GIS-based multiproxy coastline reconstruction of the eastern Gulf of Riga, Baltic Sea, during the Stone Age

HANDO-LAUR HABICHT, ALAR ROSENTAU, ARGO JÖELLEHT, ATKO HEINSALU, AIVAR KRIISKA, MARKO KOHV, TIIT HANG AND RAIVO AUNAP

The coastal regions of the Baltic Sea are rich in Mesolithic and Neolithic shore-bound settlement sites (Lübke 2002; Jussila & Kriiska 2004; Zvelebil 2006, 2008; Fischer 2007; Kriiska & Roio 2011; Rosentau et al. 2011). These sites are often situated around former estuaries and river mouths (Veski et al. 2005; Jussila et al. 2007; Kriiska et al. 2011; Rosentau et al. 2013) or lagoonal systems (Kriiska 1999; Miotk-Szpiganowicz et al. 2010; Loze 2011; Rosentau et al. 2013). These features are, at present, located at different elevations because of uneven glacial isostatic uplift, up-damming or drainage of the Baltic basin and the Holocene sea-level rise. Palaeogeographical reconstructions, especially when considering the changes in sea level and land uplift, can be useful not only for understanding the palaeoenvironment (e.g. Houmark-Nielsen & Kjer 2003; Saarse & Vassiljev 2010; Grudzinska et al. 2013) and Stone Age human habitation patterns (e.g. Fisher et al. 2010; Zwervvaegher et al. 2010; Rosentau et al. 2011, 2013), but also for predicting the locations of undiscovered prehistoric settlement sites (e.g. Brandt et al. 1992; Legg & Anderton 2010; Sturt et al. 2013; Westley et al. 2014; Carlson & Baichtal 2015).

The development of geographical information systems (GIS) along with increasingly detailed remote sensing data (e.g. LiDAR, Shuttle Radar Topography Mission (SRTM) data) and geophysical data (e.g. ground-penetrating radar (GPR), multibeam echosounder (MBES)) offer new prospects for creating accurate and detailed palaeogeographical reconstructions (Bates et al. 2007; De Smedt et al. 2013; Westley et al. 2014). However, many current reconstructions (e.g. Fisher et al. 2010; Rosentau et al. 2011; Micallef et al. 2013) have some limitations owing to the fact that the impact of the sedimentary processes subsequent to the time being modelled, especially in the areas of significant deposition or erosion (Zwertvaegher et al. 2010; Westley et al. 2014), has not been taken into account. In order to assess the possible impact of sedimentary processes, geological and geophysical data must be included in the modelling process (Leverington et al. 2002; Zwervvaegher et al. 2010; De Smedt et al. 2013; Westley et al. 2014). In order to create high-resolution regional subsurface models De Smedt et al. (2013) proposed an integrated methodology combining remote and mobile near surface sensing data with traditional sediment and peat coring. This methodology has shown potential for archaeological studies and was incorporated into the current study for detailed palaeogeographical reconstruction of a palaeo-lagoon system in the coastal zone of the Gulf of Riga, the Baltic Sea.
Our study area, the Tolkuse-Rannametsa area, is located on the eastern coast of the Gulf of Riga (Fig. 1A), where previous geological studies have suggested the existence of a Litorina Sea lagoon (Kesssel 1963; Hyvärinen et al. 1992), which, at present, hosts the 5503-ha Tolkuse Bog with a maximum peat thickness of more than 6 m. Archaeological surveys have revealed three Stone Age settlement sites (Metsaküla I–III) in the vicinity of the Tolkuse Bog (Fig. 1B; Kriiska 2001), although their relationships to the former lagoon have not been studied so far. The typology of the find material (flint, quartz artefacts and some animal bones) from the Metsaääre I and II settlements suggests Mesolithic habitation at about 10 000–8500 cal. a BP. However, the find material from the Metsaääre III settlement, including Combed Ware Pottery, indicates Neolithic habitation around 6000–5000 cal. a BP (Kriiska 2001; Kriiska et al. 2011).

Fig. 1. A. Location of the study area with present-day apparent land uplift isobases (Ekman 1996) and coastal hunter-gatherer Stone Age sites in the eastern Baltic. One dot may represent more than one settlement site. Numbers along the Estonian and Latvian coastline show the areas discussed in Table 2. B. Topography of the Tolkuse Bog and surrounding areas and the locations of the Stone Age sites discussed in the text (Kriiska et al. 2011; Rosentau et al. 2011). The numbered black squares show the locations of radiocarbon-dated sediment sequences (Table 1), including the master core (no. 6). The study area is marked by the red rectangle with the reference site for the water-level curve (C) at Paikuse (modified from Rosentau et al. 2011), located north of the area.
During these time periods, the Gulf of Riga region was presumably rather densely populated by different groups of hunters and fishermen with settlements dating back to the Early Mesolithic period at about 11,000 cal. a BP (Veski et al. 2005; Kriiska et al. 2011). However, there is a gap in knowledge with respect to the eastern coast of the gulf, where little archaeological material has been discovered so far. In the present study, we investigated the Tolkuse palaeolagoon in order to reconstruct the early to mid-Holocene shore displacement and environmental history of the area. Based on the palaeogeographical reconstructions and comparing them with the archaeological data set from the eastern Baltic region we also propose some areas that might have been suitable for prehistoric human habitation. Our study contributes to the earlier knowledge of the water-level changes and palaeoenvironmental history of the Baltic Sea, providing new chronological and shore displacement data together with GIS-based palaeogeographical reconstructions.

Material and methods

Sedimentological, biostatigraphical and dating methods

Sediments were described in the Tolkuse Bog and on the Rannametsa coastal dunes along two profiles in 38 cores and in two outcrops on the bank of the
Rannametsa River (Fig. 1B). In the Tolkuse Bog, coring was carried out using a 1-m-long Russian-type peat-corer (inner ø 50 mm) and, for sandy deposits, a 1-m-long window sampler (inner ø 50 mm) combined with a drop-weight device (Sedidrill PM10) was used. A 7.5-m master core from the Tolkuse Bog and two sediment monoliths containing buried organic matter (BOM) from the outcrops were taken to the laboratory for further analysis. Additional data on the spatial distribution of peat thickness were scanned and manually digitized from Orru et al. (1986) Orru (1995).

The altitude of different sediment intervals was calculated from a LiDAR-derived digital elevation model (DEM); in the case of riverbank outcrops, an RTK-global positioning system (GPS; Sokkia GSR2700 ISX GPS) was used.

The contents of organic matter and carbonates were determined by the loss-on-ignition (LOI), following the guidelines of Heiri et al. (2001). About 20–25 g subsamples were dried overnight at a temperature of 105 °C, after which their dry weight was measured. In order to determine the organic matter content, the samples were ignited in an oven at a temperature of 550 °C for 5 h and the proportion of carbonates was determined by further igniting the samples at 950 °C for 5 h.

Table 2. The living environments of the Mesolithic and Neolithic coastal hunter-gatherer settlement sites in the eastern Baltic according to published sources. For all 108 settlement sites the environmental conditions are reasonably well established. The locations of the sites are shown in Fig. 1A.

<table>
<thead>
<tr>
<th>No. in Fig. 1A</th>
<th>Area</th>
<th>Settlement location</th>
<th>References</th>
</tr>
</thead>
</table>
| 1             | Narva-Luga area in NE Estonia and Ingermanland (Russia) | Total: 36  
14 – Barrier spit of a lagoon  
11 – Estuary/river mouth  
7 – Barrier island of a lagoon  
3 – Lagoonal (isolated) coast  
1 – Island in a lagoon | Kriiska (1999) |
| 2             | North Estonian coast | Total: 11  
8 – Estuary/river mouth  
2 – Coast of a bay  
1 – Island | Kriiska (1997) |
| 3             | Western Estonia | Total: 3  
2 – Small island  
1 – Barrier spit of a lagoon | Kriiska et al. (1998) |
| 4             | Hiiumaa island | Total: 16  
15 – Open coast  
| 5             | Saaremaa island | Total: 14  
7 – Open coast  
4 – Coast of a bay  
2 – Small island  
| 6             | Northern coast of the Gulf of Riga | Total: 9  
7 – Estuary/river mouth  
2 – Island in a lagoon | Kriiska & Lõugas (2009) |
| 7             | Ruhnu island | Total: 6  
3 – Lagoonal (isolated) lake  
2 – Coast of a bay  
1 – Open coast | Kriiska & Lõugas (2005) |
| 8             | Southern coast of the Gulf of Riga | Total: 1  
1 – Estuary/river mouth | Zagorska (2000) |
| 9             | Western coast of the Gulf of Riga | Total: 10  
10 – Lagoonal (isolated) lake | Loze (2006) |
| 10            | Western coast of Latvia | Total: 2  
2 – Lagoonal (isolated) lake | Berzini (2008) |
For the diatom analysis, 0.5-cm³ subsamples were digested in 30% H₂O₂ and 10% HCl to remove the organic matter and carbonates, respectively; thereafter, the fine mineral particles were removed by repeated decantation (Battarbee et al. 2001). The diatom concentrations were determined by adding a known number of commercially available divinylbenzene microspheres to the cleaned sediment slurry. The slides were mounted with Naphrax™ medium and analysed for microfossils using a Zeiss Axiolab microscope (oil immersion, phase contrast, ×1000 magnification). The diatoms were grouped in accordance with their habitat type into planktonic and littoral (epiphytic and benthic diatoms) taxa, and, with respect to salinity preferences, into marine and freshwater taxa.

Seven ¹⁴C AMS measurements were carried out in the Dating Laboratory of Poznań, Poland, and Beta Analytic Radiocarbon Dating Lab, USA. A further five conventional ¹⁴C analyses were carried out in the Radiocarbon Laboratory at the University of Tartu. In addition, 16 conventional ¹⁴C age determinations from previous studies were used (Table 1). All radiocarbon ages were calibrated to calendar years with the OxCal v4.2 program (Bronk Ramsey 2009).

Geophysical methods

The geophysical studies were carried using GPR, which offers good data coverage and penetration depth in peat (Lowry et al. 2009; Plado et al. 2011) and sand (Ramos et al. 2011) deposits, and is a widely used method for investigating the bedding and distribution of sediments in the areas between boreholes (Neal 2004; Fisher et al. 2007).

The GPR fieldwork was performed with a Zond 12-e system (Radar System Inc.) using a common-offset configuration with a co-polarized 300 MHz shielded antenna orientated perpendicular to the profile. The radar antenna box was pulled across the bog, along the forest and gravel roads at walking speed. The measurements were made at constant spacing equal to ≤10 cm which was determined by an odometer wheel. For tracking, a portable GPS, which was connected to the radar, was used. The time range of measurements was 500 ns. GPR measurements were carried out in June and September 2013 and October 2014 with GPR profiles covering a total of 47 km (Fig. 1B).

The data were processed using PRISM2 software and processing included a band-pass filter to remove low-frequency induction effects, a gain control to improve the readability of deeper reflections, and correction for topography. Topographical information was derived from the LiDAR data and correction for topography was applied at every 5 or 10 m along the GPR profiles. For different sediments, different relative dielectric permittivities were used: five for dry sand (Davis & Annan 1989), 25 for water-saturated sand (Davis & Annan 1989; Fisher et al. 2007), 70 for peat (Lowry et al. 2009; Plado et al. 2011; Mustasaar et al. 2013) and 40 for clay-rich gyttja (Davis & Annan 1989).

Removal of anthropogenic relief features from DEM

Our study area is largely covered by a network of drainage ditches, some causeways and abandoned peat extraction areas, that all may influence the interpretation of the area’s suitability for prehistoric habitation.

There are two main directions from which to approach the task of removing most of these features from the DEM. The first one uses vector map data to determine the required features and to create masks according to which these features are removed from the DEM (e.g. Zwertvaegher et al. 2010; Werbrouck et al. 2011; De Smedt et al. 2013). However, this method requires a substantial amount of manual work to correct and supplement the vector data and generated masks provided the data are available at all. The second approach employs different morphometric parameters of the DEM, like the slope, aspect and curvature of the surface, to detect the specific features (e.g. Rutzinger et al. 2011; Romstad & Etzelmüller 2012; Prasicek et al. 2014; Wieczorek & Migoni 2014), which are later removed. The accuracy of the results of this kind of analysis is comparable to manual relief classification (Wieczorek & Migoni 2014), but as Chen (2007) has pointed out, the results are dependent on the fine-tuning of the aforementioned parameters, and some manual inspection is still required. We combined these two methods in order to create a semi-automatic method, which simultaneously used the feature recognition skills of a human observer and the analytical and spatial calculation powers of a computer (Quackenbush 2004). Testing showed that the most suitable morphometric parameter for finding the ditches and causeways in our study area was curvature. The applicability of curvature analysis for geomorphological studies has been addressed by many researchers (e.g. Dikau 1989; Schmidt et al. 2003; Prasicek et al. 2014). The main curvature algorithms are Evans, Shary and Zevenberger and Thorne’s algorithms, of which Florinsky (1998) considered the Evans’ algorithm to be the most accurate one. The curvature is usually measured along or perpendicularly to the slope aspect (Wilson & Gallant 2000), and it shows the rate of slope change (Thomas et al. 2014). In our study, we used the Total Curvature algorithm, which shows the overall unevenness of the surface (Wilson & Gallant 2000; Schmidt et al. 2003). As ArcGIS 10.0 does not facilitate either tools using the Evans’ algorithm or the tools capable of conducting total curvature analysis, we employed a special DEM analysis toolkit for ArcGIS, DEM Surface Tools, developed by Jenness Enterprises.

The areas of the coastal formations and rivers were omitted from the total curvature analysis, as these
features were relatively undisturbed by human activities. Furthermore, owing to their complex morphology, it was complicated to separate the anthropogenic features from natural ones in these areas. Generally, the Stone Age settlements were often situated around rivers (Veski et al. 2005; Fischer 2007; Carlson & Baichtal 2015) so altering the ground morphology in these areas could lead to misinterpretation of area's archaeological potential. Masks were created and used in order to exclude the aforementioned areas from the curvature analysis.

Based on the total curvature analysis, the modern features were removed from the DEM, and a new surface was generated in place of the removed features using the natural neighbour interpolation (Fig. 2).

**Palaeogeographical methods**

The topographical data of the study area, a LiDAR-derived 5 m DEM, were provided by the Estonian Land Board. The LiDAR measurements in this area were carried out in 2011 with an average vertical accuracy of ±0.34 m and average data coverage of ~0.45 points per m² (Estonian Land Board 2014). The bathymetric data were provided by the Estonian Maritime Administration. Most of the bathymetric measurements date back to the 1950s; newer measurements were taken in 2002 and later. From these data, a bathymetric model with a 50-m resolution was derived.

The younger sediments were stripped back from the LiDAR DEM based on the geological, microfossil and GPR data in order to create three palaeo-DEM. For the first one, we removed the peat layer in order to reconstruct the setting before the peat formation. To model the maximum depth and extent of the lagoon, we also removed the gytja layer. Finally, the Rannametsa coastal formations and the peat layer from the Maarjapeakske Bog were also subtracted in order to simulate the palaeo-shoreline of the Ancylus Lake and the possible lagoon in the Maarjapeakske area. The third palaeo-landscape model included some simplifications, as there were not enough geological data to remove other pre-Litorina Sea sediments besides the Rannametsa sand dunes. The total thickness of the pre-Litorina Sea sediments in the Tolkuse basin, which included the Ancylus Lake sands and buried peat layer was between 0.2 and 1.2 m.

The present-day water level was represented by a uniform 0 m a.s.l. surface. The surfaces of the Ancylus Lake and the Litorina Sea maximum water levels used in this study were interpolated by Rosentau et al. (2011) using the Holocene Baltic Sea shoreline database (Saarse et al. 2003). To compensate for the uneven postglacial land uplift, the water-level surfaces followed the mean isostatic tilting gradients for the aforementioned periods.

The tilting gradient and the water level for required interstage surfaces between the Ancylus Lake, Litorina Sea and present day sea level were provided by a linear calculation supported by the Paikuse (NE Pärnu Bay, Fig. 1B) water-level curve (Rosentau et al. 2011). Use

![Fig. 2. Examples of the removal of the anthropogenic features from the DEM near the Ura River (Fig. 1B). The present-day relief is shown on the profiles by the red line and the relief of the interpolated surface by the black line. On profile A, a causeway is removed, but the river valley is left unaltered; on profile B, a ditch is removed and replaced with a surface in accordance with the surrounding area.](image)
of this method assumes that the study area was small enough to be characterized by homogeneous dynamics. This calculation enabled us to compute the elevation \( H_{ni} \) of every grid cell \( n \) for a certain period \( i \) using the following equation:

\[
H_{ni} = A_n + \frac{L_n - A_n}{T} T_i + d_i
\]

where \( A \) and \( L \) are the section’s older and younger reference surfaces, respectively, \( T \) is the length of time between stages \( A \) and \( L \), \( T_i \) is the time from initial stage \( A \), and \( d_i \) is the difference in the water-level change of the sample site from the linear trend line. The calculated results were compared with the dated geological material and corrected by increasing or decreasing the water level if necessary. In order to reconstruct the palaeo-shorelines, the interpolated water surfaces were subtracted from the corresponding palaeo-DEM.

Results

Ancylus Lake coastal formations at Soometsa

The eastern side of the Tolkuse basin is fringed by up to 20 m a.s.l. coastal dunes, which were partially reblown during post-Ancylus Lake periods. The altitude of the dune foot rises in a northwards direction from about 7 to 11 m a.s.l., resulting in a shoreline-tilting gradient (0.25–0.26 m km\(^{-1}\)) very similar to that reported by Saarse et al. (2003). Terrestrial organic matter sedimentation below the Soometsa coastal formations at 6.3 m a.s.l. occurred about 11 300–10 300 cal. a BP as recorded by eight radiocarbon dates from the Lemmeoja and Võidu sites (Table 1). The BOM rests directly on the till surface and has a relatively high mineral content (>50%). At both sites, the BOM is covered with sandy deposits interbedded with thin organic layers typical of the transgressive sediments of the Ancylus Lake (Veski et al. 2005). In
the current study, the Võidu site (no. 2 in Fig. 1B) was revisited to obtain new AMS radiocarbon dates (Table 1). The new AMS dates from the Võidu site are in good agreement with conventional ages obtained from previous studies. The radiocarbon dates show that the Ancylus Lake reached its highest level just after 10 300 cal. a BP, covering the terrestrial organic deposits with coarse sand and pebbles (Fig. 3).

**Tolkuse basin**

More than 7.5 m of sediment was recovered in cores from the Tolkuse basin. However, the GPR profiling provided information about the sediment layers up to a depth of 11 m. The Tolkuse master core comprises five main sedimentary units (units A–E in Fig. 4).

The lowermost unit, A, is composed of grey detrital silt and fine sand (carbonate content up to 13%), with a maximum thickness of 60 cm, lying directly on top of glacial till. There are no GPR data on these sediments, but the coring results indicate that this layer is laterally discontinuous (Figs 5A, 6A), most likely as a result of erosion. The diatom analysis shows that the sand and silt contain large lake diatoms, such as *Ellerbeckia arenaria* and *Aulacoseira islandica* (Fig. 7), typical of the Ancylus Lake freshwater environment.

![Diagram](image)

**Fig. 4.** Stratigraphical position of radiocarbon dates from the Tolkuse sediment master core (no. 6 in Fig. 1B) with LOI results. Different sedimentary units discussed in the text are marked by letters A–E.

**Fig. 5.** A. The southern geological cross-section of the Tolkuse basin based on coring and GPR data; the master core is marked with a black triangle. The internal structure of the sand deposits is shown where possible. Note that the lower boundaries of some basal sediments, such as till and buried sand layers, were not determined in either cores or on GPR profiles. These layers were drawn to visually clarify their presence and extent. B. Location of the cross-section.
The sediments of this unit are interpreted as shallow water coastal deposits of the Ancylus Lake.

The next unit, B, is composed of a 20-cm-thick buried peat layer. The radiocarbon dates from this unit in Tolkuse (Table 1) indicate that peat accumulation at

(Fig. 6. A. The northern geological cross-section of the Tolkuse basin based on coring and GPR data. The internal structure of the sand deposits is shown where possible. The lower boundaries of some basal sediments, such as till and buried sand layers, were not determined in either boreholes or on GPR profiles. B. Location of the cross-section.)

(Fig. 7. Summary diatom diagram for the Tolkuse master core (no. 6 in Fig. 1B). Diatoms are grouped according to salinity and ecological preferences. Different sedimentary units discussed in the text are marked by letters A–E.

(Jensen et al. 1999; Veski et al. 2005). The sediments of this unit are interpreted as shallow water coastal deposits of the Ancylus Lake. The next unit, B, is composed of a 20-cm-thick buried peat layer. The radiocarbon dates from this unit in Tolkuse (Table 1) indicate that peat accumulation at
Tolkuse took place during the low water level stage during the initial Litorina Sea stage at about 8800–8200 cal. a BP. Elevation of the peat layer indicates that the sea level in the Tolkuse area remained below 1.3 m a.s.l. at that time (Fig. 5A).

Unit C is composed of beige fine sand intercalated with thin organic laminae typical of transgressive sediments found in the Pärnu area (Veski et al. 2005; Saarse et al. 2006). These sandy sediments contain a diverse assemblage of littoral diatoms characterized by a mixture of freshwater, salinity-indifferent and marine taxa, indicating deposition in the shallow and low salinity environment of the Litorina Sea lagoon (Fig. 7).

The transgressive sands are covered by about a 2-m-thick layer of clay-silt gyttja deposits (unit D). In the northern part of the basin, in the Vaskrääma area (no. 3 in Fig. 1B), the gyttja deposit lies directly on the top of a 15-cm-thick buried peat layer (Kessel & Punning 1969a). The accumulation of peat in Vaskrääma took place at about 8300 cal. a BP, whereas the onset of the gyttja deposition is dated to 7800–7600 cal. a BP (Table 1).

In a few areas in the eastern part of the bog, the contact between the Litorina Sea transgression sand deposits and overlying gyttja is distinguishable on the GPR images (Fig. 8A, C). The appearance of a gyttja layer indicates the onset of lagoonal conditions in the Tolkuse basin (Berglund et al. 2005; Lima et al. 2013). The organic matter content of the gyttja is about 18–20%, and the carbonate content is around 6%, decreasing to 3% in the upper parts (Fig. 4). In the southern part of the basin, the gyttja is much sandier than in the central and northern parts and, in places, there are thick laminae of fine sand in the gyttja layer. The sand content is also noticeably greater in the western part of the basin, where the sand was probably blown from and across the Rannametsa dunes. The sandier gyttja gives noticeably more distinguishable reflections on the GPR profiles compared to the gyttja in the central part of the basin. In addition, the interbedded sand layers, which wedge out eastward, are represented by several clear reflections on the images (Fig. 8C). It is likely that these layers indicate a marine connection (Boggs 2006) or storm surges (Liu et al. 1993).

The lower part of the gyttja (unit D) contains high values of planktonic diatoms such as *Pseudopodosira westii*, *Cyclorella choctawhatcheeana* and *Melosira lineata*. In addition, marine littoral taxa, notably *Opephora marina*, *Cocconeis scutellum* and *Diploneis smithii*, are common (Fig. 7). The diatom evidence implies that the Tolkuse basin developed from a slightly brackish to a marine environment; the relatively abundant occurrence of pelagic planktonic diatoms suggests an increase of the water level and rather deep-water conditions, whereas the lagoon has a broad connection with the open sea. Moreover, the absolute abundance of diatom flora increases, indicating higher primary production.
The diatom evidence from the upper part of the gyttja sequence (unit D) is characterized by an apparent decline in planktonic marine diatoms (Fig. 7). Small-sized fragilarioid marine littoral taxa that live attached to sand and silt grains, such as *Pseudostauropsis geocollegarum*, *Fragilaria sopotensis* and *F. amicorum*, are abundant. Simultaneously, benthic saline water diatoms, such as *Campylodiscus echeneis*, *C. clypeus*, *Planothidium delicatulum* and *Karayevia submarina*, occur. The diatom composition suggests a considerable decrease in the water level and a narrowing of the connection between the lagoon and the sea.

The gyttja is overlain by a peat deposit (unit E in Fig. 4), indicating isolation of the lagoon. The AMS radiocarbon dates from the isolation interval in the Tolkuse basin suggest that the overgrowing of the lagoon took place between 3800 and 3500 cal. a BP (Table 1). In the Tolkuse Bog, a GPR signal reflection originating from the boundary between the overlying peat and the underlying coastal and lagoonal sediments is distinguishable in most of the GPR images. The aforementioned reflection is absent from the deeper parts of the basin, especially in the central part of the bog. The lack of reflections from the gyttja surface is most likely caused by its clay content, which tends to attenuate the radar wave significantly, and by the similarity of physical properties between gyttja and decomposed peat (Plado *et al.* 2011). The lower part of the layer consists of wood peat in the middle of the basin and reed peat on the side of the basin. On the GPR, profile the less-decomposed components, such as remnants of wood, are marked by hyperbolic reflections.

**Metsaääre I–III Stone Age settlement sites**

Although there were numerous archaeological finds from the Metsaääre settlement sites, there was little material available for radiocarbon dating. The only substantial sample, a cremated (δ¹³C = -26.5‰) terrestrial mammal bone (identified by Dr Lembi Lõugas, Tallinn University, Institute of History) from the Metsaääre I site was dated to about 8000 cal. a BP (Table 1), suggesting habitation during the Litorina Sea transgression period. Based on the typology of the stone and flint artefacts and the absence of pottery, the Metsaääre II settlement was probably inhabited during the same period as Metsaääre I. Find material, including a sherd of Comb Ware, suggests inhabitation of the Metsaääre III settlement site around 6000–5000 cal. a BP (Kriiska 2001).

**Litorina Sea coastal landforms and dunes at Rannametsa**

The highest dunes at Rannametsa (also the highest in Estonia) reach up to 35 m a.s.l. and have a relative height of about 20 m. Such features are often formed during transgressions when there is an abundance of sediments in shallow water offshore (Bird 1994, 2008; Lima *et al.* 2013). The series of spits, consisting of medium-grained sand, in the northern part of the dune chain (Fig. 1B) indicates a northwards direction of sediment transport (Bird 2008; Viiska & Soomere 2013). The sedimentological features in the Rannametsa dunes were distinguishable on the GPR profiles for up to 20 m in depth (Fig. 8C).

In the current study, the Rannametsa site (no. 4 in Fig. 1B) was revisited to obtain additional radiocarbon dates and investigate the possible passage area of the Tolkuse lagoon. Organic sedimentation below the Rannametsa coastal formations occurred at about 8900–8500 cal. a BP, as recorded by seven radiocarbon dates (Table 1). The peat layer is covered with fine sand intercalated with thin organic laminae in which a slightly flattened trunk of a diffuse-porous deciduous tree (ø 15 cm) was found. The trunk was located about 15 cm above the buried peat layer in the transgressive sediments and dated to 7700 cal. a BP (Fig. 9, Table 1), indicating the onset of the Litorina Sea transgression. According to Hyvärinen *et al.* (1992), the basal part of this sand layer contains a mixture of littoral freshwater and brackish water diatoms, but the upper parts contain only brackish water taxa such as *Campylodiscus clypeus*. The transgressive
sands are covered with fine sand in which landward-dipping reflections at an angle of about 30° are observable in some parts the GPR profiles above the water table (Fig. 8C). Under the water table, several sand layers tilted towards the sea are present, which contain coarser material. On the western foot of the dunes, GPR images show reflections indicative of progradational sediment deposition caused by the regression of the sea (da Rocha et al. 2013). On the GPR, profiles running along the dunes, features indicative of longshore sediment transport are seen; however, in the area of the southern passage of the lagoon, reflections inherent to cross-shore transport are visible.

Fig. 10. Palaeogeographical reconstruction of the Tolkuse-Rannametsa area in the eastern coast of the Gulf of Riga. The palaeo-coastlines and water depths of the eastern coast of the Gulf of Riga with indication of water-level isobases (m a.s.l.) during the different stages of the Baltic Sea are shown on the reconstructions: A. Ancylus Lake maximum at about 10 200 cal. a BP. B. Initial Litorina Sea lowstand around 8800 cal. a BP. C. Litorina Sea maximum 7300 cal. a BP. D. The shallowing of the lagoon and narrowing of the northern passage around 6000 cal. a BP. E. Isolation of the lagoon and the start of peat formation in the Tolkuse basin around 4000 cal. a BP. Areas <0.5 m above the water level are marked with a chequered pattern. The locations of the Metsäari Stone Age settlement sites during the period of possible habitation are shown in panels B, C and D. Red areas mark the regions with suitable environments for Stone Age habitation based on the archaeological material from the surrounding areas.
Palaeogeographical reconstructions

Palaeogeographical reconstructions for five periods are presented in Fig. 10A–E. The time slices were chosen according to their relevance to the sea-level changes and to the development of the nearby Stone Age settlements. Our reconstructions show that postglacial land uplift, sea-level fluctuations and sedimentological processes can have a significant effect on the geomorphology and environment of the coastal regions of the Gulf of Riga. The high-resolution LiDAR elevation data used in this study provide an accurate representation of the present-day relief and reveal several morphological details about the geological evolution of the area that were not depicted on the earlier topographical maps, but that play important roles in determining the potential areas of Stone Age habitation. For example, a complex spit system in the northern part of the Rannametsa dunes and numerous old coastal landforms were revealed.

The methodology for removing the anthropogenic features from the present-day DEM developed in this study enabled us to remove morphological elements that might have led to a misinterpretation of some areas with respect to their suitability for prehistoric human occupation. Compared with the methodologies used by, for example, Zwertiaegher et al. (2010) or De Smedt et al. (2013), our approach requires less input data and manual work, and should be more suitable for use in remote areas, where manmade structures may be poorly mapped, if mapped at all. The current curvature-based method did not classify the features, only detected them, although, as Prasicek et al. (2014) have shown, it is possible to develop curvature-based methods further for the automated identification of specific landforms.

The Holocene shore displacement and archaeological potential of the Tolkuse-Rannametsa area

The reconstruction and understanding of past coastal landscapes play a significant role in geoarchaeological studies, as coastal zones are now widely recognized as environments that often supported relatively large hunter-gatherer populations (Ricklis & Blum 1997). Sedimentary and chronological data, together with GIS-based palaeogeographical reconstructions, from the Tolkuse-Rannametsa area indicate three main phases in the Holocene development of the area. Analysing and comparing the palaeogeographical and environmental reconstructions with palaeogeographical knowledge about more than one hundred already known Mesolithic and Neolithic coastal settlements from the eastern Baltic, which in our study includes sites from Estonia, Latvia and Ingermanland in Russia (Fig. 1A; Table 2), provides the possibility to propose potential areas suitable for Stone Age habitation in the study area.

The open coast environment of the Ancylus Lake

The AMS-dated wood from the buried peat layer at the Viõdu site (Fig. 3), close to the highest shoreline, indicates that the Ancylus Lake transgressed our study area and reached its highest level just after 10 300 cal. a BP (Table 1). During this period open nearshore conditions existed in the Tolkuse area (Fig. 10A) with deposition of fine sand and silt containing typical Ancylus Lake diatoms such as Ellerbeckia arenaria and Aulacoseira islandica (Fig. 7). The first archaeological evidence of human habitation in the Gulf of Riga area is also related to the Ancylus Lake period. The oldest dated settlement site, Pulli (10 800–10 200 cal. a BP; Poska & Veski 1999; Kriiska & Lõugas 2009), located only about 20 km north of our study area at the lower reaches of the contemporary Pärnu River, was inhabited during the period of the Ancylus Lake transgression. The settlement site was flooded by the waters of the Ancylus Lake around 10 200 cal. a BP, as evidenced by the coastal sandy deposits on the top of the cultural layer (Veski et al. 2005). As is the case for the Pulli site, the majority of the Stone Age settlement sites in the eastern Baltic from this period were not located directly on the coastline, but were some distance upstream from the river mouths (Jussila et al. 2012). Therefore we argue that, in the Tolkuse-Rannametsa area, Early Mesolithic settlements could have existed around the former river mouths (Table 2) and lower reaches of the Häädemeeste, Rannametsa, Reiu and Ura rivers (Fig. 10A).

The low water level during the initial Litorina Sea

It is probable that, after the drainage of the Ancylus Lake around 9800 cal. a BP (Andrén et al. 2011), the water level in our study area dropped for a short period close to the present-day sea level, or even below it (Figs. 1C, 10B), which opens up the possibility of searching also for submerged archaeological sites. During this period, the first seal-hunter dwelling sites appeared in the eastern Baltic Sea region (Lõugas 1997; Zagorska 2000; Ukonen 2002; Halinen & Mökkönen 2009). Several submerged Mesolithic sites, located in an area with a very similar uplift history (Litorina Sea maximum limit at 8 m a.s.l.; Yu et al. 2007), have recently been discovered on the bottom of the Hanõ Bay at a depth of ~5–7 m (D. Hammarlund, pers. comm. 2015). About 15 km north of the Tolkuse Bog in an area of slightly faster uplift (Litorina Sea maximum limit at ~10 m a.s.l. (Veski et al. 2005)), the Mesolithic seal-hunter dwelling sites Sindi-Lodja I and II (Fig. 1B) are located at an altitude of 3–4 m a.s.l. and are dated to 9200–8800 cal. a BP (Kriiska 2001). In the Tolkuse area, the lowermost peat layer found is at an elevation of 1.3 m a.s.l., indicating that the Baltic Sea level was below this elevation at about 9000–8600 cal. a BP (Table 1).
Litorina Sea lagoon

Based on the radiocarbon dates from the BOM layer, a tree trunk from the marine sands at Rannametsa and a lagoonal gyttja deposit at Vaskriäärma (Table 1), the onset of the Litorina Sea transgression in our study area occurred after the 8200 cal. a BP cold event (Barber et al. 1999), most probably between 8200 and 7700 cal. a BP. During this period, sandy deposits alternating with thin organic laminae formed in the area in shallow water conditions with an active wave regime and erosion of organic sediments lying beneath. These sandy deposits contain a diverse assemblage of the littoral brackish-water diatoms (Fig. 7), indicating deposition in the shallow, semi-enclosed Litorina Sea lagoon.

The stabilized shoreline position at Rannametsa at the end of the transgression around 7500–7300 cal. a BP (Veski et al. 2005) probably initiated the dune formation on top of the coastal ridge. During that time, a 25-km-long and 5-km-wide lagoon existed in the Tolkuse area (Fig. 10C). The water level in the lagoon was about 9 m a.s.l. in the north and about 6 m a.s.l. in the south, and the estimated water depth was up to 5.5 m. Our reconstructions show that the Tolkuse lagoon had two passages: one in the north and another in the south. The northern passage was about 3.5 km wide and functioned initially as a main connection route with the Baltic Sea basin, and the southern passage was more than 1 km wide. The presence of sufficient water exchange between the lagoon and open sea for brackish water environment together with a relatively low-energy wave regime are suggested by the high abundance of marine and brackish water diatoms in the gyttja deposit in the deeper part of the lagoon. However, around the southern passage, the presence of sand interlayers in the gyttja suggests that cross-shore sediment transport into the lagoon intensified periodically. After the transition into the land uplift induced relative sea level fall around 7300 cal. a BP (Fig. 1C), the water level in the lagoon lowered, and the passages started narrowing. Our models indicate that the northern passage was probably the first to close, some time after 6000 cal. a BP (Fig. 10D), owing to the more intense land uplift compared to the southern part of the basin and northward growth of the barrier spit. A brackish water lagoon existed in the Tolkuse area for over 4000 years and was terminated around 3800–3500 cal. a BP (Fig. 10E) when peat formation started in the present-day Tolkuse Bog (Fig. 5A).

Based on the current findings from this period in the eastern Baltic (Table 2), the most likely areas to have Stone Age settlement sites in the Tolkuse-Rannametsa area are river mouths (Fig. 10C, D). Furthermore, lagoonal systems often attracted Mesolithic and Neolithic communities in many areas around the Baltic Sea, including the coastal regions of Estonia, Latvia and Ingermanland in Russia (Table 2). Around the Tolkuse lagoon, one Neolithic and two Mesolithic settlements are presently known (Fig. 1B). The dated terrestrial bone material from the Metsäääre I Mesolithic site and the typology of the find material from Metsäääre II indicate that settlement sites existed during the time of the Litorina transgression around 8000 cal. a BP (Table 1). Both settlement sites were located on river terraces at the lower reaches of the ancient Reiu River, which entered into the lagoon (Fig. 10C). However, it is difficult to estimate how close to the lagoon shore these two settlements were located, as the Litorina Sea level rose rapidly during that time (Yu et al. 2007; Rosentau et al. 2013), causing a rapid regression of shorelines towards inland. The youngest settlement, Metsäääre III, existed around 6000–5000 cal. a BP and was probably located at the lower reaches of the ancient Reiu River, about 2–3 km from the lagoon shore (Fig. 10D). The current relative scarcity of archaeological finds in the surroundings of the lagoon may be explained not only by limited archaeological prospection works, but also by the fact that many areas with high archaeological potential (Fig. 10C, D) in the western part of the lagoon have been buried under an up to 3-m-thick peat layer (Figs 5A, 6A). This opens up the possibility of finding well-preserved settlement sites and artefacts below the protective peat layer, below the groundwater level. On the southern coast of the Gulf of Riga and western coast of Latvia, several peat-covered coastal sites, such as Särnate (5480–4490 cal. a BP; Berzinš 2008) and Silinėupe (around 5000 cal. a BP; Zagorska 2000), situated around former lagoonal lakes (Table 2) have contained numerous well-preserved finds, including wooden artefacts.

Conclusions

- Radiocarbon-dated sediment stratigraphies and diatom analyses, supported by GPR data and GIS-based modelling, were used to strip back younger sediments and landforms from the present-day elevation model, which enabled us to create detailed early to Mid-Holocene palaeogeographical reconstructions for the Tolkuse-Rannametsa area on the eastern coast of the Gulf of Riga. This, in turn, allowed us to reconstruct palaeogeographical situations for the Metsäääre Stone Age settlements and to propose potentially suitable areas for prehistoric human habitation.
- Owing to the uneven postglacial land uplift, the highest coastal landforms of the Ancylus Lake are located at a present-day altitude of 10.5 m a.s.l. in the northern part and at 6.5 m a.s.l. in the southern part of the study area, with an average shoreline tilting gradient of 0.25–0.26 m km$^{-1}$. The radiocarbon dates from the buried organic matter below the
highest shoreline show that it was formed just after 10 300 cal. a BP. At that time, an open coast environment existed in the area with several rivers entering into the Ancylus Lake. The areas around these former river mouths are considered potential areas in which to search for Early Mesolithic settlements.

- After the drainage of the Ancylus Lake, at about 9000–8600 cal. a BP, the water level in our study area briefly dropped close to the present-day sea level, or even below it, as indicated by the lowest buried peat layer found here, which is at an elevation of 1.3 m a.s.l.

- The waters of the Litorina Sea flooded the study area between 8200 and 7700 cal. a BP, forming a 25-km-long and up to 5.5-m-deep lagoon with two connections to the sea. This brackish water lagoon existed in the Tolkuse area for over 4000 years and was isolated from the Baltic Sea around 3800–3500 cal. a BP when peat formation in the present-day bog began. Around the lagoon, one Neolithic and two Mesolithic settlements are presently known. The dated terrestrial bone material from the Metsaääre I Mesolithic site and the typology of the find material from Metsaääre II show that these settlement sites correspond to the time of the Litorina transgression around 8000 cal. a BP. Both settlement sites were located on river terraces at the lower reaches of the ancient Reiu River, which entered into the lagoon. The Neolithic settlement, Metsaääre III, existed around 6000–5000 cal. a BP and was probably located at the lower reaches of the ancient Reiu River, about 2–3 km from the lagoon shore. The current scarcity of archaeological finds in the surrounding areas of the lagoon may be explained not only by limited archaeological prospection works, but also by the fact that many areas with high archaeological potential have been buried under a several-metre-thick peat layer.

Acknowledgements. – The authors express their thanks to Merle Muru, Hanna Raig and Triine Post for the assistance during fieldwork. Furthermore we would like to express our gratitude to Kersti Kihno for the identification of plant macro-remains and Lembi Lõugas for the identification of the bone found at the Metsaääre I settlement site. We also thank Dan Hammarlund and an anonymous reviewer for their comments and suggestions for improving the manuscript. This multidisciplinary study was supported by the Estonian Research Council research grants PUT456 and IUT1-8 and by the Estonian Science Foundation grant ETF9011.

References


Wieczorek, M. & Migoń, P. 2014: Automatic relief classification vs. expert and field based landform classification for the medium-altitude mountain range, the Sudetes, SW Poland. Computers & Geosciences 59, 133–146.


Yu, S.-Y., Berglund, B. E., Sandgren, P. & Lambeck, K. 2007: Evidences of late Pleistocene and Holocene coastal uplift from LiDAR data, a case study in Flanders (Belgium). Expert Systems with Applications 38, 8178–8185.