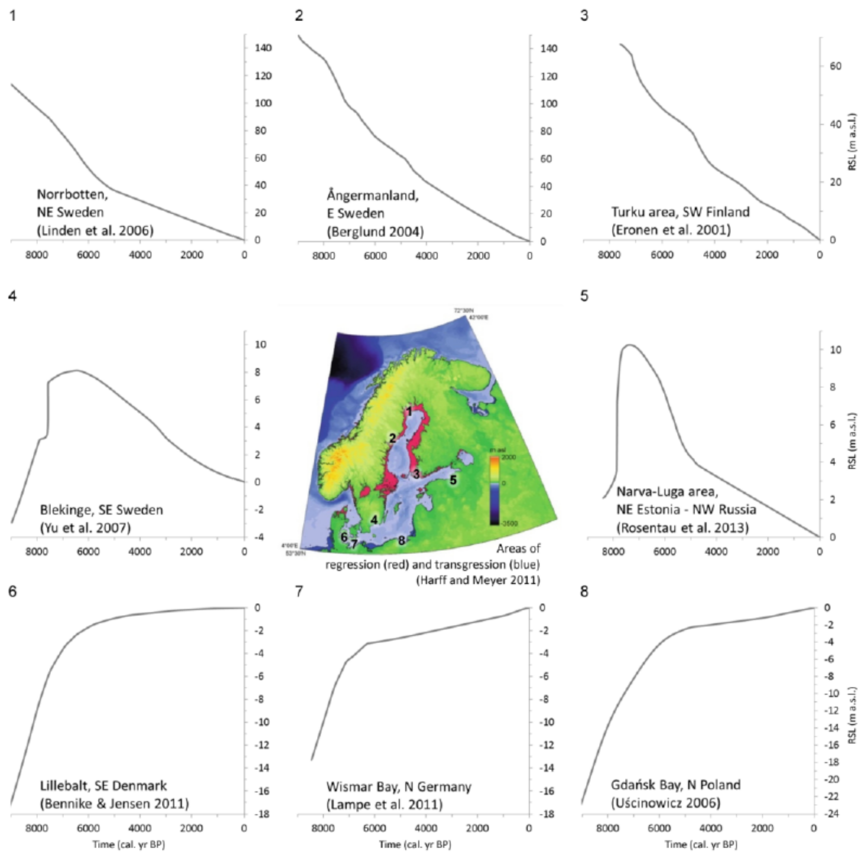

Figure 2. The RSL changes in different parts of the BSB since the onset of the Litorina transgression at about 8.0 cal. ka BP. Figure from Rosentau et al. (2017).

The RSL curves for Estonia display three prominent regression phases interrupted by the AL and LS transgressions. There are sufficient data about RSL highstand periods because the highest shorelines of AL and LS can be followed in the relief. However, there are less data (sea-level index points; see ch. 4.1.1) regarding the lowstand periods, as concurrent sediments are buried under several metres of subsequent transgressive sediments and are therefore much more difficult to access. Thus, the timing and levels of the RSL lowstands need further clarifications.

The transgression and regression rates and the highest and lowest RSL levels vary considerably in different regions in Estonia, depending upon the variations in GIA rates. For example, the AL transgression reached ca. 5–46 m a.s.l. at ca. 10.2 cal. ka BP and the LS maximum levels reached ca. 7–27 m a.s.l. (Saarse et al., 2003). On both cases, the highest relative shore levels characterize the NW parts of Estonia, such as, for example, Hiiumaa Island where the GIA rates are the highest, while towards SE the shore levels are successively lower due to slower uplift rates (Figure 2). Nevertheless, the main temporal patterns of RSL fluctuations in Estonia (e.g. the age determinations of AL and LS RSL culminations) are rather similar due to the relatively small area. On the larger scale, the patterns may be different and the timing of the fluctuations slightly asynchronous. For example, according to some Swedish and Danish studies, the LS transgression consisted of several transgressive episodes (e.g. Berglund et al., 2001, 2005; Mörner, 1970; Seppä et al., 2000; Christensen and Nielsen, 2008; Barliaev, 2017), but in Estonia and Finland only one uniform transgression has been described (e.g. Eronen et al., 2001; Miettinen, 2002; Saarse et al., 2009; Rosentau et al., 2013; Muru et al., 2017). Such discrepancy probably results from differences of the isostatic and eustatic changes among the mentioned regions.

The surroundings of the Baltic Sea have one of the highest densities of sea-level data in the world, including geological, geomorphological and biostratigraphic evidence, but also archaeological evidence from submerged and uplifted shore-bound Mesolithic sites. This offers a good opportunity for multidisciplinary geoarchaeological studies which in western coastal Estonia have been in a growing trend. Geoarchaeology is a growing subfield of cross-disciplinary research at the intersection between geomorphology, environmental history, and archaeology (Butzer, 2008). In other words, it combines methods of the geosciences to address archaeological questions, such as discovering new archaeological sites and documenting their internal structure, analysing sediments, soils, and human impact on the landscape and creating paleoenvironmental reconstructions, but it also includes the physical analysis of archaeological materials and the integration with social archaeology. Using the GIS approach with increasingly detailed elevation data provides new insight into the prehistoric settlement pattern in the context of Holocene RSL changes. Analysing sea-level change at different temporal and spatial scales helps us to understand, how these changes influenced prehistoric people in coastal regions (Asturp, 2018).

The onset of the Holocene at 11.7 cal. BP marks the beginning of the current warm period, but at the beginning, the climate was still generally cool and moist (Seppä et al., 2005). Although Paleolithic reindeer (*Rangifer tarandus*) hunters started to colonize ice-free areas near the retreating ice-sheet margin already during the BIL (Terberger, 2006) and their communities occupied the area from the southern Baltic Sea region to the River Daugava and Lielupe terraces in Latvia (Zagorska, 2007; Zvelebil, 2008), the signs of human occupation in Estonia at that time are not known.

The emergence of new land during the YS lowstand in combination with the rapid amelioration of climate at around 11.5 cal. ka BP favoured the spread of forests and thus, provided more varied subsistence for people, including plants, fruits, terrestrial and also marine mammals and fish (Bell and Walker, 2005; Jöns, 2011). Highly articulated coastline and emerging archipelagos turned out to be suitable for first coastal settlements, where the Late Palaeolithic/Early Mesolithic people already exploited marine resources. The establishment and end of these settlements depended directly upon local RSL changes (Fischer, 1996; Gustafson, 1999). No settlements from that time have been found in Estonia. Even if there were settlements established along the coast of the YS at the lowstand period, these were buried during subsequent transgression phases and are still undiscovered.

The size of Mesolithic human population in Europe was generally low and the density and distribution mainly depended upon the proximity of the coastline (Price, 1999), being the highest among the coastal hunter-gatherers (Kelly, 1995; Astrup, 2018). The habitation of Mesolithic people spread along the coasts of the Ancylus Lake, and some of them also reached Estonia (Lang and Kriiska, 2001). These people were generalists who were able to exploit different kinds of resources available in their vicinity (Zvelebil, 2008; Jöns, 2011). The earliest known human settlement in Estonia, a seasonal hunting and fishing camp Pulli was established ca. 11.1–9.9 cal. ka BP at the lower reaches of the River Pärnu (Lõugas, 1997; Poska and Veski, 1999; Kriiska and Tvauri, 2007). The location near the river and forest offered various options for providing food. The site was later flooded in course of the AL transgression (Lõugas, 1997; Poska and Veski, 1999; Veski et al., 2005; Rosentau et al., 2011).

At about 9.8 cal. ka BP, when the Scandinavian Ice Sheet was fully melted, the people had settled all areas around the BSB (Zvelebil, 2008). In the eastern Baltic Sea region, the first signs of coastal lifestyle are known from the second half of the Mesolithic period between 9.8–8.5 cal. ka BP (Kriiska, 2001; Gerasimov et al., 2010; Jöns, 2011). The choice of settlement locations followed the gradually changing coastline of the Baltic Sea (Kriiska, 2001; Jussila and Kriiska, 2004) and the most preferred locations were associated with river mouths (Nuñez and Okkonen, 1999; Rosentau et al., 2011), sheltered bays, archipelago systems (Kriiska, 2003) and coastal lakes and lagoons (Kriiska, 2000; Bērziņš, 2008). Due to favourable conditions for human occupation, western Estonia with its islands is rich in Stone Age archaeological finds.

Due to the sea-level rise and widening connection to the ocean, the brackish environment spread all over the BSB around 8.5 cal. ka BP, increasing primary production and the number of species. After the gold event at 8.2 cal. ka BP, which was probably triggered by a major pulse of freshwater from glacial Lakes Agassiz and Ojibway to the North Atlantic (Barber et al., 1999; Clark et al., 2001; Clarke et al., 2003), began a dry, warm and stable climate period, called the Holocene Thermal Maximum (Seppä et al., 2005). The spread of abundant shore-bound settlements all over the coasts of the Baltic Sea increased at this period because people did not have to move their coastal settlements as often due to a more stable coastline configuration (Astrup, 2018). This also favoured the development of the maritime economy of humans, with seal and porpoise hunting as the primary subsistence strategy (Christensen, 1995; Larsson, 1997; Kriiska, 2000; Kriiska and Lõugas, 2009; Jöns, 2011).

Therefore, the onset of coastal habitation around the BSB dates back to ca. 11 cal. ka BP and it continued in many areas until the Neolithic times around ca. 6 cal. ka BP. Due to differential regional glacio-isostatic land uplift and eustatic sea-level rise, these Mesolithic and Neolithic coastal settlements around the BSB are now located at different altitudes. In the southern Baltic Sea region, where transgression episodes have been more extensive, many settlement sites have been found in the present seabed (Fischer, 2011; Lübke et al., 2011). However, in the northern Baltic Sea region, prehistoric coastal settlements have been uplifted because of post-glacial rebound (Siiriäinen, 1982; Vaneeckhout, 2008). In the transitional areas in the Baltic Sea region, terrestrial landscapes and associated coastal settlements experienced transgression and regression phases owing to competition between glacial isostatic land uplift and eustatic sea-level rise. There some prehistoric settlements have been submerged (Hansson et al., 2018a, 2018b, 2019), and some are located inland due to slow postglacial uplift (Rosentau et al., 2011, 2013). However, the latter were buried under the sediments of the transgressional periods when the sea-level rise temporarily exceeded the land uplift in this region (Jussila and Kriiska, 2004; Veski et al., 2005; Gerasimov et al., 2010; Rosentau et al., 2011).

The introduction of agriculture and animal husbandry to the Baltic Sea region around 6.0 cal. ka BP brought a change in this settlement pattern (e.g. Andersen, 1993; Ahlfont et al., 1995) because people started to move away from the coast to arable farmlands (Schmölcke et al., 2006; Jöns, 2011). However, the discoveries of fishing and hunting tools and bones of marine mammals, together with pottery, indicate that many settlements were still established on the eastern coasts of the Baltic Sea until the Late Neolithic period (Kriiska, 2003; Veski et al., 2005; Bērziņš, 2008; Gerasimov et al., 2010).

At the beginning of the PLS at about 4.5 cal. ka BP (Hyvärinen et al., 1988; Grudzinska, 2015), the coastal zone had lost its centrality for the inhabitants' nutrition due to the spread of farming and gained new importance for trade and communication. Since then, the Baltic Sea, together with nearby rivers and lakes, formed a prehistoric transportation network (Jöns, 2011). The remains of harbours and jetties provide useful information about RSL changes in the Late Holocene.

3. MATERIAL AND METHODS

3.1 Description of the study areas

The study areas in western Estonia are located along the periphery of the Fennoscandian isostatic land uplift zone in the eastern Baltic Sea region (Figure 1a), where the Holocene RSL history has been complex, with alternating transgression and regression periods. Two of the study areas, Vintri and Salme, are located on Saaremaa Island, north of the Gulf of Riga and Pärnu site lies on the north-eastern coast of the Gulf of Riga. The fourth site is located on the Kõpu Peninsula of the Hiiumaa Island, on the eastern coast of the Baltic Sea Proper.

Vintri and **Salme sites** on Saaremaa Island are located on the eastern coast of Sõrve Peninsula. The main topographic features of the area are inherited from the last glaciation and were later reworked by waters of the Baltic Sea. The area is characterized by slow postglacial isostatic rebound, with apparent uplift (relative sea-level rise) rates of about 1–1.5 mm/yr (Ekman, 1996) and absolute isostatic uplift of about 2.3 mm/yr (Suursaar et al., 2019). A buried amber-bearing organic deposit was discovered in Vintri village about 500 m from the present coastline in the area of about 60–100 m^2 (Ots, 2012). The discovery of this unique deposit (first of its kind in Estonia) has created a possibility to hypothesize that some prehistoric archaeological amber found on Saaremaa Island may be of local origin.

Salme site is located in Salme village, on both sides of River Salme. The river is a relict of Salme palaeostrait, which was a part of a trade route and a passage to settlements on the coast of Saaremaa during the Viking Age and before it. The easternmost part of Salme River flows through a sandy-gravelly beach deposit. On the eastern side, the beach deposit has formed a steep slope bordered by the sea, whilst on the west, the relief lowers slowly towards the Salme River. Most of the Salme palaeostrait can now be described as a low coastal plain. A unique burial of two rowing ships has been discovered in Salme, containing Scandinavian type artefacts and remains of human and animal skeletons (Konsa et al., 2009; Peets et al., 2011, 2013; Price et al., 2016). The burial has been dated to the Pre-Viking Age, around 750 AD (Peets et al., 2011).

The **Pärnu study area** encompasses the inner part of the Pärnu Bay and the surrounding coastal lowland of SW Estonia, including the surroundings of the River Pärnu. The river channel is up to 300 m wide and 10 m deep (3–4 m on average) and is characterized by low gradient (0.5 m along its ca. 6 km long lower reaches) in longitudinal profile and low flow energy. The River Pärnu drains into the Pärnu Bay, which is a shallow (depth up to 8 m) semi-enclosed basin in the NE part of the Gulf of Riga. Presently, the area is characterised by slow postglacial isostatic rebound with relative uplift rates of about 1 mm/yr (Ekman, 1996) and absolute isostatic uplift of about 1.7 mm/yr (Suursaar et al., 2019). The low topography of the area makes it highly sensitive to even minor changes in relative water levels of the Baltic Sea, thus there are several coastal wetlands, which were once lagoons or bays (Habicht et al., 2016). The Pärnu area is rich in Stone Age archaeological finds, such as, for example, the oldest known settlement site in Estonia, Pulli. Settlement sites are concentrated along the banks of rivers and by the sea and follow the gradually changing coastline of the Baltic Sea. In addition, a rich collection of archaeological finds from the Early Mesolithic up to the Middle Ages have been found from the riverbed of the lower reaches of the River Pärnu, which are not related to any known settlement site.

Hiiumaa Island lies in the eastern part of the BSB, ca. 22 km west of the mainland Estonia. Our study area with Kõivasoo bog and surrounding coastal landforms is located in the central part of the ca. 20-km-long Kõpu Peninsula (Figure 1a). Steep sloped Kõpu upland forms a central part of the peninsula with a 10 m high Tornimägi hill (68 m a.s.l.) in its western part and highest dunes of the island in the eastern part. Kõivasoo is a small raised bog in the central part of the Kõpu Peninsula, which is surrounded by a series of coastal scarps in the north and low sandy spit formations in SW and SE. The apparent uplift rate in the area is about ca. 2.4 mm/yr (Ekman, 1996) and absolute isostatic uplift about 3.2–3.3 mm/yr (Suursaar et al., 2019; Vestøl et al., 2019). 17 Stone Age settlement sites are known from Hiiumaa, all in Kõpu Peninsula. Most of the discoveries belong to the Mesolithic period – from pre-pottery time to Narva Culture, but some Neolithic Comb Ware culture and one Corded Ware culture site are also represented.

3.2 Fieldwork and sedimentological analyses

The fieldwork for each study included surveying and coring in the study area. Different techniques were used for coring: a Russian-type peat corer for organic and organic-rich sediments in Kõivasoo bog, Salme site and Pärnu Bay (Figure 3b, d); a drilling rig with an auger drill was used to extract sediments in Pärnu site (Figure 3a), where organic sediments were buried deep under the Litorina Sea sand; and a window sampler combined with a percussion coring device (Figure 3c) was used to describe the mineral sediments below the digging range. Altitudes of the coring sites were determined from the LiDAR digital elevation model (DEM) or using real-time kinematic (RTK)-GPS.

The stratigraphy of the sediment cores was described in the field and samples for sedimentological, biostratigraphical and age determination analyses were collected later in the lab, except for luminescence samples, which were collected directly from the certain sediment layer in the field (Figure 4a). The luminescence samples were collected from the seaward side of the beach ridges from undisturbed sandy sediments using the opaque plastic tubes.

The content of organic matter in the sediment samples was determined by loss-on-ignition (LOI), following the methodology of Sutherland (1998) and Heiri et al. (2001). The grain size distribution in the mineral component was analysed using the Mastersizer 3000 laser diffraction particle size analyser, which measures the intensity of light scattered as a laser beam passes through a dispersed sample and then calculates the size of the particles that created the scattering pattern (Malvern Instruments Ltd., 2013). Before measurement, the samples were dispersed using a sodium pyrophosphate solution and ultrasonic action. The degree of sorting and grain sizes were classified following the methodology provided by Folk and Ward (1957). Grain characteristics such as mean grain size and sorting were analysed using the computer program GRADISTAT (Blott and Pye, 2001).

Figure 3. Different techniques of coring during the fieldworks: **a)** using a drilling rig with an auger drill in Pärnu site; **b)** using a Russian-type peat corer at Kõivasoo bog; **c)** using a window sampler combined with a percussion coring device in Vintri site; **d)** using a Russian-type peat corer from the ice cover of the Pärnu Bay.

3.3 GPR and seismo-acoustic survey

Ground-penetrating radar (GPR) surveys were conducted in the Pärnu, Kõpu and Salme areas to get more information about the bedding and distribution of sediments in the areas between the coring sites (Figure 4b). Different GPR systems were used at fieldworks: a 300 MHz Zond 12-e system (Radar System Inc.) with 100 MHz antennae in the Pärnu and Salme areas, and a GSSI SIR-3000 radar with a single-channel 270 MHz antennae in the Kõpu area. The data were processed using either the PRISM2 or Radan 7 software, which allows the necessary corrections to be made on the profiles, e.g. removing low-frequency induction effects, improving the readability of deeper reflections, applying topographical corrections based on LiDAR data, and converting the measured time-scale to depth-scale.

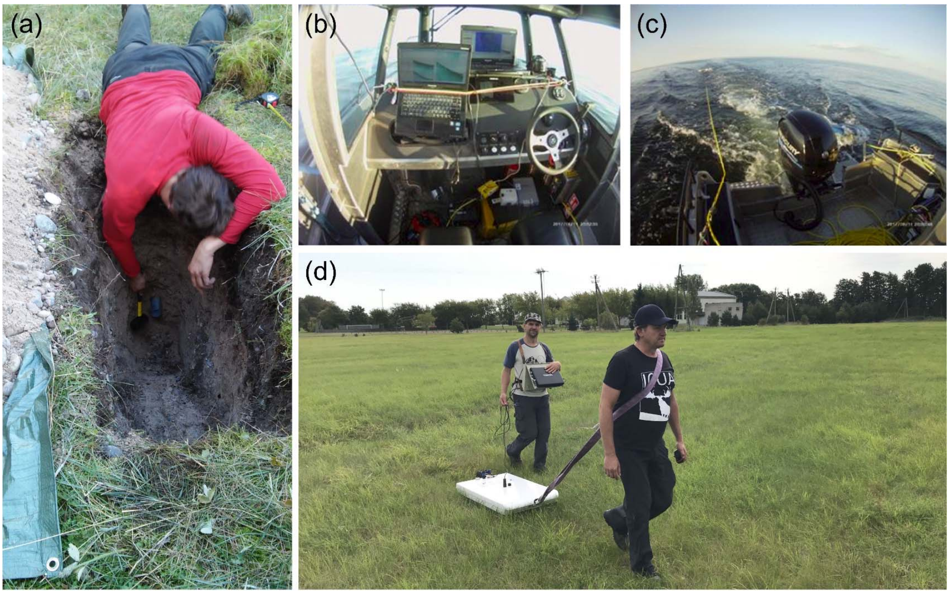

Figure 4. Some examples of other kinds of fieldworks: **a)** collecting luminescence samples from the Salme area; **b, c)** equipment used for seismo-acoustic mapping the offshore of the Pärnu Bay; **d)** a GPR profiling in the Salme area.

The seismo-acoustic mapping of the shallow seafloor of the Pärnu Bay (Figure 4b, c) was carried out using a 7-meter-long aluminium vessel and the following equipment: low frequency (0.4–24 kHz transducer) boomer type profiler, multi-frequency (2–9 kHz and 10–20 kHz transducers) chirp type profiler and Sparker type high frequency (24 kHz transducer) profiler. Side-scan sonar with 900 kHz frequency was used for better interpretation and understanding the relations between sea-bottom surface sediment characteristics, bottom configuration and seismic profiles. The position of the profiles was continuously measured by using Trimble R8 RTK-GPS GNSS system and the Estonian Land Board reference stations network was used for signal corrections, allowing cm precision for the measurements. The data were collected using Meridata Collecting software (MDCS) ver. 5.2. and analysed using Meridata Processing software (MDPS) ver 5.2.

3.4 Chronology and RSL reconstructions

Seeds of terrestrial plants and pieces of wood were collected from the sediments for AMS (Accelerator Mass Spectrometry) radiocarbon dating, and the samples were analysed in Beta Analytic Radiocarbon Dating Lab, USA and Tandem Laboratory, Sweden. Some archaeological objects were dated at the Leibniz Lab for Radiometric Dating & Stable Isotope Research, Germany and at the Poznań Radiocarbon Laboratory, Poland. The radiocarbon ages were converted to calibrated ages (cal. ka BP, within 2 sigma deviation – probability 95.4%) using the IntCal 13 calibration curve (Reimer et al., 2013) in the OxCal v4.2.3 software (Bronk Ramsey, 2009). The same program (with P_sequence option) was used to create age-depth models to assess the sediment accumulation rate for the whole sediment sequence of interest.

Luminescence dating measurements were carried out at the University of Bern, Switzerland (samples from Hiiumaa) and in Lund Luminescence Laboratory, Sweden (samples from Salme). The luminescence ages for Kõpu site were determined as IRSL (infrared stimulated luminescence) ages and ages for the Salme area as OSL (optically stimulated luminescence) ages. Elevation of each sample was corrected to correspond to the elevation of the lower limit of aeolian sediments of the sampled beach ridge, inferred from sediment cores.

Previously published dates together with new radiocarbon and luminescence dates from geological and archaeological sites were used to compile a database of the shore displacement indicators for each study area. The data was reported following the HOLSEA sea-level database format, which offers the most comprehensive approach to a unified sea-level database construction, with several error sources (Hijma et al., 2015). Newly calculated errors may differ from originally published data, which may lead to revised rates for RSL change, and to improved palaeoreconstructions. After the data were critically reviewed (see ch. 4.1.1), only reliably dates were used to reconstruct the shore displacement curve. The elevations of the sample sites were corrected against the differential land uplift according to the methodology described in Rosentau et al. (2011) and all sites were transposed to the central parts of the study areas. The elevations of the pre-Ancylus Lake and Ancylus Lake sites were corrected in respect to the AL shore-level surface and the Initial Litorina and Litorina Sea sites in respect to the modelled LS surface (Saarse et al., 2003; 2007). For correction of the LS regression sites, the LS surface was combined with the Baltic Sea surface at 100 years ago (Ekman, 1996) assuming a linear decay in shoreline tilting gradient. The differences in elevations were calculated depending upon the age of each site. This spatio-temporal interpolation method was used for shore displacement modelling as well as for palaeogeographic reconstructions.

3.5 Palaeogeographic modelling

Palaeogeographic reconstructions were generated using DEM in order to clarify the locations of historical shorelines for understanding the situation of coastal areas and to provide helpful visualisations of past periods.

The palaeogeographic reconstructions were created for each study area using the LiDAR elevation data (Estonian Land Board 2012–2020) and GIS approach (MapInfo Professional 10.5 with Vertical Mapper 3.7 or ArcMap 10.5). The high-resolution LiDAR elevation data provides an excellent source for the analysis of the coastal development based on detailed analysis of relief and morphology of the landforms (Muru, 2017). The bathymetric data for Pärnu Bay were provided by the Estonian Maritime Administration. The modelling is based on the subtraction of a palaeo-water-level surface model (which is deformed due to uneven land-uplift) from the present-day digital elevation model (Rosentau et al., 2011). The interpolated water-level surface for the modern Baltic Sea is based on sea-level measurements complemented by geodetic data (Ekman, 1996). The surfaces of the Ancylus Lake and the Litorina Sea maximum water levels were interpolated by Rosentau et al. (2011) using the Holocene shoreline displacement database for eastern Baltic Sea, compiled by Saarse et al. (2003). To compensate for the uneven postglacial land uplift, the water-level surfaces followed the mean isostatic tilting gradients for the periods of interest. The tilting gradient and the water level for the interstage surfaces between the AL, LS and present-day sea level were calculated following the methodology provided by Habicht et al. (2017). In order to create accurate palaeoreconstructions, the younger sediments were subtracted from the LiDAR-derived DEM based on available data from fieldwork and published sources.

GIS-based viewshed analysis was applied to identify the possible sea-crossing routes into the study area at Hiiumaa Island during the time of the Litorina Sea high-stand (Rennell, 2012; Astrup, 2018). This method estimates the line of sight between the DEM-model and the horizon or surrounding landforms and shows the area (a view zone) where any specific point (e.g. the highest top of some landform) could be seen.

The mean elevations of the highest shorelines of the study areas were also calculated based on the LiDAR-DEM by mapping and measuring the ridges or escarpments which indicate the palaeoshoreline position.

4. RESULTS AND DISCUSSION

4.1 Holocene RSL changes in western Estonia

4.1.1 RSL indicators and vertical and chronological uncertainties in RSL data

RSL studies are based on the identification of specific sea-level indicators, which estimate the RSL at a certain time and place, with associated uncertainty. Reliable sedimentary indicators usually originate from or near the border of marine and terrestrial sediments, such as transgression contacts, basal peat, and the borders of marine and aeolian sand. RSL indicators are divided into three groups according to their indicative meaning: 1) sea-level index points (SLIP); 2) lower (marine/lake) limiting data (ML); and 3) upper (terrestrial) limiting data (TL). Indicative meaning reflects the position of the RSL in relation to the data point at its time of deposition (Shennan, 1982; Hijma et al., 2015; Khan et al., 2019). Therefore, for example, radiocarbon dates from coastal peatlands or archaeological settlements can usually be used as upper limiting data, but data points from marine sediments may provide useful lower limiting data. RSL indicators used in papers I–IV are listed in Table 1.

The usefulness and reliability of geological sea-level data increases significantly if they are subjected to strict error analysis with well-quantified uncertainties (Hijma et al., 2015). In papers I–IV, new RSL data were used together with previously-published RSL data from the nearby geological and archaeological sites in order to reconstruct Holocene RSL changes for the study areas in Pärnu (Paper I – Nirgi et al., 2020), Hiiumaa (Paper II – Rosentau et al., 2020), and Saaremaa (Papers III and IV – Nirgi et al., 2017 and Nirgi et al., manuscript). The data were critically revised and gathered into a unified database that was based on the HOLSEA format, which allows the storage and analysis of large numbers of sea-level indicators according to a well-defined error protocol (Hijma et al., 2015). Therefore, vertical and chronological uncertainties of the RSL data being used were re-evaluated and presented in supplementary files of the papers.

Altogether, a total of 180 sea-level data points were presented in papers I–IV, including 24 rejected data points. The largest number of rejected data is related to chronological uncertainties. A total of 92 data points were gathered from the Pärnu study area (Paper I), 56 from Hiiumaa Island (Paper II), and 32 from the Saaremaa study areas (Paper IV). Further frequency distribution in terms of analysed data, with intervals of around a thousand years, is shown in Figure 5. Only about 13% of the data points are SLIPs, represented by basal peat, raised beach ridges, and some archaeological indicators, and less than 10% provide marine limitations. A little less than two-thirds are terrestrial limiting points which are mostly represented by freshwater peat deposits, buried organic sediments, and Mesolithic and Neolithic cultural layers from the coastal zone. The biggest volume of RSL data come from the period between 9.0 to 8.0 cal. ka BP and are related to the research interest to study the low water-level period before the LS transgression (Figure 5). However, the number of SLIPs from this period is unfortunately low, which makes it difficult to compile a detailed and reliable RSL curve. The period between 4.0 to 3.0 cal. ka BP has the lowest number of sea-level indicators.

Table 1. Summary of the indicative meanings used to estimate the relative elevation of the SLIPs and limiting points. Indicative ranges are relative to mean sea level (MSL) in respect to Amsterdam zero.

Sample Type	Evidence	Indicative range relative to MSL
Index points		
Isolation basins	Stage of isolation determined from lithology, geochemistry, LOI and diatom and ostracod assemblages (Grudzinska, 2015; Paper II – Rosentau et al., 2020)	typically MSL ±0.2 m
Historical coastal constructions	Parts of a seashore boardwalk in Kuressaare (Paper IV – Nirgi et al., manuscript)	MSL
Raised beach ridges	Sandy to gravelly raised beach ridges with downlap points marking the transition from beachface to upper shoreface (Hede et al., 2015)	typically MSL ±0.5 m
Highest shorelines	The foot of the beach ridges and other coastal landforms with OSL, IRSL or radiocarbon ages from the same or neighbouring sites	MSL±0.5 m
Fen peat to brackish-water or marine sediment transition (transgressive contact)	Intercalated fen peat with brackish-water (gyttja) or marine sediments (sand) on top	MSL±0.5 m
Marine and Ancylus Lake limiting points		
Marine and lagoonal deposits	Marine and lagoonal deposits from isolation basin sediments	below MSL
Terrestrial limiting points		
Freshwater peat	Freshwater peat or wood that does not show a direct relationship with sea level	above MSL
Archaeological cultural layers	Cultural layers of Mesolithic and Neolithic sites on the coast	above MSL
Historical coastal constructions	Kuressaare palisade walls (Paper IV– Nirgi et al., manuscript)	above MSL

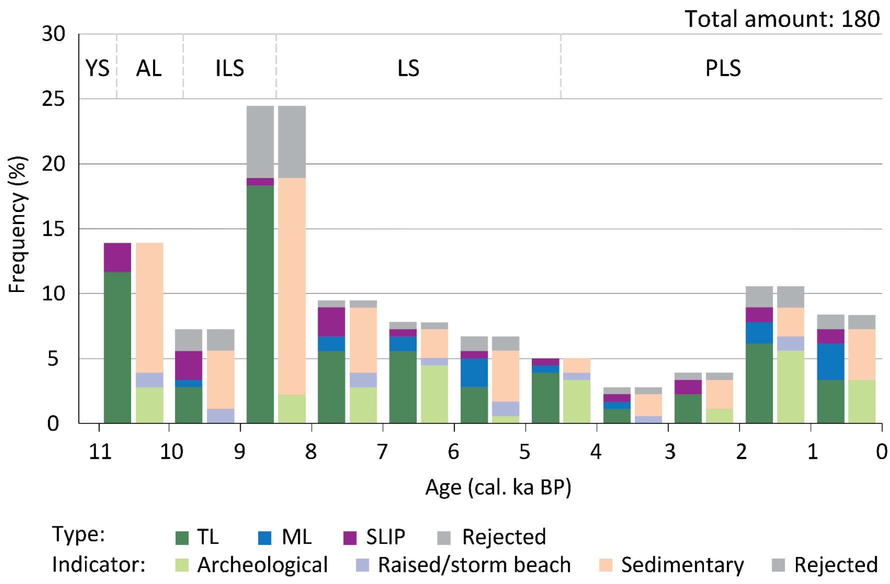

Figure 5. Frequency distribution, with ca. 1000 years intervals, of SLIPs, limiting and rejected data points from the study areas. The Baltic Sea stages are shown according to Andrén et al. (2011).

Chronological uncertainty depends upon the material and sedimentary environment of the dated sediment, but also on the dating method being used and the number of dated samples. Radiocarbon dates are expressed by laboratories in terms of a central value and an associated error (+/–) which is derived from a variety of analytical errors such as contamination during sample preparation and analytical uncertainty in the AMS (Törnqvist et al., 2015). The expressed error reflects the precision of the date, but not dating accuracy. The latter depends directly upon how well the sample describes the phenomenon that is the target of dating (Törnqvist et al., 2015). For example, the radiocarbon date of bulk organic material could be analytically precise, but it probably reflects the mean age of a mixture of organic carbon from different sources, including material that is irrelevant to the target of the dating process. Therefore, AMS dating is preferred over traditional radiometric techniques as it allows the use of significantly smaller and hence better-defined samples and gives more accurate results. Dating accuracy also depends upon the possible need of a reservoir correction of the age estimation, especially when the age has been derived from carbonate sediments or marine carbonates such as gastropods or bivalves, due to contamination from old carbon.

Evaluating vertical error is even more complex. Vertical uncertainties in the geological RSL data depend upon the sampling uncertainties and accuracy of the elevation (LiDAR) data. Sampling uncertainties can be related to measuring the depth and thickness of the sample within a core or section, being typically ±0.01 m (Shennan, 1986). Sampling errors are in turn affected by core stretching or shortening, especially for rotary coring and vibracoring (Hijma et al., 2015). The error is typically set at ±0.15 m for rotary coring and vibracoring (Morton and White, 1997), ±0.05 m for hand coring and ±0.01 m for a Russian peat sampler (Woodroffe, 2006). The uncertainty evaluation in the study areas was based mainly upon the same principles but, in some cases, the margin of error was increased or decreased due to the characteristics of a specific site and sample, such as in terms of the depth of the sample.

The most precise elevation data is obtained through the instrumental measurement of the sampling site (e.g. RTK positioning). In this case, the uncertainty depends mainly upon the accuracy of the measuring device, but variable satellite coverage or restricted reception (e.g. surrounding forest) can also increase the error. The standard error for a (D)GPS base station is ±0.04–0.1 m (Törnqvist et al., 2004). If the elevation of the land surface is not instrumentally measured during the fieldwork, but the coordinates of the sampling site are known, the elevation can be estimated using high-resolution DEMs. The associated error depends upon the vertical accuracy of the DEM (usually 0.1–0.2 m), but also on the accuracy of the coordinates, especially in areas with significant relief (an error of ±0.5 is assigned) (Hijma et al., 2015).

For archaeological sites vertical uncertainty also depends upon the extent and topography of the individual settlement site and remains typically between ±0.25 m and ±1.75 m. For example, at the Hiiumaa site the total vertical uncertainty together with the indicative range of the uncertainty (Hijma et al., 2015) was estimated to be around ±1 m for geological, and ±1–2 m for archaeological RSL data, while at Saaremaa these figures were at ±1 m and ±1–1.45 m respectively. However, fishing structures and constructions of coastal boardwalks or docks, such as the remains of the boardwalk constructions in Kuressaare (Paper IV – Nirgi et al., manuscript), can show a relatively precise position of the historical coastline.

If a sea-level indicator clearly has a major error such as, for instance, where the age is too young or too old compared to other related samples, or the dating material is doubtful, but it is impossible to assess the error, then the sea-level indicator can be rejected. Thanks to this several sea-level indicators were rejected in Pärnu, Hiiumaa and Salme study areas due to uncertainties in their chronology such as, for example, uncertainties in relation to dating bulk gyttja. Also, an IRSL date was omitted from the Hiiumaa data due to a too wide age distribution rage. All of the rejected data, together with explanations for rejection, were still added to the databases but were not further used in RSL reconstructions.

4.1.2 Holocene RSL lowstands, AL transgression and submerged landscapes

Estimating the minimum levels of the YS shoreline in western Estonia has been a challenge due to the complicated accessibility of the data, as concurrent sediments are buried under younger sediments. Hansson et al. (2018a) presented the YS lowstand minimum levels at 24–25 m b.s.l. just before 10.8 cal. ka BP in the Blekinge area, Sweden, in an area in which GIA rates are similar to those of the Pärnu study area. Therefore, the RSL in Pärnu may also have been at lower levels than the present sea level. However, in the Pärnu area the lowest RSL has previously been described based on very sparse data, at about –2 m a.s.l. (Talviste et al., 2012), about 0 m a.s.l. (Veski et al., 2005), or at least below 3 m a.s.l. (Rosentau et al., 2011). There are many sea-level indicators, but these are mostly from buried organic layers and are usable only as terrestrial (upper) limiting data points. Among other indicators, there are two conventional dates from the palaeosoil layers of the Pulli settlement site (Kriiska and Lõugas, 2009) which indicate terrestrial conditions at the YS lowstand. Sea-level index points from this period were unfortunately lacking.

New data concerning the YS lowstand were obtained from Pärnu study area, where a buried river channel (Figure 6) was found (Paper I – Nirgi et al., 2020). The initial down-cutting of the channel took place during the YS lowstand. According to the seismo-acoustic data, the initial channel can also be traced along the seabed to a water-depth of at least to 5.5 m, which marks the lowest reported Holocene RSL in the study area (Figure 7). Dated terrestrial plant remains which were collected from the lower contact of the initial River Pärnu channel sediments suggest the end of the lowstand and the beginning of the rise in the AL water level at about 10.76–10.57 cal. ka BP (Figure 6, 7).

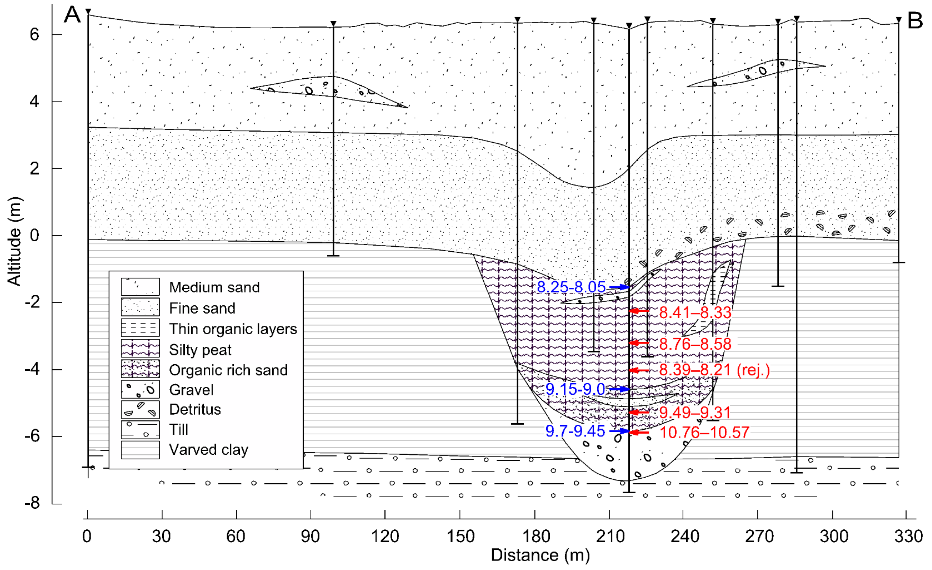

Figure 6. Geological cross-section (A–B) across the buried channel of the River Pärnu. The AMS ages (cal. ka BP) are shown in red and modelled ages for the sediment borders are shown in blue colour (based on Paper I – Nirgi et al., 2020).

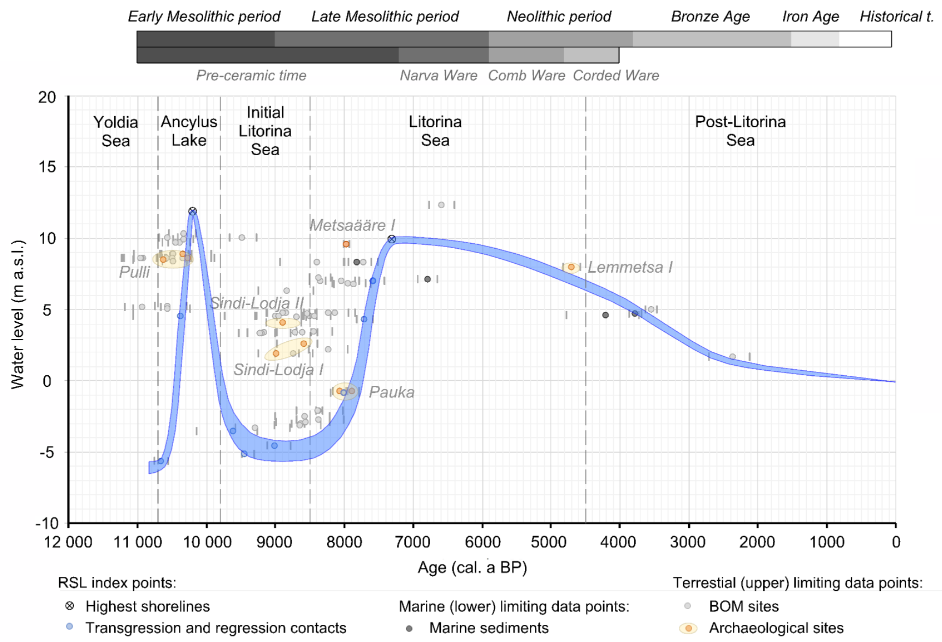

Figure 7. The RSL curve for the Pärnu study area with positions of the RSL indicators (Paper I – Nirgi et al., 2020). The Baltic Sea stages according to Andrén et al. (2011) and archaeological periodization according to Kriiska et al. (2017).

The subsequent AL transgression was rapid. Independent age estimations about the up-damming show that it started around 10.8–10.7 cal. ka BP and culminated around 10.3–10.2 cal. ka BP (Björck, 1995; Andrén et al., 2000; Rosentau et al., 2011; Muru et al., 2017; Hansson et al., 2018a). Earlier radiocarbon ages from the buried layers of organic matter and new data from the Pärnu area suggest the beginning of the AL transgression at about 10.7 cal. ka BP. The oldest known settlement site in Estonia, Pulli (11.1–9.9 cal. ka BP) in the lower reaches of the River Pärnu, was probably inhabited during the AL transgression period (Kriiska and Lõugas, 2009). The transgression caused extensive flooding of western Estonia and led to terrigenous sedimentation, which covered the organic material of the YS lowstand period. In Hiiumaa the Kõivasoo basin was flooded, which today can be verified by the appearance of ostracods and large lake diatoms in the sediments (Paper II – Rosentau et al., 2020).

In Estonia, the AL transgression reached mainly to 5–45 m a.s.l. at ca. 10.2 cal. ka BP (Saarse et al., 2003). Well-developed geomorphological shoreline evidence in western Estonia mark the culmination of the transgression at different altitudes: 46.6–47.7 m a.s.l. in the Kõpu and Kõivasoo area (Paper II – Rosentau et al., 2020); ca. 12 m a.s.l. in the northern part of the Pärnu study area (Rosentau et al., 2011) and ca. 6.5 m a.s.l. in the southern part (Habicht et al., 2017). In the Pärnu study area the water level rose at least 17.5 m at an average rate of 35 mm/yr, which is 5–6 m more than has been proposed by earlier studies (Veski et al., 2005; Rosentau et al., 2011). Similar rapid transgression (40 mm/yr), of about 21–22 m, has also been documented in the Blekinge area between 10.8 and 10.3 cal. ka BP (Hansson et al., 2018a).

The transgression was followed by a regression due to AL drainage into the ocean (Björck, 1995; Bennike et al., 2000; Lemke et al., 2001; Bendixen et al., 2017). Comparison of the RSL curves for Pärnu (Paper I – Nirgi et al., 2020) and Hiiumaa (Paper II – Rosentau et al., 2020) reveals differences in the durations of the AL regression and subsequent ILS lowstand period (Figure 7, 8). In the Pärnu area, the regression of ca. 15 m has been recorded at around 10.2–9.8 cal. ka BP. In Kõivasoo a drainage of 20 m led to the formation of a freshwater lagoon with an accumulation of calcareous gyttja. After the drainage of the AL, the land was exposed once again and the formation of peat deposits and soils began in the newly emerged areas. The ILS stage was a long and stable period with a relatively low water level, thus organic-rich deposits from that period are significantly more expressive when compared to the pre-Ancylus Lake deposits. The RSL data from the Pärnu area indicates a long period of ca. 1500 years of low water levels during the ILS and at the beginning of LS (Figure 7), being a few hundred years more in total when compared to the Haväng (Hansson et al., 2018b) and Blekinge areas (Hansson et al., 2019) in southern Sweden. A stable water-level period in the Kõpu area has been recorded at a similar time, but this was characterised by slow regression (of 3 m) which was caused by more intensive isostatic land uplift when compared to the Pärnu area (Figure 8). In some areas around the BSB, the ILS

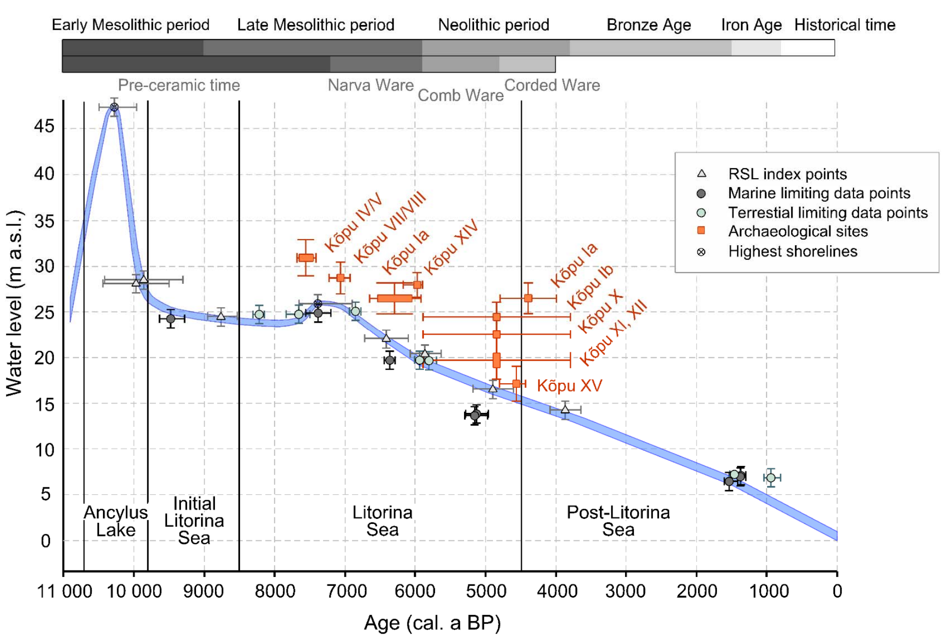

Figure 8. RSL curve for the Kõpu area with the positions of the RSL indicators (Rosentau et al., 2020). The Baltic Sea stages are shown according to Andrén *et al.* (2011) and archaeological periodization according to Kriiska *et al.* (2017).

lowstand period is unrecognisable due to the even more intensive glacio-isostatic rebound and, hence, continuous regression (Eronen et al., 2001; Lindén et al., 2006). However, on the southern coast of the BSB, where the glacial rebound has been slower than the eustatic sea-level rise and transgression has dominated almost throughout the entire Holocene, with the exception of the YS regression, the ILS period was characterised by a rapid transgression (Bennike and Jensen, 1998; Uścinowicz, 2003).

The dated buried organic deposits in the Pärnu study area (e.g. Pärnu, Uku and Reiu sequences) indicate that RSL dropped below the present-day water level, down to ca. –4 m a.s.l. around 9.0–8.1 cal. ka BP (Figure 9). This is further

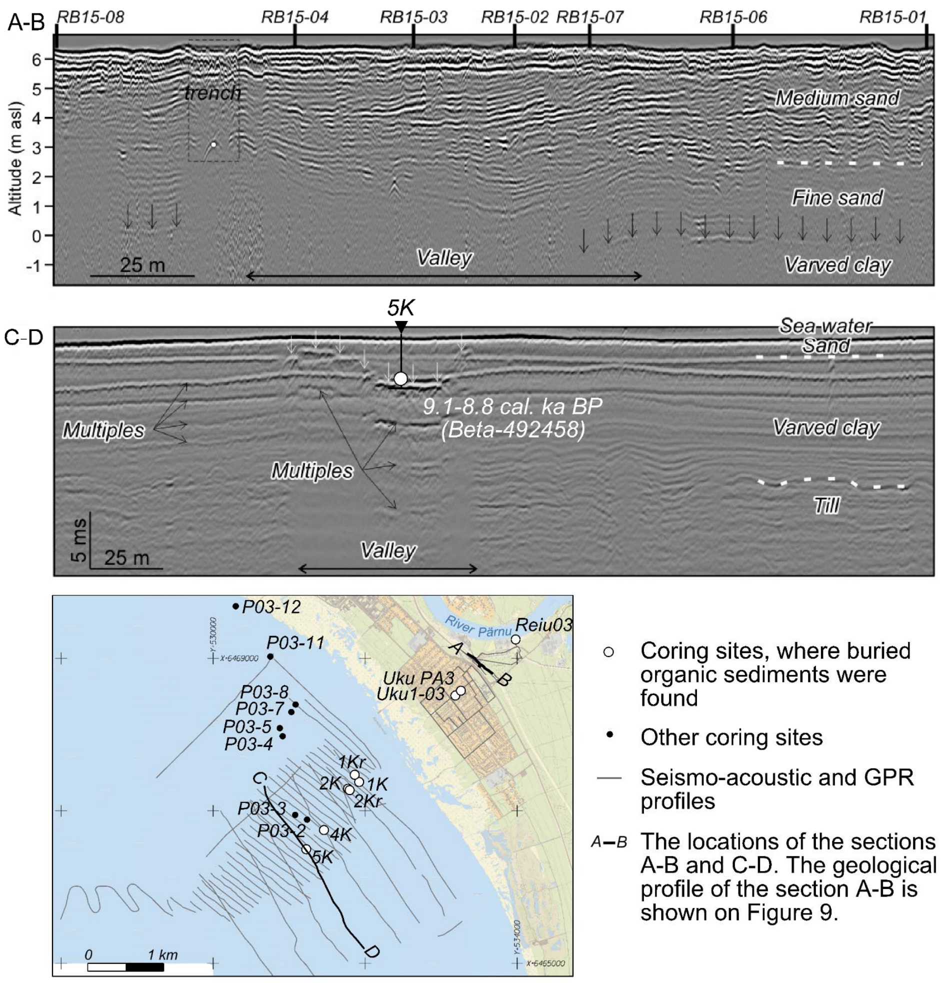

Figure 9. A GPR image of section **A–B**, where the buried channel is indicated by down bending reflectors in the central part of the profile, and a seismic section **C–D** across the submerged channel, where two-way travel time of 5 ms corresponds to 3–4 m depending on lithology. The locations of the sections are shown below, on the map of Pärnu study area (Estonian Land Board, 2018). (based on Paper I – Nirgi et al., 2020).

confirmed by the palaeochannel sediments at the bottom of Pärnu Bay, with the upper surface visible in the geophysical and in coring data at a similar elevation. In previous studies the lowest RSL was considered to be around 0 m a.s.l. (Veski et al., 2005; Rosentau et al., 2011). In the Haväng area, the RSL has been determined to about –10 m a.s.l. (Hansson et al., 2018b) and in the Blekinge area to about –4 m a.s.l. (Hansson et al., 2019) during the ILS.

Diatom data combined with ostracod data show the existence of the Kõivasoo lagoon in the Kõpu area during the ILS. The lagoon was isolated from the BSB around 8.8–8.6 cal. ka BP likely due to the balance between eustatic and isostatic movements. The lowest water level in the Kõivasoo basin, around 24 m a.s.l., was established at the beginning of the LS around 8.2–7.7 cal. ka BP.

This kind of stable environment with coastal lagoons/lakes and rivers was also suitable for people who were now able to remain located in one settlement for a longer period of time. Therefore, the ILS lowstand period in SW Estonia, including on the mainland and on Saaremaa Island, is rich in archaeological data, but data regarding settlements on Hiiumaa Island from this period is unknown. The new data about low water levels from the Pärnu area creates the theoretical possibility of the existence of undiscovered submerged settlements or temporary camp sites at the bottom of Pärnu Bay, including shallow offshore areas around Kihnu, Manija, and Sorgu islands (Figure 10), and provides a fascinating new

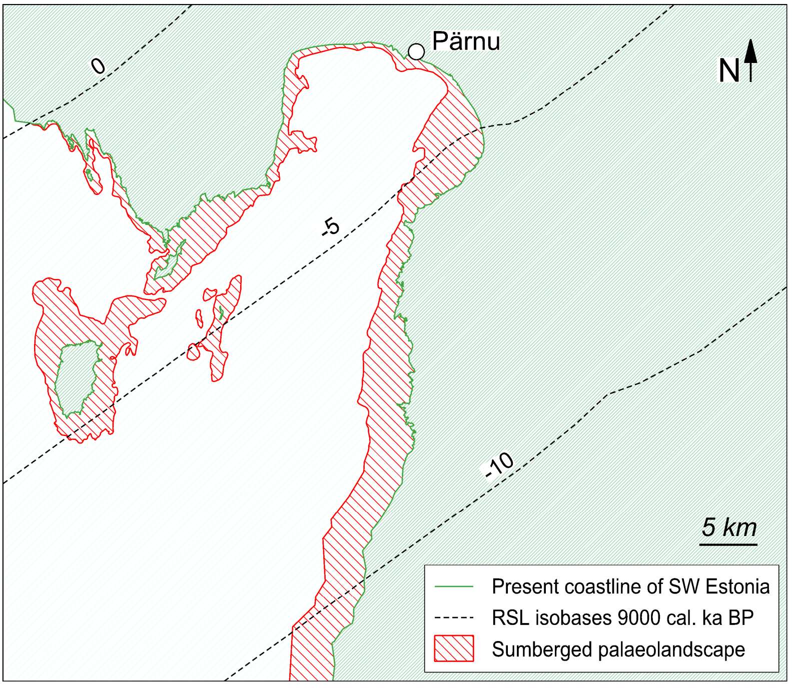

Figure 10. The estimation of the areas of the present seafloor of the SW Estonia that were potentially exposed during the ILS lowstand, i.e. areas where it is possible to locate submerged landscapes. The map is based on the lowest shoreline levels at Pärnu area at 9000 cal. ka BP (Paper I – Nirgi et al., 2020).

study subject for future investigation. Submerged palaeolandscapes and settlement sites have been discovered in the southern areas of the BSB where isostatic land uplift has been slow such as, for example, in the Blekinge region (Hansson et al., 2019).

4.1.3 Litorina Sea transgression and Mid-Holocene RSL highstand

LS transgression, which started at about 8.5 cal. ka BP and culminated around 7.7–7.3 cal. ka BP was more complex when compared to the AL transgression. In some sea-level studies, such as in SE Finland and NW Russia, researchers have argued for the possibility of multiple transgressions (Hyvärinen et al., 1992; Miettinen, 2004). Berglund et al. (2005) described five regional LS transgressions (L1–L5) in the Blekinge area. The first (L1) at 8.5–8.2 cal. ka BP matches up with the beginning of the transgression in the Pärnu area, while the second (L2) at 7.8–7.3 cal. ka BP is simultaneous with the most rapid transgression phase described in the Pärnu and Hiiumaa sites. However, a regressive event between L1 and L2 is not reflected in our data, either due to the lack of geological evidence or the probability that the regression simply did not reach western Estonia. After 7.3 cal. ka BP the RSL in Estonia turned to regression and there are no indications towards transgressions L3–L5 between 6.8–5.0 cal. ka BP.

The Pärnu study area, which is characterised by its slow isostatic uplift, experienced a rapid transgression, with the amplitude of the RSL rise being comparable to that of the AL transgression (Figure 7). On the other hand, in the Kõpu study area where the land uplift rate is higher, the RSL rise was slower and of an amplitude that was several metres lower (Figure 8). According to our new data, the RSL rise had already begun ca. 8.5 cal. ka BP in the Pärnu area, but in the Hiiumaa area, it did not start before 7.7 cal. ka BP. The LS reached its maximum level in Pärnu just after 7.6 cal. ka BP, most probably around 7.3 cal. ka BP (Veski et al., 2005), which is also consistent with new data from Hiiumaa (7.4 cal. ka BP) and earlier interpretations from areas with similar or somewhat slower or faster land uplift rates. For example, in the Narva-Luga region on the SE coast of the Gulf of Finland where the land uplift rate is a little slower than in Pärnu, the transgression has been estimated to have occurred between 8.5–7.3 cal. ka BP (Rosentau et al., 2013). In Tallinn, where the land uplift rate is similar to that of Kõpu, the transgression has been dated between 8.5–7.7 cal. ka BP and the transgression maximum between 8.1–6.8 cal. ka BP (Muru et al., 2017). In the Stockholm region, in an area with an uplift rate twice as rapid compared to that of Hiiumaa Island, the transgression occurred between 8.5 and 7.3 cal. ka BP (Karlsson and Risberg, 2005).

The LS transgression maximum level is also marked by a well-developed shoreline, which is mostly parallel with the AL shoreline but is located at lower altitudes. The RSL in Pärnu rose about 14 m at an average rate of 12 mm/yr and the maximum level reached ca. 10 m a.s.l., whereas, due to different land uplift rates the maximum RSL in Hiiumaa probably remained near 27 m a.s.l. Therefore, the oldest settlement site in Hiiumaa, the Late Mesolithic Kõpu IV site

(7.6–7.4 cal. ka BP) at elevations 29–33 m a.s.l. was not inundated by the LS transgression. Average RSL rates for the LS transgression in western Estonia were close to concurrent rates for the eustatic sea-level rise that was calculated from the far-field sites by Lambeck et al. (2014). However, the LS transgression rates exceed the far-field rates at around 7.8–7.6 cal. ka BP as is also noted in some studies from the slowly uplifting areas in Blekinge (Yu et al., 2007), Narva-Luga (Rosentau et al., 2013), and Samsø (Sander et al., 2015).

The RSL curves for Pärnu and Hiiumaa reflect somewhat different patterns of LS transgression and subsequent regression. The Pärnu curve shows significantly more rapid transgression, but a calmer regression when compared to the Hiiumaa curve (Figure 7, 8). However, there are areas around the BSB, in the faster GIA zones, where the ILS lowstand period and the culmination of LS are unrecognisable on the RSL curves (Eronen et al., 2001; Lindén et al., 2006), or visible as a plateau, which turns into a regression (Eronen et al., 2001; Karlsson and Risberg, 2005). At the same time, the shoreline on the southern coast of the BSB has been transgressive since ca. 9.5 cal. ka BP (Bennike and Jensen, 1998; Uścinowicz, 2003).

4.1.4 Mid- to Late Holocene RSL variability and its relations with present-day land-uplift

Due to the slowdown in global sea-level rise at around 7.0 cal. ka BP (Lambeck et al., 2014), the isostatic land-uplift started to dominate, giving rise to regressive shore displacement and intensive paludification between the highest Litorina Sea and the present-day coastline in western Estonia (Rosentau et al., 2011). The cultural layers and PLS organic deposits in the Pärnu study area indicate slightly slower regression rates of the LS at the beginning of the regression at about 7.0–4.5 cal. ka BP, compared to the regression rates at 4.5–2.7 cal. ka BP. Similar conclusions were reached in the sea-level study on the Ruhnu Island, ca. 100 km SW from the Pärnu study area (Muru et al., 2018). The data from the Kõpu area, on the other hand, suggest that RSL lowering between 7.4 and 6.0 cal. ka BP (about 4.3 mm/yr) was slightly more rapid than after 6.0 cal. ka BP (3.3 mm/yr). The latter is similar to present-day land uplift rates relative-to-geoid of 3.25–3.5 mm/yr (Vestøl et al., 2019). Absolute average uplift rate due to GIA is estimated to be 3.7 mm/yr in the Kõpu area for the last 6000 years (Suursaar et al., 2019), thus the 0.4 mm/yr differences between absolute rates and RSL rates can be attributed to concurrent ocean rise about 2–3 m (Lambeck et al., 2014). Unlike the Hiiumaa curve, the RSL curve of the Pärnu area shows a slow-down of the regression since ca. 2.7 cal. ka BP (average rate ca. 0.7 mm/yr).

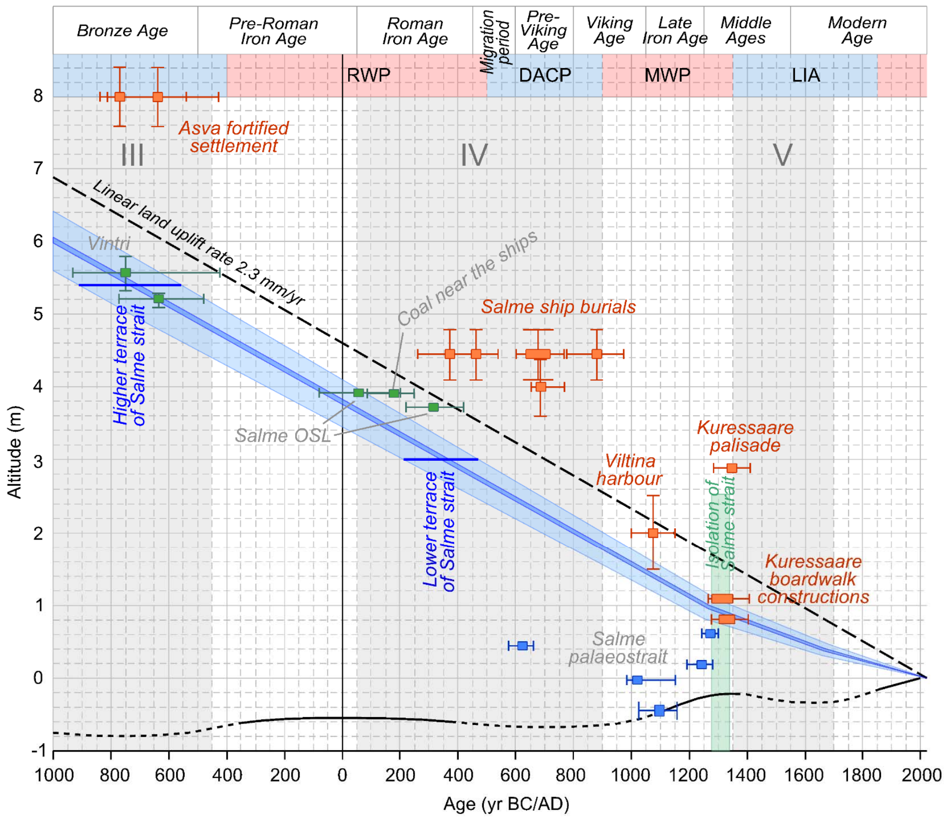

Figure 11. Late Holocene RSL curve for Salme compared with the curve of the Pomeranian non-uplifting coast (Lampe and Janke 2004) and with absolute land uplift rate. Late Holocene storm periods III, IV and V according to Sorrel el al. (2012) are marked as grey zones and the alternation of warm and cold periods according to Reimann et al. (2011) and Neukom et al. (2019) are marked by blue and red zones at the top of the graph (LIA – Little Ice Age, DACP – Dark Age Cold Period, MWP – Mediaeval Warm Period, RWP – Roman Warm Period).

The RSL curve for Saaremaa shows a nearly linear regressive trend for the past 3000 years due to the continuous glacial rebound outpacing the declining rates of absolute sea-level rise (Figure 11). The average RSL fall since 2.7 cal. ka BP was about 2 mm/yr, therefore, ca. 0.3 mm/yr slower when compared to the present-day absolute land uplift rate. This difference is probably attributed to slow eustatic sea-level rise during the Late Holocene (Lambeck et al., 2014). A Late Holocene RSL curve from the West Pomeranian non-uplifting coast reveals the concurrent sea-level rise in the Baltic Sea to be about 90 cm (Lampe and Janke, 2004; Figure 11). If we were to include this value in our RSL curve, the total uplift for the area would be 6.2 m and the average uplift rate 2.3 mm/yr, which coincides with the present-day geodetic observation data for Saaremaa (Vestøl et al., 2019). Thus, the postglacial land uplift since 2.7 cal. ka BP has been rather stable, and some fluctuations in the Late Holocene RSL are probably related to climatic events including cyclic changes in the strength of the westerly atmospheric circulation (Suursaar et al., 2006). It seems that some slowdown in regression occurs after 1300 AD which may be related to accelerated sea-level rise after the LIA and during the industrial period. However, our data is still rather thin when it comes to making final conclusions about the Late Holocene RSL fluctuations or in terms of relating the RSL changes with certain climatic events.

Rosentau et al. (2012) compared the geological RSL records for Litorina and Post-Litorina Sea with tide gauge and GPS derived crustal velocity measurements in BSB region. The comparison revealed similar NE–SW oriented elongated dome of the post-glacial rebound and showed the relative stability of the rebound centre at the west coast of the Bothnian Sea and the zero-line in the SE Baltic during the last 8000 ^{14}C yrs BP. As the land uplift slows down in time, the shoreline tilt gradients also decrease: initially the decrease was exponent-like, but last 3000 ^{14}C yrs BP the trend has been nearly linear (Rosentau et al., 2012). This is also consistent with the Late Holocene RSL curve compiled for Salme study site (Paper IV – Nirgi et al., manuscript).

In Estonia the Late-Holocene RSL regression mainly continues, as isostatic rebound rate exceeds the eustatic sea-level rise. However, the glacial rebound slowly subsides over time (Lambeck et al., 2014; Suursaar et al., 2019) and the eustatic sea level continues to rise, causing a slow-down of the regression. The sea-level rise together with an increase in the prevalence of storms and a decreased winter ice cover period will probably increase the extent of floods in several coastal areas in Estonia, which already have problems with storm surges (Rosentau et al., 2017). Therefore the future of coastal areas in Estonia will most likely be characterised by regression slowly turning into transgression. According to the Intergovernmental Panel for Climate Change (IPCC) predictions, the long-term RSL fall in Estonia is expected to change into an RSL rise during the 21st century (Church et al., 2013). Considering the continuing land uplift and the IPCC team's global mean sea-level projections, the slight RSL rise is already expected to have begun before the year 2030.

The RSL is already rising on S and SE coasts of the BSB where isostatic uplift has been close to zero (Uścinowicz, 2003) during the Late Holocene. According to the variations in annual average RSL in Estonian tide gauge data until 2016 (Estonian Environment Agency), the gradual long-term sea-level rise is still partly compensated by the glacial rebound. The shorelines of Saaremaa and Hiiumaa are still regressive, however, in the Pärnu area, which is sensitive to coastal floods due to its long coastline and flat topography, the relative mean sea level has increased ca. 0.9 mm/yr in 1924–2016 (Tõnisson et al., 2019).

4.2 Geoarchaeology of the prehistoric sites on the coastal zone in western Estonia

4.2.1 Stone Age settlements and RSL changes in Pärnu area

The AMS dates for ecofacts from the Pulli cultural layer suggest habitation around 11.1–9.9 cal. ka BP (Kriiska and Lõugas, 2009). Due to the rapid transgression and dating uncertainties of the cultural layer, it is rather difficult to reconstruct shoreline position during the settlement phase. According to the new radiocarbon dates from the ancient River Pärnu channel sediments, the beginning of the transgression of the AL started around 10.76–10.57 cal. ka BP. This age is only slightly older from the mean AMS age (10.5 cal. ka BP) of the Pulli settlement. Thus, the Pulli settlement was located along the lower reaches of the River Pärnu, probably about 15 km from the lowest AL shoreline level (Figure 12a), which is ca. 5 km further from the coast than previously proposed (Rosentau et al., 2011). The habitat location was most probably chosen for its suitability for the pikeperch and pike fishing, and the hunting of water birds, beaver, elk, and other animals (Kriiska and Lõugas, 2009). The rising Ancylus Lake flooded the Pulli site within the next few hundred years and covered it with a 2-m-thick coastal sand deposit. The rapid burial of the cultural layer was essential for the preservation of organic and archaeological material.

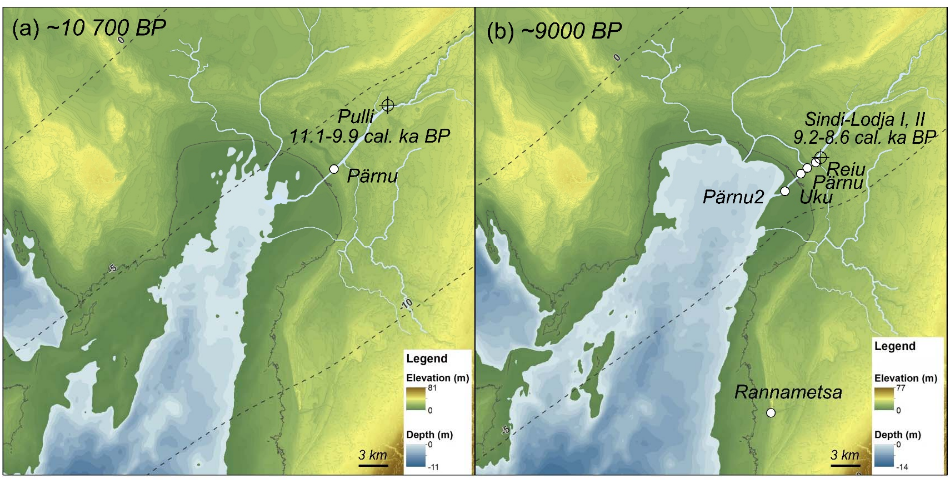

Figure 12. Palaeoreconstructions for the lowstand episodes of the Pärnu Bay area with the indication of RSL isobases (m a.s.l.): a) at the beginning of the AL transgression at 10.7 cal. ka BP, and b) at the ILS at 9.0 cal. ka BP during the coexistence of two channels of the River Pärnu. (Paper I – Nirgi et al., 2020).

The rectilinear configuration of the lower reaches of the River Pärnu changed during the subsequent RSL regression and lowstand period due to the changing coastline, the S-N-orientated longshore sediment transportation along the eastern coast of the Gulf of Riga, and intensive sediment accumulation at the back of the bay (Orviku, 2004; Soomere and Viška, 2014). The old river channel was eventually blocked up by coastal sediments and the water found an alternative, meandering N-W channel, which it still uses today.

Subsequent signs of human activity originate from the Initial Litorina Sea lowstand period when the Stone Age people settled on the banks of the rivers Pärnu, Reiu, and Audru (Kriiska, 2001; Kriiska and Lõugas, 2009; Habicht et al., 2017). The ILS stage is characterised as a long and stable period with relatively low water levels, which was suitable for people, who were now able to remain in one settlement for a longer period. According to a single AMS date for charcoal from the cultural layer, Mesolithic Sindi-Lodja I and II settlement sites (Kriiska and Lõugas, 2009) were inhabited at about 9.2–8.7 cal. ka BP (Kriiska, 2001). If this age is accurate (mean age ca. 9.0 cal. ka BP) then our new data from the Pärnu area places the settlements ca. 3 km from the concurrent coastline, on the left bank of the ancient River Pärnu, which still had its old configuration (Figure 12b). Thus, the settlements were probably located further inland than previously shown (Rosentau et al., 2011).

Rich archaeological find material from the Sindi-Lodja I and II sites, including animal and fish bones, refer to human habitation at least during the springtime, which was the best time for hunting ringed seal and pikeperch. In the other hand, the general Mesolithic contexts may justify the assumption of year-round habitation (Kriiska and Lõugas, 2009), with temporary fisher camps along the coastline (Larsson, 1980) which were most probably located on the shore of this ancient river at the bottom of the present-day Pärnu Bay. These first signs of evidence for submerged Mesolithic landscapes in the waters of Estonia provide a new perspective for further studies of submerged landscapes with possible prehistoric settlement or campsites (Figure 10).

In addition to the well-known Stone Age settlement sites, a large assemblage of archaeological objects was collected from the riverbed in the lower reaches of the River Pärnu in the beginning of the 20th century during sand and gravel quarrying work (Glück, 1906, 1914; Indreko, 1932). A large number of well-preserved finds may point to undiscovered buried permanent settlements. Two artefacts from this collection (Jonuks, 2013, 2016) have been AMS dated to 8.0–7.8 cal. ka BP and 8.2–8.0 cal. ka BP respectively, referring to the Litorina Sea transgression period. These finds may associate with the former Pärnu River floodplain ca. 400 m downstream from the mouth of the River Reiu, where organic sediment accumulation was active around 8.2–7.8 cal. ka BP. However, the interpretation of the collection is complicated as no object has been recorded in situ and, according to typological dating, these finds represent different periods between the Early Mesolithic and Iron Age. This means that it is also possible that the River Pärnu eroded some undiscovered riverside settlement sites and the archaeological objects then accumulated on the former floodplain. In this case, the erosion must have been rapid and the transportation distance short, because the good preservation of the objects does not reflect intensive erosion.

There are also several Neolithic settlement sites in the Pärnu area associated with LS regressive coastline (Kriiska and Lõugas, 2009). A new radiocarbon date from Lemmetsa I Comb and Corded Ware site, presented in the paper I, shows habitation at the mouth of the River Audru at about 4.8–4.6 cal. ka BP (Figure 13). Typologically dated Late Mesolithic Sindi-Lodja III site and Neolithic settlement sites at Sindi-Lodja III, Jõekalda, Lemmetsa II, Malda and Metsaääre III were all situated along the lower reaches of the rivers close to the retreating shoreline of the LS, which represent typical locations for prehistoric fisher-hunter-gatherers in the eastern Baltic region before the expansion of agriculture around 4.8 cal. ka BP.

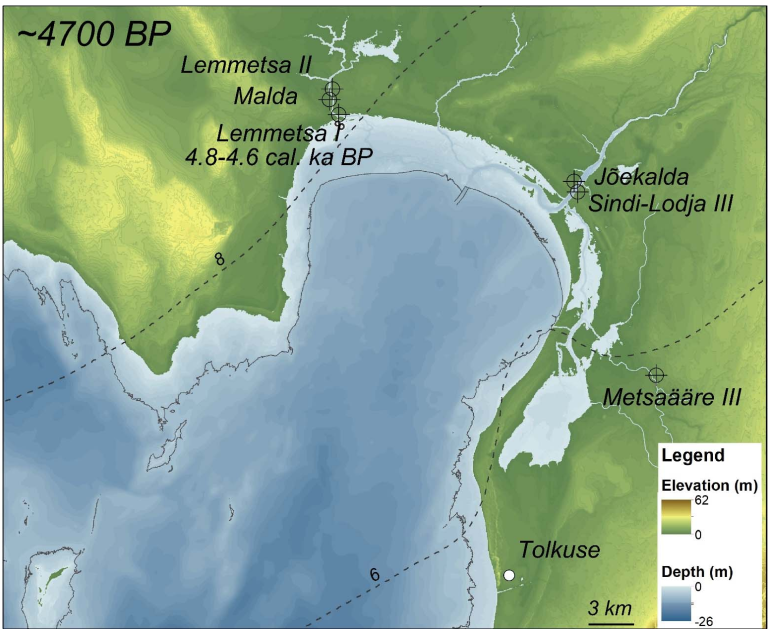

Figure 13. Palaeogeographic reconstructions of the Pärnu Bay area with the indication of RSL isobases (m a.s.l.) at LS regression at about 4.7 cal. ka BP (Paper I – Nirgi et al., 2020).

4.2.2 Stone Age settlements and RSL changes in Hiiumaa Island

Hiiumaa started to emerge during the YS lowstand, but its first inhabitants, early hunter-gatherers, reached the island (at that time, a Kõpu paleoislet) ca. 7.6–7.5 cal. ka BP, just before the LS transgression. Interpretation of archaeological find material suggests that they probably visited the islet on a seasonal basis from Saaremaa Island, where Late Mesolithic habitation was already established (Kriiska, 2001, 2002). This assumption was based on similarities between archaeological finds from the Kõpu Ia site on Hiiumaa and the Kõnnu site on Saaremaa, e.g. the vessels from both sites belong to the Narva-type ceramics, forming a local group within this classification (Kriiska and Lõugas, 1999). Now this is also supported by methods of natural sciences. According to the viewshed analysis (Paper II – Rosentau et al., 2020), the highest part of the Kõpu islet was visible from the Late Mesolithic Pahapilli I/II and Võhma I–VII settlements on the northern coast of Saaremaa (at the distance of ca. 43 km), and from the sea within a radius of ca. 36 km (Figure 14). It is most likely that people wanted to explore the land that they saw on the horizon. Early migrations from Saaremaa to the smaller islands were probably also induced by the need to follow the most important pray, seals (Kriiska and Lõugas, 1999).

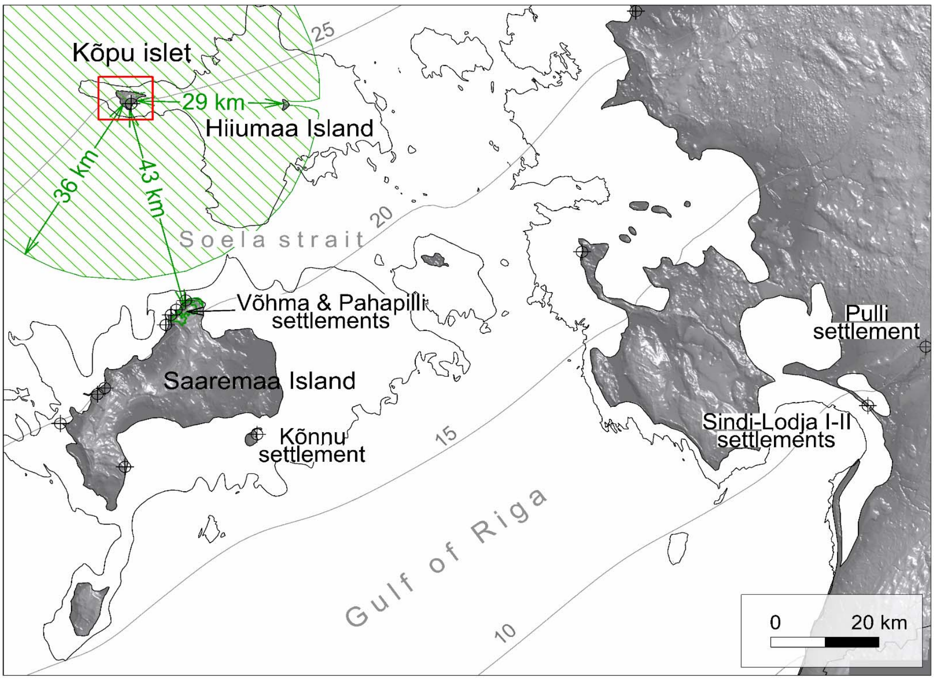

Figure 14. Western Estonia with Mesolithic settlements and a viewshed from the highest point of the Kõpu palaeoislet (green areas) during LS highstand at about 7.4 cal. ka BP (sea-level isobases, m a.s.l., according to Saarse et al. (2003). The present coastline is shown by black contours (Paper II – Rosentau et al., 2020).

New datings from the Kõpu coastal deposits and the Kõivasoo Bog indicate a somewhat different situation for Mesolithic human habitation in this area. Revision of the RSL and newly obtained geological and archaeological data which is presented in Paper II challenge the idea of an early and diachronous marine transgression on the island and indicates more shore-related coastal habitation than has been referred to in previous studies (Saarse et al., 2000; Grudzinska, 2015; Vassiljev et al., 2015). Reconstructions show that the earliest campsites from the Sindi-Lodja sub-period and Narva culture were successively established along the shores of the Kõpu palaeobay at a lower elevation following the shoreline retreat during the LS regression (Figure 15). Archaeological bone material from new-born ringed seal pups from the cultural layer of the Kõpu IA settlement (Kriiska and Lõugas, 1999) refers to crossings to the island during the late winter to early spring months, which is the best season for seal hunting (Itkonen, 1924; Art, 1988).

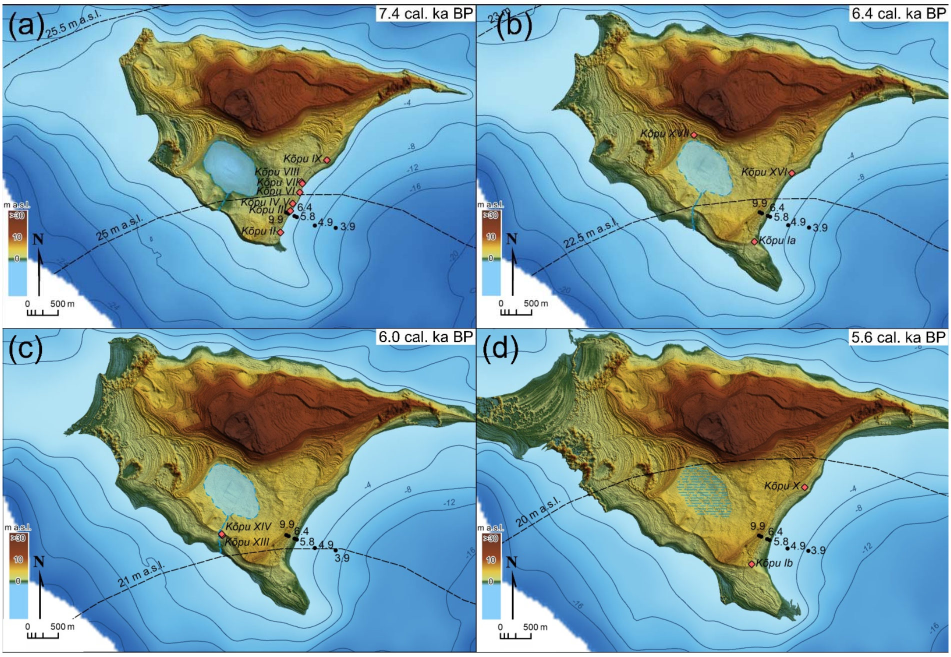

Figure 15. Palaeogeographical reconstructions of the development of the Kõpu palaeo-island during LS with RSL isobases and concurrent archaeological sites (red diamonds): **a)** LS maximum at 7.4 cal. ka BP, during the earliest Narva culture settlement sites; **b)** at 6.4 cal. ka BP; **c)** at 6.0 cal. ka BP, prior to overgrowing of the Kõivasoo lake, and **d)** at 5.6 cal. ka BP, during the onset of peat formation in Kõivasoo. Black dots mark the mean IRSL ages (ka) from the studied coastal section and white areas at the bottom corners mark the present-day Baltic Sea (Paper II – Rosentau et al., 2020).

Three Late Mesolithic sites in the Kõpu area (Kõpu XIII, XIV, XVII) were connected to the freshwater lake and its outflow area in the southern part of the palaeoisland suggesting a different settlement pattern from the earlier onshore camps. These locations are well suited to summer (or ice-free season) occupations rather than for winter camps. The Kõpu XVII settlement was located inland, on the northern shore of the shallow freshwater Kõivasoo palaeolake, while Kõpu XIII and XIV were located on the shore of the small river that connected the palaeolake to the Litorina Sea (Figure 15). This rather scarce archaeological and subfossil record may suggest that boat trips during the ice-free seasons were also made from Saaremaa to Hiiumaa at least since the time of the Kõpu XIV settlement at about 6.18–5.92 cal. ka BP.

Larsson (1980) proposed a possible settlement pattern in Scania, southern Sweden, at ca. 7.4–8.4 cal. ka BP, showing that the same group of prehistoric people may have occupied different regions throughout the year (Figure 16). He described a settlement model in which the coast was occupied primarily in the spring and early summer, while during the autumn people moved further inland to the freshwater lake or the upper reaches of rivers, and in winter people established camps at accessible distances from the coast. As the palaeogeographic situation in the Kõpu palaeoislet ca. 6.0–7.4 cal. ka BP was broadly the same as in Larsson's description (Figure 15), a similar settlement pattern can also be considered.

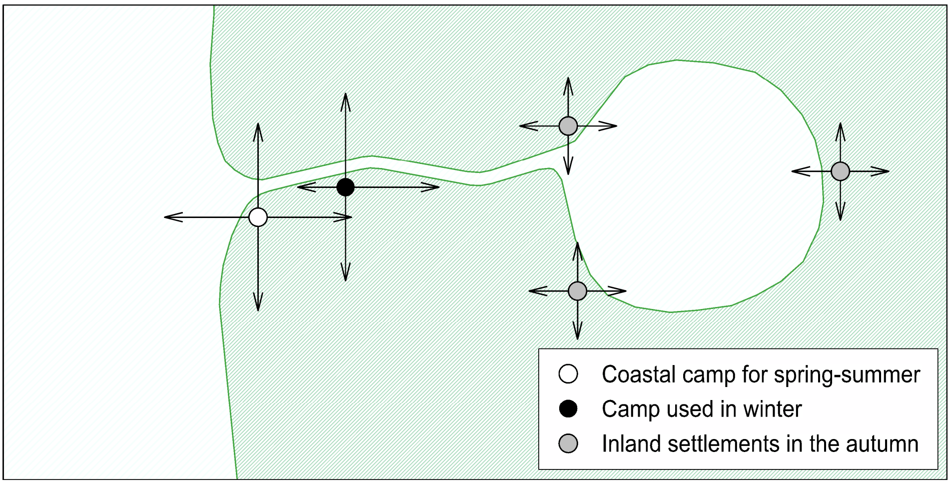

Figure 16. A settlement model proposed for central and southern Scania (Larsson, 1980; Astrup, 2018).

The choice of the settlement location in Hiiumaa Island and in many other areas in eastern Baltic (Kriiska, 2000) changed significantly when the Corded Ware culture spread with the beginning of agriculture and animal husbandry. The Kõpu 1a Corded Ware settlement with probably permanent habitation was established at a former beach away from the shore. Later, early metal age fields, pastures and graves were established in this area.

4.2.3 Bronze Age amber finds in coastal deposits in Saaremaa Island

At the beginning of the Post-Litorina Sea at about 4.5 cal. ka BP (Hyvärinen et al., 1988; Grudzinska, 2015), the coastal zone had lost its centrality for the nutritional requirements of the inhabitants due to the spread of farming (Schmölcke et al., 2006) and, together with rivers and lakes, had gained new importance as a prehistoric transportation network (Jöns, 2011). However, many settlements were still established on the eastern coasts of the Baltic Sea and on the islands until the Late Neolithic period (Kriiska, 2003; Veski et al., 2005; Bērziņš, 2008; Gerasimov et al., 2010) such as, for example, the Asva and Ridala fortified settlements on Saaremaa Island (Lang, 2007). Since Saaremaa Island was in the middle of the Bronze Age trade route, which reached around the Baltic Sea and along the River Daugava (Šturms, 1935), there are a good many archaeological finds that have equivalents in both Scandinavia and Central Europe (Lang, 1991; Gustavsson, 1997). Most of the bronze items of that time which have been found in Estonia came from Scandinavia, but central Sweden and SW Finland were the most important area for the exchange of elite prestige items (Lang, 2007). The Late Bronze Age archaeological record also indicates direct contact between the islanders of Saaremaa and Gotland (Lindquist, 1974).

One of the main Late Bronze Age exchange items in Estonia and all around the eastern Baltic was amber (Lang, 2007; Ots, 2012). Archaeological material from Saaremaa Island often includes amber items (Figure 17a) but, due to the

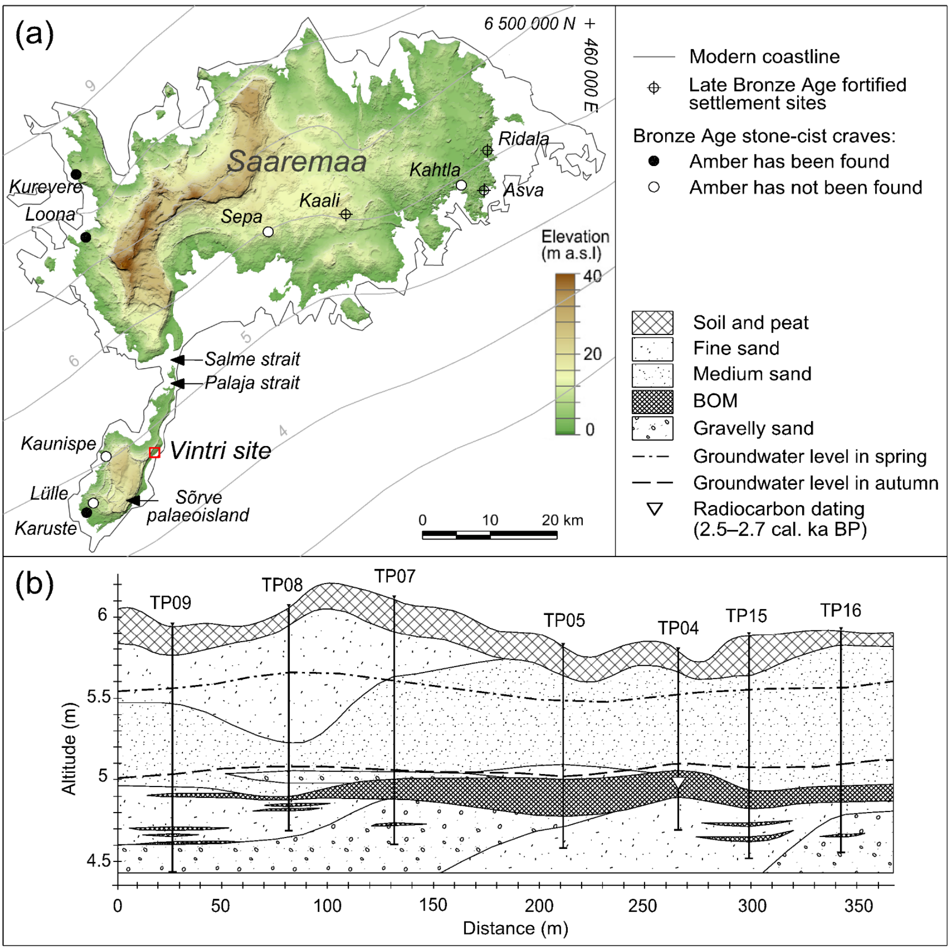

Figure 17. a) Late Bronze Age palaeogeographical reconstruction of the Saaremaa Island at 2.6 cal. ka BP with sea-level surface isobases (m a.s.l.), Bronze Age fortified settlements and stone-cist graves according to Lang (2007) and Ots (2012). b) Geological cross-section from Vintri site (parallel with present-day coastline). BOM – buried organic matter. (based on Paper III – Nirgi et al., 2017).

lack of local amber deposits in Estonia, these were considered to be gifts or trading items that had been brought from communities along the coasts of Latvia, Lithuania, and the Kaliningrad district (Russia) (e.g. Indreko, 1945; Kriiska and Tvauri, 2002). From that perspective the discovery of an amber-bearing deposit along the eastern coast of the Sõrve peninsula on Saaremaa and its geological context (Paper III – Nirgi et al., 2017) are important when attempting to understand the Bronze Age sociocultural processes on Saaremaa and more widely across the eastern Baltic Sea.

The layer of organic matter that has been discovered in Vintri contains the largest known concentration of amber in Estonia (Ots, 2012; Figure 17b). ATR-FT-IR (Attenuated total reflection Fourier transform infrared) spectroscopy analysis of amber from Vintri referred to Baltic amber, also known as succinite (Paper III – Nirgi et al., 2017), which is common along the S and SE coasts of the BSB (Wolfe et al., 2015). The stable isotope ratio also indicated the formation of the amber at lower latitudes than that of Saaremaa Island, which implies possible transportation from the SE Baltic coast. The amber was probably transported to Vintri within organic matter along the main SW–NE orientated current flows from the southern Baltic, where secondary Paleogene and Quaternary amber deposits are known to exist widely and where coastal erosion has dominated during the Late Holocene (Wiśniewski and Wolski, 2011). Cool and stormy LIA-type climatic periods at about 4.2, 2.9, 1.4, and 0.4 cal. ka BP (Reimann et al., 2011) probably brought about even more intense erosion along the coast. So, these periods may have been the most favourable for amber transportation to Saaremaa. According to an AMS date, the amber-bearing organic layer was deposited in Vintri during the Late Bronze Age at about 2.7–2.5 cal. ka BP (Paper III – Nirgi et al., 2017), which is close to the LIA period at 2.9 cal. ka BP. In the Gdansk region of Poland similar amber-bearing buried organic layers have been described in Holocene coastal sediments, with the youngest layer dated to 2.6–2.3 cal. ka BP (Kosmowska-Ceranowicz, 2004, 2008). A palaeoreconstruction of this period shows an island of Sõrve a few km offshore from Saaremaa (Figure 17a) and also a little Läätsa islet between Saaremaa and Sõrve, bordered by two narrow straits, the Salme and Palaja, which exist today as rivers.

Geoarchaeological evidence that is presented in Paper III (Nirgi et al., 2017) revealed that at least during the functioning period of the Bronze Age fortified settlements, it was possible for the inhabitants to collect amber on their own shore. The richest Bronze Age amber site is the fortified settlement of Asva where, besides processed items, many lumps of raw material have been found (Lang, 2007). The processed items are only slightly and unskilfully processed, which could be explained by the scarcity of local raw materials which prevented people from acquiring the skills and tools for working it (Ots, 2012). However, contemporaneous Bronze Age finds from Latvia also show a relatively low professional working level, which seems to be characteristic of Late Bronze Age workshops in this region (Denisova et al., 1985). The Vintri layer contains lumps that are big enough for making ornaments (Ots, 2012), hence the possibility exists that at least some Bronze Age archaeological amber objects could be made of local materials rather than being the result of trade with southern neighbours, as was formerly thought.

Although amber has not so far been found alongside other buried organic deposits in Estonia, the discovery of the Vintri deposit increases the possibility of the existence of similar amber-bearing layers in the former coastal areas around Estonia. It is likely that other similar buried layers are spread along the coastal areas of the Sõrve Peninsula, where the coastline has developed under the same conditions. In this case, the future discovery of new layers would certainly allow us to discuss whether the amount of amber found would have been great enough for the Saaremaa islanders not only to process it but also to trade it with other communities around the Baltic Sea.

4.2.4 Palaeoenvironmental changes in Salme since the Pre-Viking Age

Palaeographic reconstructions for the Salme area show the development of a former Salme palaeostrait between 700 BC and 1300 AD, which separated the Sõrve Peninsula from the Saaremaa mainland. In the Late Bronze Age (Figure 17a), at ca. 700 BC, the strait was up to 2 km wide and ca. 5 m deep and was probably a part of Bronze Age transportation network. In the south it was bordered by a small Läätsa palaeoisland and in the east by a S-N elongated spit system which, according to new OSL and radiocarbon dates, had already started to form as an underwater landform around 3300–3500 BC (Paper IV – Nirgi et al., manuscript).

The continuous RSL regression due to the land uplift in this area changed the Salme strait, making it shallower and narrower over time. During the presumed Pre-Viking period (Vendel Period) battle around 750 AD which ended with the death of the Salme crew and was followed by their burial, a semi-enclosed strait existed at Salme with a western section that was ca. 1-km-wide and an eastern section that was 80–100-m-wide (Figure 18). The water depth in the strait was 2–2.8 m and the relatively steep and wind-protected sandy-gravelly shores in the narrow part of the strait were probably the best places in the Salme area for landing the Viking ships.

Viking Age ship burials are well-known and have been thoroughly studied in Scandinavian archaeology, however Pre-Viking Age mass graves with ship burials are rare in Europe (Konsa et al., 2009), hence the uniqueness of the burials in Salme. The archaeological find material suggests that the vessels were sailed by a group of Vikings from the Stockholm-Mälaren region in Scandinavia (Konsa et al., 2009; Peets et al., 2011; Price et al., 2016). The crews were probably attacked during a crossing of one of the main trade routes across the Baltic Sea that ran across the archipelago of the Åland islands towards the amber-rich Courland region of Latvia (Price et al., 2016).

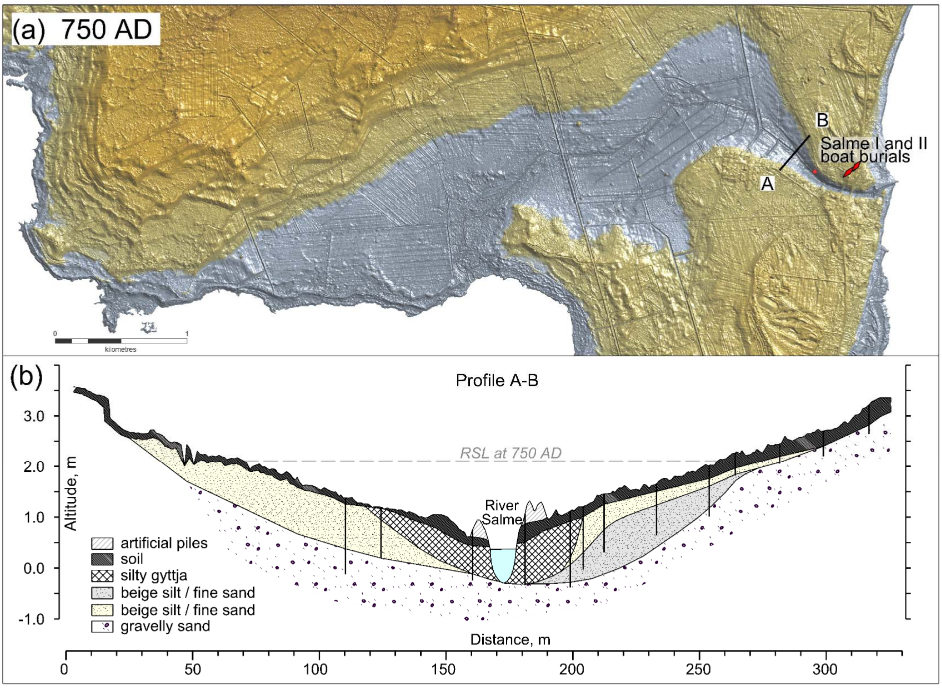

Figure 18. a) A palaeogeographic reconstruction of Salme strait at the Vendel Period at 750 AD, when the ships were buried to Salme; b) A geological profile across the Salme palaeostrait with coring sites (based on Paper IV – Nirgi et al., manuscript).

Geoarchaeological evidence presented in Paper IV revealed that Salme ship burials were not initiated on the shores of the Salme strait, and neither on the eastern coast. A palaeogeographic reconstruction (Figure 18a) shows that the burials are located about 2–2.5 m above coeval sea level and about 170 m (Salme I) and 130 m (Salme II) from the shores of the former strait (Paper IV – Nirgi et al., manuscript). The distances from the burial sites to the eastern sandy-gravelly coastline were 90 m and 130 m respectively. The Salme I and II ships were buried into a sandy-gravelly coastal deposit which had accumulated in the open coastal zone about 450–710 years earlier. Therefore, it is likely that both ships were moved from the shore to the higher ground for the burial. The orientation of the ship hulls suggests that they were most likely moved to the burial place from the shore of the narrow Salme strait.

Due to the ongoing uplift, closing of the Salme palaeostrait occurred around 1270–1300 AD, which can be confirmed by the sedimentological evidence, as well as by the diatom data. The mass occurrence of diatom species with the ability to survive successfully in a rapidly changing environment, coupled with the decline of marine/brackish periphytic diatoms, is considered to be an indicator of the closing (Grudzinska et al., 2013). Furthermore, the scanning electron microscope results indicate a diminishing marine impact on grain transportation and refer to non-marine influence coming, for example, from a fluvial and somehow less-energetic environment.

4.2.5 Methodological aspects of the geoarchaeological approach to reconstruct prehistoric coastal landscapes

The geoarchaeological approach, which includes carrying out assessments of the shoreline development and palaeogeographic situation, and a determination of the ages of deposits, is essential in coast-related research in order to understand prehistoric cultural heritage. One aim of the approach is to provide 4D reconstructions (i.e. 3D×time) of the land surface in different contexts in order to be able to reconstruct the changing topography, living conditions, and ecology of human habitats (Brown, 2008).

LiDAR scanning, which has the capability of producing DEMs of cm-level accuracy over large areas, is valuable for geoarchaeology in terms of showing variations in vegetation and soil moisture and giving it a surveying and remote sensing capability (Carey et al., 2006). LiDAR data is also essential for creating palaeoreconstructions for time slices that are of particular interest and was therefore used in papers I–IV. Palaeoreconstructions illustrate the environment in which prehistoric people preferred to live and therefore help to understand habitation patterns. Most Mesolithic settlements and camp sites that are known in western Estonia are nowadays located inland, which does not fit archaeological views of prehistoric settlement patterns. Geological knowledge together with palaeogeographic reconstructions have provided an understandable explanation about past shoreline changes and has placed these sites into an objective context that also fits with archaeological understanding.

A detailed description of the sediment stratigraphy of an archaeological site is essential as it contextualises and delimits the find material and provides the basic data for interpretations. A GPR survey combined with coring and sedimentological analyses was useful in the Pärnu area for the delimitation of the edges of the buried River Pärnu palaeochannel, and for describing the coastal sediments at the Kõpu and Salme sites, e.g. helped to reveal the locations of the Salme Viking ships. It could not, however, be used for evaluating the thickness of the channel infill at Pärnu due to the high groundwater levels and the palaeochannel fill material, which have low relative dielectric permittivity levels. In similar cases, electrical resistance (ER) has been used and combined with the GPR survey (Brown, 2008). A GPR survey may also help to locate further buried archaeological sites that are yet to be discovered and to map out the extent of the buried cultural layers or even settlements. The discovery of a buried palaeochannel at the bottom of present-day Pärnu Bay provides a new perspective for looking for submerged landscapes and possible Stone Age settlement sites on the shores of this river channel which is about 9000 years old.

Archaeological sea-level indicators, together with geological data, are used in creating RSL curves. RSL curves are in turn helpful for archaeological studies because they provide limiting dates which make it possible to assess the ages of typologically-dated coastal sites (Astrup, 2018). Thanks to this, an interdisciplinary approach which combines geological methods with archaeological knowledge has great significance in terms of decoding the prehistory of coastal habitation. The methods that have been presented in papers I–IV have proven to be useful and, therefore, have great potential in future studies on similar topics.

5. CONCLUSIONS

Three new RSL curves were constructed for western Estonia based on 180 critically reviewed geological and archaeological sea-level indicators from the Pärnu, Hiiumaa and Saaremaa study areas that provide new information about Holocene RSL trends. The RSL reconstructions led to the following main conclusions:

- New data from the buried River Pärnu channel suggest a sea level of at least –5.5 m a.s.l. prior to the Ancylus Lake transgression at about 11 cal. ka BP and a sea level of at least –4 m a.s.l. during the Initial Litorina Sea lowstand at about 9 cal. ka BP, both of which provide new perspective in terms of future studies in Mesolithic submerged landscapes in the Pärnu Bay area.
- A rapid Ancylus Lake transgression at an average rate of 35 mm/yr was documented in the Pärnu area between 10.7 and 10.2 cal. ka BP, which is similar to the transgression documented in southern Sweden. The subsequent drainage of the Ancylus Lake at around 10.2–9.8 cal. ka BP resulted in a RSL drop of 15 m in the Pärnu area and 20 m in the Kõpu area. Also in the Kõpu area, the RSL then lowered by another 3 m due to the more intensive isostatic land uplift in comparison to that of the Pärnu area.
- The Litorina Sea transgression in the Pärnu area, where the GIA uplift rates are among the slowest in Estonia, started around 8.5 cal. ka BP and the RSL rose about 7 m, but in the Kõpu area, where the land uplift rate is higher, the RSL rise began 700–900 years later, while being slower and with a lower amplitude of several metres. Our data support the conclusion from other slowly uplifting areas in the western BSB that the RSL at around 7.8–7.6 cal. ka BP exceeded the concurrent rates of the eustatic sea-level rise that has been calculated from the far-field sites.
- The RSL curve for Saaremaa shows a nearly-linear regressive trend of 2 mm/yr for the past 2700 years, and some slowdown in regression after 1300 AD which may be related to accelerated sea-level rise after the LIA and during the industrial period. The RSL trend has been a little slower when compared to the present-day absolute land uplift rate, indicating slow eustatic sea-level rise during the Late Holocene. The shorelines of Saaremaa and Hiiumaa are still regressive, as the isostatic rebound rate exceeds the eustatic sea-level rise. However, in the Pärnu area the relative mean sea level already shows signs of rising.

Implemented RSL and palaeogeographic reconstructions and investigations of Holocene sedimentary sequences show the utilisation of the coastal landscapes in western Estonia since the Stone Age. The geoarchaeological approach helps to improve the notion of prehistoric cultural heritage and settlement patterns in the coastal zone of the Baltic Sea:

- Pulli settlement was established at the lower reaches of the River Pärnu, probably about 15 km from the Ancylus Lake's lowest shoreline, which is ca. 5 km further from the coast than was previously proposed, and the Sindi-Lodja

I–II settlements were located ca. 3 km from the concurrent Initial Litorina Sea coastline, which is also further inland than was previously thought. Therefore, the general Mesolithic context may justify the assumption of year-round habitation, with temporary fisher camps along the coastline, possibly at the bottom of the present-day Pärnu Bay.

- Hiiumaa was first inhabited ca. 7.6–7.5 cal. ka BP, probably by hunter-gatherer groups from Saaremaa with the closest settlements about 43 km to the south. Palaeogeographic reconstructions show the shores of the south-eastern exposed Kõpu palaeobay as the most preferred camping locations for prehistoric hunter-gatherers, but the surroundings of the Kõivasoo palaeolake and its outflow were also utilised around 6.2–5.9 cal. ka BP. Late Mesolithic and earlier Neolithic campsites along the shores of the Kõpu palaeobay were successively located at lower elevations following the shoreline retreat during the Litorina regression, while Corded Ware and early metal age sites were established away from the shores.
- The palaeogeographical context of the amber-bearing organic deposit along the eastern coast of the Sõrve peninsula allows for the assumption that the locals were able to collect amber from their own shores during the Late Bronze Age. Therefore, the possibility exists that at least some Bronze Age archaeological amber objects could be made of local materials rather than being present as a result of trade with southern neighbours as was formerly thought.
- During the presumed battle in the Pre-Viking period, around 750 AD, which ended with the death of the crew of the Salme Viking ships, a semi-enclosed 2–2.8-m-deep strait existed in Salme with a ca. 1-km-wide western section and an eastern section that was 80–100-m-wide. The ship burials were not initiated on the shores of the strait and neither were they initiated along the eastern coast but were instead moved for burial from the shore of the Salme strait to the higher ground on top of Salme spit.

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SUMMARY IN ESTONIAN

Läänemere veetaseme muutused Holotseenis ja esiajaloolise rannikuasustuse geoarheoloogia Lääne-Eestis

Meretaseme muutuse uurimine on tänapäeval aktuaalne seoses kliima soojenemisest põhjustatud jääkilpide sulamisega poolustel, millega kaasneb globaalne meretaseme tõus, kujutades otsest ohtu lauge ja madala reljeefiga rannikupiirkondadele. Veehulga muutusest tulenev eustaatiline meretaseme tõus aga ei avaldu kõikjal ühtviisi. Näiteks kerkib kunagistel jäätumisaladel liustiku raskusest vabanemise järel maapind, mis sõltuvalt kerke intensiivsusest võib osaliselt või täielikult kompenseerida eustaatilise meretaseme tõusu. Selliste nähtuste koosmõjul toimuva suhtelise meretaseme muutumise selgitamine, aga ka usaldusväärsete tulevikuprognooside tegemine, nõuab tihedat uuringualade võrgustikku ja täpseid instrumentaalseid mõõtmisi. Paraku on instrumentaalsete mõõtmiste aegread suhteliselt lühikesed, ulatudes näiteks Eesti rannikualadel vaid üksikutel juhtudel saja ja enama aastani, mis ei ole piisav tulevikuprognooside tegemiseks. Seetõttu kasutatakse pikaajalise meretaseme ajaloo uurimisel geomorfoloogilisi, sedimentoloogilisi, biostratigraafilisi, kronoloogilisi ja muid meetodeid, et leida kunagise veetaseme indikaatoreid. Oluliseks suhtelise meretaseme indikaatoriks on ka meso- ja neoliitiline asustusmuster, mis on Eestis järginud meretaseme muutusest tingitud rannasiiret. Ja ka vastupidi, kunagise rannajoone ja rannikumaastike mudelid on aidanud arheoloogidel avastada asulapaiku ja mõista eelistusi nende valikul. Vastastikune huvi on pannud aluse geoarheoloogilistele uuringutele, millele on hoogu lisanud järjest täpsemad maapinna kõrgusandmed, mis võimaldavad geoinformaatika vahendite (GIS) abil modelleerida veetaseme, rannajoone, maastike ja asustusmustrite muutusi ajas.

Viimase mandriliustiku sulamine, perioodiline ühenduse tekkimine ja katkemine ookeaniga ning liustiku raskuse alt vabanenud maakoore kerkimine on põhjustanud Läänemere nõos olulisi pärastjääaegseid veetaseme muutusi. Tulenevalt maakerke intensiivsuse suurest varieeruvusest, mõjub Läänemere veetaseme muutumine selle erinevatele rannikupiirkondadele erinevalt. Nii toimub Läänemere põhjapoolsetel aladel, kus paiknes liustiku kese, kiire maakerge ja sellest tingitud suhtelise veetaseme langus, kuid lõuna pool, nullilähedase maakerkega aladel on olukord vastupidine. Eesti rannikul, mis paikneb maakerke äärealal, on korduvalt toimunud mere pealetunge ja taandumisi. Kõrgema veetasemega perioodidest annavad aimu vanad rannamoodustised nüüdisaegsest rannajoonest kümnete kilomeetrite kaugusel sisemaal ning madalaveelistele perioodidele viitavad rannasetete alla mattunud turvas ja teised orgaanikarikkad setted, sh kunagiste asulapaikadega seotud kultuurkihid, mis on tänuväärne andmestik Läänemere kesk- ja hilis-Holotseeni veetaseme muutuste ja inimasustuse seoste selgitamisel.

Käesoleva väitekirja eesmärk on täpsustada Läänemere veetaseme muutumise ajalugu Lääne-Eestis Pärnu (Trükis I – Nirgi et al., 2020), Hiiumaa (Trükis II –

Rosentau et al., 2020) ja Saaremaa (Trükised III ja IV – Nirgi et al., 2017 ja käsikiri) näitel ning rekonstrueerida sealse rannavööndi muutusi ja seoseid esiajaloolise asustusega. Uuring põhineb geoloogilisel ja geoarheoloogilisel lähenemisel, kombineerides meretaseme muutuste aegridade loomiseks nii settelisi, geomorfoloogilisi, arheoloogilisi kui ka bioloogilisi indikaatoreid, mida on võimalik seostada kunagise Läänemere veetasemega. Selleks dateeriti setteläbilõikeid olenevalt sette eripärast kas radiosüsiniku- või luminestsentsmeetodil. Nii uus kui ka varasem kronoloogiline andmestik vaadati kriitiliselt üle ning hinnati ka dateeringute täpsust kvantitatiivselt. Usaldusväärsete andmete alusel koostati kolm uut Läänemere veetaseme muutumise mustrit kirjeldavat veekõverat, mille omavahelise võrdlemise alusel saab hinnata piirkondlikke erinevusi muutuste toimumise ajas ja amplituudis, aga koostada ka tuleviku muutuste stsenaariume. Kogutud andmestik seoti GIS-rakenduse ja LiDAR-mõõdistusel põhinevate maapinna kõrgusmudelite abil paleorekonstruktsioonidega, mis illustreerivad huvipakkuvate perioodide rannikukeskkondi ja täpsustavad varasemaid teadmisi esiajaloolise rannasidusa asustuse paiknemisest.

Pärnu uuringualal, sh Pärnu lahe põhjas, avastati ja kaardistati Pärnu jõe kunagine säng, mis on täitunud orgaanikarikaste setetega ning mattunud enam kui 7 m paksuse liivakihi alla. Sängisetete uurimisel ja dateerimisel selgus, et Joldiamere madalseisu ajal, ca. 11 000 kal a t (radiosüsinikumeetodil dateerimise põhine ajaskaala **kal**ibreeritud **a**astat **t**agasi), ulatus meretase Pärnu kandis vähemalt 5,5 m allapoole tänast meretaset ning Litoriinamere madalseisu perioodil, ligi 9000 kal a t, umbes 4 m allapoole tänast meretaset (Trükis I – Nirgi et al., 2020). Mõlemad tasemed on oluliselt madalamad kui varem arvatud ning avavad uusi perspektiive kiviaegse rannasidusa asustuse otsimisel Pärnu lahe põhjasetetest.

Esimesele madalaveelisele perioodile järgnes Läänemere arenguloos umbes 10 700–10 200 kal a t kiire veetaseme tõus ehk Antsülusjärve transgressioon, mis oli seotud liustiku sulamisvee kiire juurdevooluga. Tulenevalt järgnevast järve mahajooksust Põhjamerre ligikaudu 10 200–9800 kal a t toimus omakorda kiire veetaseme langus ehk Antsülusjärve regressioon. Veetase langes Pärnu piirkonnas umbes 15 m võrra (Trükis I – Nirgi et al., 2020), kuid Hiiumaal, kus pärastjääaegne maakerge on intensiivsem, isegi kuni 20 m võrra (Trükis II – Rosentau et al., 2020).

Tulenevalt ookeanitaseme tõusu ja maakerke kiiruse sarnasusest kestis teine madalaveeline periood pärastjääaegse maakerke äärealadel ligikaudu 1500 aastat. Sellele järgnes uus veetaseme tõus ehk Litoriina transgressioon, mis oli seotud Laurentia ja Antarktika jääkilpide sulamisest tingitud eustaatilise meretaseme tõusuga. See algas aeglase maakerkega Pärnu ümbruses umbes 8500 kal a t (Trükis I – Nirgi et al., 2020) ja kiirema maakerkega Hiiumaal ligi 900–700 aastat hiljem (Trükis II – Rosentau et al., 2020). Kuigi maksimaalne veetase saavutati umbes samal ajal, oli veetaseme tõusu amplituud Hiiumaal kiirema maakerke tõttu, mis kompenseerib osaliselt veetaseme tõusu mõju, oluliselt madalam kui Pärnus.

Pärastjääaegse maakerke kiirus ületas ookeanitaseme tõusu Lääne-Eestis uuesti alates 7500–7300 kal a t, tuues kaasa suhtelise meretaseme alanemise, mis on jätkunud Eestis kuni ajaloolise ajani (Trükised I, II, IV). Saaremaa hilis-Holotseeni meretaseme geoloogilised ja arheoloogilised indikaatorid näitavad veetaseme suhtelist alanemist viimase 3000 aasta jooksul keskmise kiirusega ligi 2 mm/a (Trükis IV – Nirgi et al., käsikiri). Meretaseme indikaatorite võrdlus instrumentaalsete mõõtmistulemustega näitab, et maakerke kiirus on püsinud viimasel kolmel aastatuhandel suhteliselt muutumatuna, samas kui kaasaegsetest kliimamuutustest tingitud ookeanitaseme tõus on oluliselt aeglustanud suhtelise meretaseme alanemist, mille kiirus on Saaremaal tänapäevaks kahanenud ligi 0,1 mm/a (Trükis IV – Nirgi et al., käsikiri).

Läänemere veetaseme muutuste uued rekonstruktsioonid võimaldasid täpsustada erinevate Lääne-Eesti esiajalooliste rannasidusate asulakohtade paleogeograafiat. Nii paigutuvad näiteks Eesti vanimad kiviaegsed asulapaigad, Pulli ja Sindi-Lodja I–II, rannajoonest varem eeldatust kaugemale, mis tähendab, et need võisid olla püsiasulad, kust mindi kalapüügiperioodidel rannas paiknenud ajutistesse laagritesse, mis uute veetaseme andmete valguses ilmselt paiknevad tänase Pärnu lahe põhjas veel uurimata paleomaastikel (Trükis I – Nirgi et al., 2020). Analoogseid uppunud asulapaiku ja ajutisi kalurite asumeid sarnastest perioodidest on teada näiteks Rootsi lõunarannikult.

Esimesed inimasustuse märgid Hiiumaal pärinevad ajavahemikust 7600–7500 kal a t, mil esimesed kütid-korilased jõudsid sinna ilmselt Saaremaalt. Sellise järelduseni jõuti GISi abil nähtavusulatuse analüüsimisel, millest selgus, et Kõpu saar võis olla nähtav sel ajal u 43 km lõuna pool elanud Saaremaa asukatele (Trükis II – Rosentau et al., 2020). Paleorekonstruktsioonidelt nähtub, et esialgu eelistati Kõpu saarel elamiseks tuultest varjatud saare kagurannikut, kuid ajavahemikust 6200–5900 kal a t on teada asulapaiku ka tollase Kõivasoo järve kallastelt, millest tänaseks on saanud raba. Hilis-mesoliitilised ning neoliitilise kammkeraamika inimeste laagripaigad Kõpu saare kagurannikul paiknevad järjest madalamatel kõrgustel ehk inimesed liikusid taanduva rannajoonega kaasa. Samuti näitavad uued paleorekonstruktsioonid, et hilisemad nöörkeraamika ja varase metalliaja asulakohad Kõpu saarel paiknesid omaaegsest rannajoonest juba oluliselt kaugemal, mis näitab, et neile ei olnud mere lähedus esmatähtis.

Saaremaa pronksiaja arheoloogilises leiumaterjalis hulgaliselt sisalduv merevaik on paelunud uurijate tähelepanu juba pikemat aega. Kuna Põhja-Baltikumis merevaiku looduslikult ei esine, on leidusid interpreteeritud kui naaberrahvaste poolt kingitusena toodut, viidates ühtlasi pronksiaja inimeste suhteliselt ulatuslikule liikumistrajektoorile. Nüüd aga on Lõuna-Saaremaalt Vintri külast leitud mattunud orgaanikakiht, mis sisaldab infrapuna-spektroskoopia analüüsi põhjal tüüpilist Läänemere merevaiku ehk suktsiniiti. Geoarheoloogilised uuringud ja paleorekonstruktsioon näitavad, et merevaiku sisaldava kihi kuhjumise ajal paiknes piirkond intensiivse settetranspordiga rannajoonel. Selle teadmise valguses on võimalik, et vähemalt osa arheoloogiliste leidude merevaigust pärineb kohalikust rannast. Tõenäoliselt kandus merevaik Sõrve säärele tugeva lainetusega

Läänemere lõuna- ja kagurannikult LIA-tüüpi tormiderohkel perioodil ca. 2700–2500 aastat tagasi. Ühtlasi annab sellise kihi avastamine lootust, et sarnaseid, Eesti mõistes eksootilisi merevaiku sisaldavaid kihte, leidub veel, olles huvitav tuleviku uuringusuund.

Sõrve sääre idarannikul on veel teinegi põnev arheoloogiline leid – kaks eel-viikingiaegset laevamatust Salme külas, mis sisaldavad seitsme mehe luustikke. Setete uuringule ja vanusemäärangutele toetuvad paleorekonstruktsioonid näitavad, et sel ajal, umbes 750 AD, oli praeguse Salme jõe asemel väin, mis nii pronksi- kui ka viikingiajal lühendas oluliselt Ida-Lääne suunalist kaubateed. Eel-viikingiajal oli väin umbes 2–2,8-m-sügavune ning selle laius oli lääneosas ca. 1 km ja idapoolses osas 80–100 m. Tollase rannajoone asendi rekonstruktsiooni alusel järeldub, et erinevalt seniarvatust ei toimunud Salme laevamatused mitte rannas ega ka väina kaldal, vaid paadid on veetud pärast arvatavat lahingut vanale maasäärele, mis paiknes tollasest meretasemest ligi 2–2,5 m kõrgemal (Trükis IV – Nirgi et al., käsikiri).

Käesolev väitekiri ja selle tulemused annavad panuse Läänemere regiooni idaosa kiviaja asustust ja rannikualade muutuseid käsitlevatesse uurimisprojektidesse ETF 9011 ja PUT 456 ning Salme I laevamatuse ja selle paleokeskkonna uuringutele orienteeritud projekti MHVAJ18304.

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PUBLICATIONS

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1. **Nirgi, T.**, Rosentau, A., Ots, M., Vahur, S., Kriiska, A. (2017) Buried Amber Finds in the Coastal Deposits of Saaremaa Island, Eastern Baltic Sea – Their Sedimentary Environment and Possible Use by Bronze Age Islanders. *Boreas* 46 (4), 725–736.
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6. **Post, T.**, Rosentau, A., Jonuks, T., Kihno, K., Hang, T., Habicht, H-L., Kriiska, A., Risberg, J. (2016) Organic sediments from the buried river valley record low sea level in Pärnu region before the Litorina transgression. *Abstract Volume & Field trip Guidebook: The 13th Colloquium on Baltic Sea Marine Geology, 12–16.09.2016. Gdansk, Poland. Ed. Kramarska, R., Pączek, U., Uścinowicz, G., Uścinowicz, S., Woźniak, M. Polish Geological Institute, 31.*
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9. **Nirgi, T.**, Rosentau, A., Muru, M., Tõnisson, H., Bjursater, S., Hang, T., Kriiska, A., Sohar, K. (2019) New data about Holocene shore displacement and Stone Age seal-hunters from Hiiumaa Island, eastern Baltic Sea. *IGCP Project 639 "Sea Level Change from Minutes to Millennia" 4th meeting, 13–19.10.2019. Xiamen, China.*

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1. **Nirgi, T.**, Rosentau, A., Ots, M., Vahur, S., Kriiska, A. (2017) Buried Amber Finds in the Coastal Deposits of Saaremaa Island, Eastern Baltic Sea – Their Sedimentary Environment and Possible Use by Bronze Age Islanders. *Boreas* 46 (4), 725–736.
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