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Submerged Landscapes in the Hanö Bay

Early Holocene shoreline displacement and human environments in the southern Baltic Basin

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Submerged landscapes in the Hanö Bay

Early Holocene shoreline displacement and human
environments in the southern Baltic Basin

Anton Hansson



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Quaternary Sciences
Department of Geology

DOCTORAL DISSERTATION

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Dr. Jørn Bo Jensen

Geological Survey of Denmark and Greenland

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Front cover: A rooted stump protruding from the organic sediments at Haväng. Photograph Arne Sjöström.

Back cover: The author after his first (and only) dive with a double tank system. Photograph Arne Sjöström.

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PAPPER



Organization LUND UNIVERSITY Department of Geology Sölvegatan 12 SE-223 62 Lund Sweden Author: Anton Hansson	Document name DOCTORAL DISSERTATION Date of issue: 2018-05-22 Sponsoring organization	
Title and subtitle: Submerged landscapes in the Hanö Bay – Early Holocene shoreline displacement and human environments in the southern Baltic Basin		
<p>Abstract</p> <p>During times of lower global sea level, vast areas of the coastal shelf were exposed and converted into ecologically diverse coastal landscapes that were attractive for human occupation. The landscapes were subsequently flooded during the deglaciation, but well-preserved remains of these landscapes and their inhabitants can today be found on the seafloor. In the southern Baltic Basin, where the complex relative shoreline displacement history exposed large coastal areas, many submerged landscapes can be found. However, in Swedish waters, the research interest in these landscapes has been limited. The Hanö Bay area in southeastern Sweden, where well-preserved remains of early Holocene coastal landscapes can be found off the coast at Haväng in eastern Skåne and in the near-shore waters in western Blekinge, is an exception. The overall aim of this thesis is to increase the understanding of these coastal landscapes, their inhabitants and the water level changes that formed, and later inundated, the landscapes.</p> <p>High-resolution bathymetry data, organic sediment sequences, surveillance and sampling of wood remains and archaeological artefacts by divers and GIS-based palaeogeography modelling were used in this multidisciplinary project to investigate the shoreline displacement, coastal environments and human resource exploitation in the Hanö Bay region during the early Holocene.</p> <p>Based on the depth and age of submerged rooted stumps and organic sediments from Haväng, the early Holocene shoreline displacement in the area has been refined. The Yoldia Sea lowstand level was determined to 24–25 m b.s.l. and the subsequent Ancylus Lake transgression lasted approximately 500 years, from 10,800 to 10,300 cal BP, with a mean rate of 4 cm yr⁻¹. The maximum Ancylus Lake level was determined to about 5 m b.s.l., while the lowstand level of the subsequent Initial Littorina Sea Stage was determined to approximately 10 m b.s.l. The maximum level of the Littorina Sea Stage in the area was determined to about 4 m a.s.l. at c. 6000 cal BP.</p> <p>During the Yoldia Sea and Ancylus Lake Stages, the Haväng area was a pine-dominated open woodland with a slow-flowing nutrient-rich stream characterized by ponds and wetlands. Recovered bones with slaughter marks show that aurochs and beaver were hunted in the area. During the subsequent Initial Littorina Sea Stage, the river mouth developed into a productive lagoon surrounded by a more closed forest with both coniferous and deciduous trees. The findings of several stationary fishing constructions, dated to 9000–8400 cal BP, indicate that the subsistence was focused on large-scale fishing, which suggests a development towards a sedentary lifestyle and year-round presence in the coastal landscape. The area was finally inundated during the Littorina Sea transgression phase, at about 8000 cal BP.</p> <p>The preservation of the submerged landscapes and their artefacts in the Hanö Bay region is dependent on generally sheltered conditions, either by covering organic sediments in a river-mouth or lagoonal environment and/or little or no exposure to extreme wave activity. Even though these landscapes have survived for thousands of years, their future is uncertain. By introducing marine nature reserves, these valuable archives can be better protected for future generations.</p> <p>This study shows that submerged landscapes can be excellent natural and cultural archives and that a geoarchaeological approach can maximise the research output, providing detailed information on shoreline displacement, landscape dynamics and coastal human societies.</p>		
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*“Why do we seek to conquer space when seven tenths of our universe
remains to be explored - the world beneath the sea.”*

Karl Stromberg

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List of papers

This thesis is based on the four papers below.

Paper I

Hansson A, Nilsson B, Sjöström A, Björck S, Holmgren S, Linderson H, Magnell O, Rundgren M and Hammarlund D. 2018. A submerged Mesolithic lagoonal landscape in the Baltic Sea, south-eastern Sweden - Early Holocene environmental reconstruction and shore-level displacement based on a multiproxy approach. *Quaternary International* 463, 110-123. DOI: 10.1016/j.quaint.2016.07.059. Reprinted with permission from Elsevier.

Paper II

Hansson A, Björck S, Heger K, Holmgren S, Linderson H, Magnell O, Nilsson B, Rundgren M, Sjöström A and Hammarlund D. 2017. Shoreline displacement and human resource utilization in the southern Baltic Basin coastal zone during the early Holocene: New insights from a submerged Mesolithic landscape in south-eastern Sweden. *The Holocene*, 1-17. DOI: 10.1177/0959683617744262. Reprinted with permission from Sage Publishing.

Paper III

Hansson A, Hammarlund D, Landeschi G, Sjöström A and Nilsson B. manuscript. A new early Holocene shoreline displacement record for Blekinge, southern Sweden, and implications for underwater archaeology. Submitted to *Boreas*.

Paper IV

Hansson A, Boethius A, Hammarlund D, Lagerås P, Magnell O, Nilsson Brunlid A and Rundgren M. manuscript. Shoreline displacement, coastal environments and human subsistence in the Hanö Bay region during the Mesolithic. To be submitted to *Quaternary*.

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SUBMERGED LANDSCAPES IN THE HANÖ BAY

Finally, I would like to thank Henning Rodhe and Havängs museiförening for their interest in my work and for letting me core in Henning's garden.

Introduction and background

During times of lower global sea level, vast areas of the coastal shelf were exposed and converted into fertile, ecologically diverse coastal landscapes attractive for human occupation (Bailey *et al.*, 2017a; Harff *et al.*, 2016a). At the Last Glacial Maximum about 20,000 years ago, when the sea level was about 130 m lower than at present (Caruso *et al.*, 2011), some 20 million km² of additional terrestrial landmass was exposed globally. These coastal landscapes were used as pathways for the dispersal of humans around the world and most likely, the earliest development of marine exploitation and seafaring occurred here (Harff *et al.*, 2016a). The shelf areas were subsequently flooded during the deglaciation, but well-preserved remains of these landscapes and their inhabitants can today be found on the seafloor. The existence of these remains has been well known by the local population and fishermen, and traces from the submerged landscapes have been recorded for centuries; bones, wood, tools and peat have been caught in fishing nets and tree stumps have been sighted during times of extreme low water marks (e.g. *Cambrensis*, 1191; Wilcke, 1850; Reid, 1913; Fischer, 1995; Gaffney *et al.*, 2009). Historically, such findings were often used as a proof of Noah's flood, and it was not until the early 20th century that the findings were synthesized and put into a scientific context (Reid, 1913). Research on submerged sites has been ongoing for many years (e.g. Andersen, 1985; Flemming, 1968; Galili *et al.*, 1988; Larsson, 1983), but the last decade has seen increased global scale collaboration and a development from site-specific research towards a focus on the landscape level, which is manifested in the output of numerous text books (Bailey *et al.*, 2017b; Benjamin *et al.*, 2011; Evans *et al.*, 2014; Flemming *et al.*, 2017a; Harff *et al.*, 2016b). This increased research interest is driven not only by industrial seafloor exploitation and technological advances in high-resolution underwater surveys, but also by the mutual benefits in a wide range of disciplines in the collaboration between geologists and archaeologists (Chiocci *et al.*, 2017; Harff *et al.*, 2016a).

The Baltic Basin has had a complex relative shoreline history since its southernmost parts were deglaciated about 16,000 years ago (e.g. Andrén *et al.*, 2011; Björck, 1995). Indicators of past higher water levels were observed already in the 18th century by e.g. Linné, Celsius and Swedenborg, who attributed this change to a lowering of the Baltic Sea water level (*vattuminskningen*) (Lundqvist, 1958). During the mid-19th century, it was proposed that the Ice Age was followed first by a subsidence and then a subsequent uplift of the land which had first formed a glacial sea, the Yoldia Sea, followed by a saline sea, the Littorina Sea (Nordlund, 2001). During the 1880s, De Geer proposed that the landmass had subsided and risen several times in order to explain the Baltic Sea development (De Geer, 1882), while Munthe found evidence of a lake

stage, the Ancylus Lake, between the Yoldia Sea and Littorina Sea Stages (Munthe, 1887). Munthe (1902) further proposed the occurrence of an initial glacial lake, the Baltic Ice Lake, which preceded the Yoldia Sea. However, land uplift as the sole cause of the water level changes was questioned at the turn of the last century, and instead eustasy was proposed as the reason for the past fluctuations (Nordlund, 2001). The debate was lengthy, and it was not until the 1920s, when Ramsay (1924) proposed a combination of isostasy and eustasy to explain the development of the Baltic Basin that the mechanisms for the shoreline displacements were better understood (Nordlund, 2001). Since then, numerous publications regarding different aspects of the development of the Baltic Basin have been published, ranging from topics such as the timing and shoreline levels of the different Baltic Basin Stages, the hydrographic history, drainage events and the positions of the outlets. Although the main framework for the development of the Baltic Basin is well established, there are still uncertainties in critical details, such as the Ancylus Lake-Initial Littorina Sea transition and the lowstand levels of the Yoldia Sea and Initial Littorina Sea.

In Europe, where the landmass area increased by about 40% at the height of the last Ice Age (Flemming *et al.*, 2017b), more than 2600 Prehistoric submerged archaeological sites have been discovered (SPLASHCOS network, 2016). Many of these sites are situated in the southern Baltic Sea (Figure 1), where the complex relative shoreline displacement history exposed large coastal areas, which subsequently were inundated. Geoarchaeological research on these sites has led to numerous publications, mainly based on investigations in German and Danish waters (e.g. Fischer, 1995; Hartz *et al.*, 2014), whereas in Swedish waters, the interest has been relatively poor. However, the Haväng area in the Hanö Bay is an exception (Figure 1). Here, a submerged landscape from the early Holocene, consisting of organic sediments, abundant wood remains and well-preserved organic artefacts, has been discovered. Due to its more northern location, and thereby higher isostatic uplift, compared to most other known submerged sites in the Baltic Sea, remains from the Yoldia Sea, Ancylus Lake and Initial Littorina Sea Stages are easily accessible in shallow waters. Therefore, the submerged landscape at Haväng plays a foremost role in the understanding of the coastal landscape development in the southern Baltic Basin and sheds new light on the human way of life during the early Holocene.

Scope of the thesis

The overall aim of this thesis is to increase the understanding of the landscape development and the shoreline displacement in the Hanö Bay region during the early Holocene. The main emphasis has been placed on the submerged landscape at Haväng, which contains

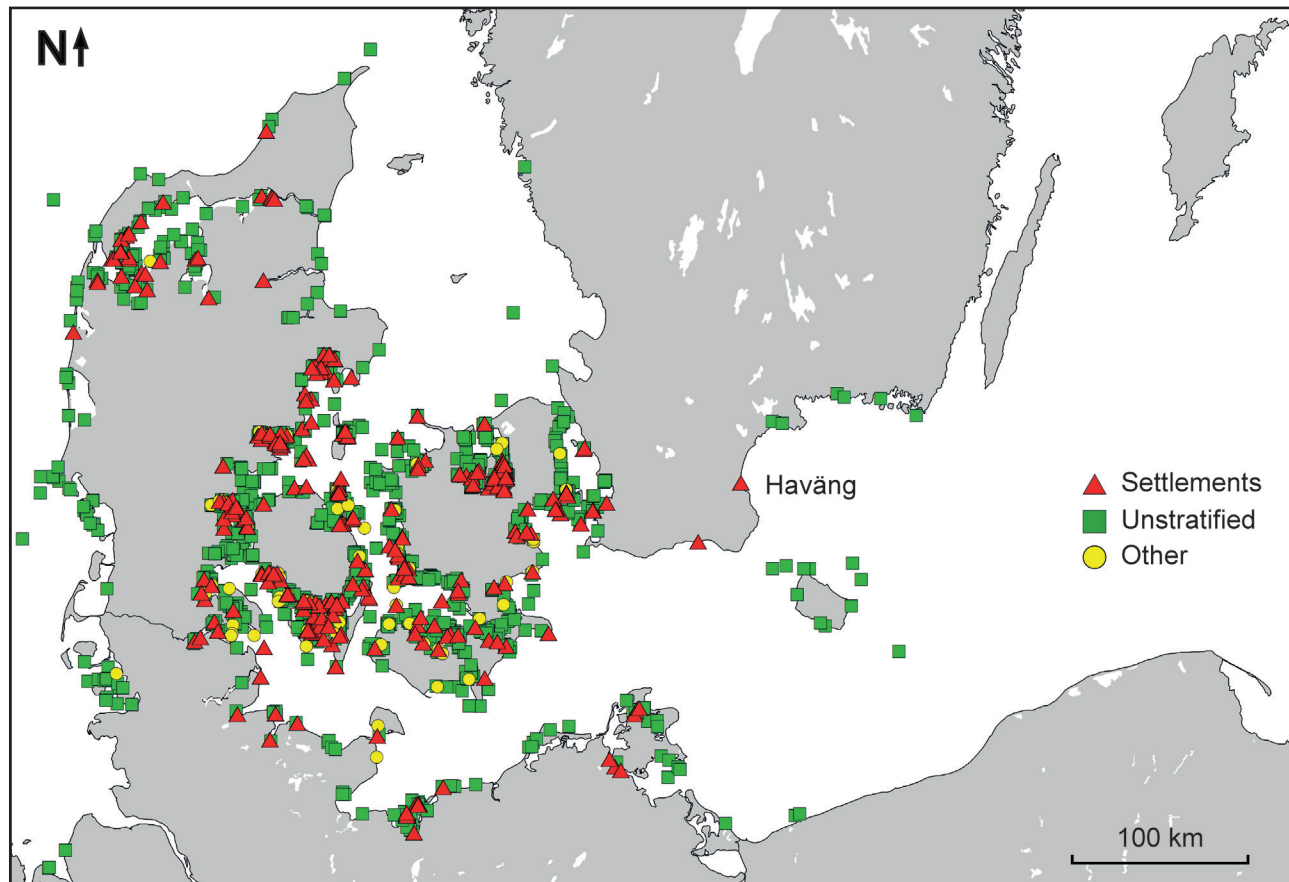


Figure 1. Map of the southwestern Baltic Basin and the locations of submerged archaeological sites in the Baltic Sea and along the Danish coastline registered in the SPLASHCOS database (SPLASHCOS network, 2016). The sites are grouped into settlements (326 sites, red triangles), unstratified finds (1549 sites, green boxes) and other (92 sites, yellow circles). Base map © EuroGeographics.

well-preserved organic geological and archaeological remains. The thesis has a geoarchaeological approach, aiming at describing the interplay between the changing landscape and human populations through detailed landscape and shoreline displacement reconstructions and archaeological research. Generally, the shoreline displacement in most parts of the Baltic Basin is well known, but there is still a lack of knowledge regarding periods during the early Holocene, when the water level was lower than today, which this thesis addresses. Specifically, the following research questions are addressed.

- How did the submerged landscapes in the Hanö Bay develop during the early Holocene and how were they affected by the contemporaneous and later water level fluctuations?
- What were the lowstand levels of the Yoldia Sea and Initial Littorina Sea Stages and how rapid were the subsequent Ancylus Lake and Littorina Sea transgressions?
- In what ways did human populations exploit the terrestrial and aquatic resources in the region and what can that tell us about the way of life during the Mesolithic?

Regional setting

Landscape and climate development during the late Pleistocene and early to mid-Holocene

The Scandinavian Ice Sheet receded from southern Sweden at about 16,000–14,000 cal BP (Stroeven *et al.*, 2016). At 14,700 cal BP, at the onset of the Bølling-Allerød interstadial, large parts of the Northern Hemisphere experienced an abrupt warming triggered by a substantial strengthening of the Atlantic Meridional Overturning Circulation (AMOC) as deep water formation resumed (*e.g.* McManus *et al.*, 2004; Weaver *et al.*, 2003). The warm conditions, which lasted for approximately 2000 years, were interrupted by several short colder phases (*e.g.* Lowe *et al.*, 2008). The Bølling-Allerød interstadial was followed by the Younger Dryas stadial at 12,900 cal BP (Steffensen *et al.*, 2008). This climate deterioration was most likely triggered by the outflow of freshwater into the North Atlantic, which shut down the AMOC (Björck *et al.*, 1996; Teller, 2013). During the Bølling-Allerød and Younger Dryas periods, southern Scandinavia was characterized by tundra vegetation, dominated by pioneer herb and shrub taxa (Mortensen *et al.*, 2011; Wohlfarth *et al.*, 2018). The humans who lived in southern Scandinavia during the latter part of the Bølling-Allerød and the Younger Dryas periods belong to the Late Palaeolithic Bromme and Ahrensburg cultures, which were mobile

Box 1. Geological and archaeological chronologies

Time scales are vital for geologists and archaeologists alike when discussing and comparing their research, yet several types of chronologies are still in use today, and in this thesis. In order to make comparisons between the different time scales, they are presented here in relation to each other. Even though some of the time scales are rarely in use today, they are often seen in older literature where radiometric dating is lacking.

A geochronological age is a global, clearly defined, subdivision of the geological time scale. Archaeological periods are based on cultural developments, meaning that the timing of the subdivisions differs regionally. A chronozone is a subdivision of the geological time scale based on climate fluctuations. The presented subdivision represents the climatic fluctuations in northwestern Europe (Björck *et al.*, 1998; Mangerud *et al.*, 1974). Archaeological culture chronologies were established before the development of radiometric dating and are based on typological comparisons of flint material. The cultures presented here are geographically limited to southern Scandinavia and northernmost Germany. The culture transitions were not instant events, but rather a development over several generations, as represented by the dashed subdivisions (Jessen *et al.*, 2015; Knarrström, 2007). The history of the Baltic Basin has been divided into stages based on shifting water levels and salinity (*e.g.* Andrén *et al.*, 2011). The lowstand phases at Haväng and in western Blekinge are marked in grey. The climatic development in the North Atlantic region is represented here by the $\delta^{18}\text{O}$ record from the NGRIP ice core from Greenland (Rasmussen *et al.*, 2006; Vinther *et al.*, 2006). The transient cooling episodes the Preboreal Oscillation, the 9.3 kyr event and the 8.2 kyr event, as defined by Lowe *et al.* (2008), are marked by grey boxes.

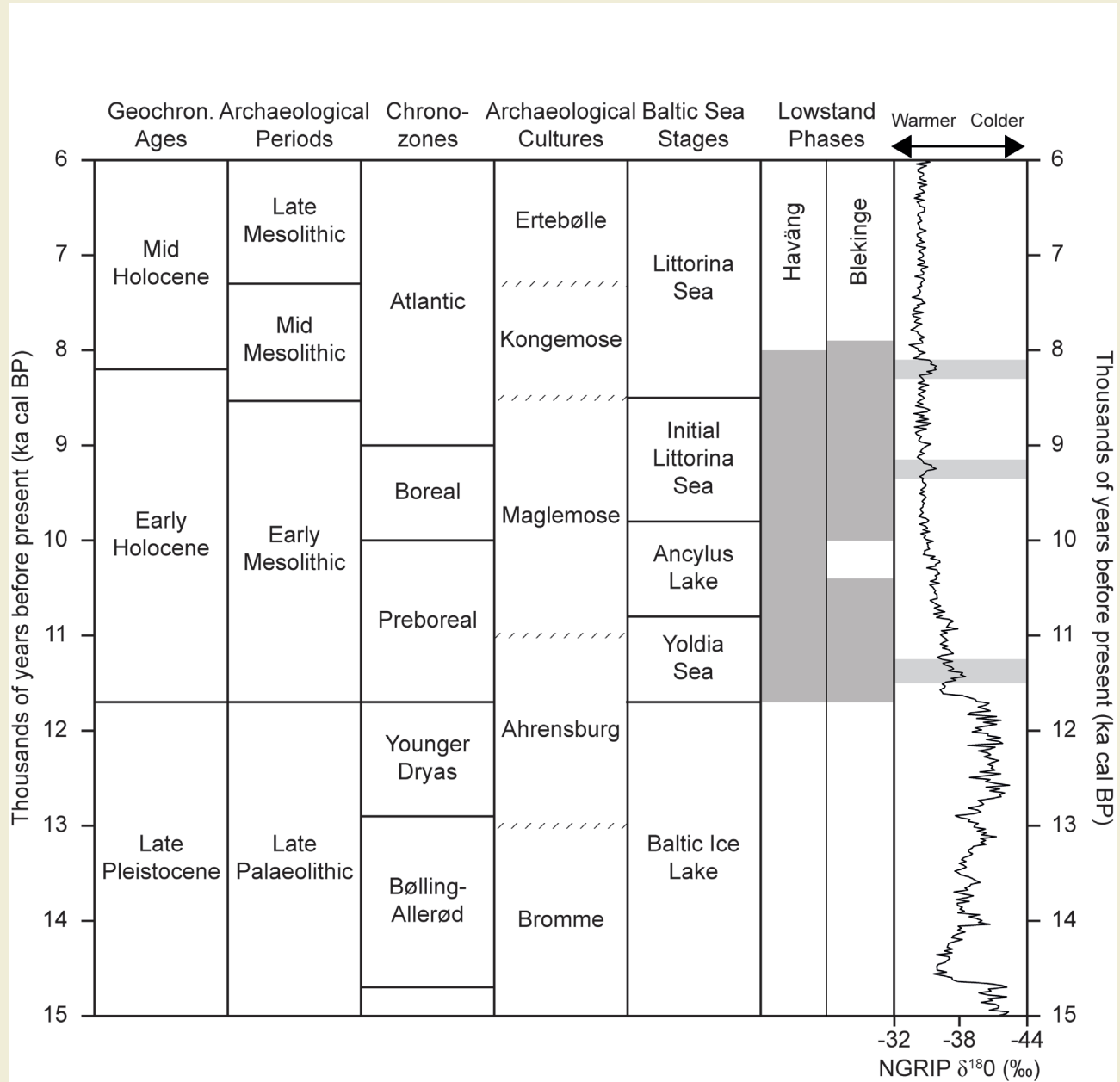


Figure B1. Geological and archaeological time scales, Baltic Sea lowstand phases and climatic development for the period 15,000–6000 cal BP.

hunters who focused their subsistence on hunting of reindeer (*Rangifer tarandus*) and other big game (Larsson, 1996; Vang Petersen and Johansen, 1996).

The onset of the Holocene, at 11,700 cal BP (Walker *et al.*, 2009), marks the beginning of the current warm period. In southern Scandinavia, the early Holocene climate was characterized by increasing temperatures (e.g. Seppä *et al.*, 2005) interrupted by three abrupt climate oscillations; the Preboreal Oscillation (PBO), the 9.3 kyr event and the 8.2 kyr event (e.g. Björck *et al.*, 1997; Bos *et al.*, 2007; Daley *et al.*, 2011; Kobashi *et al.*, 2007; Rasmussen *et al.*, 2007; van der Plicht *et al.*, 2004). The oscillations were caused by freshwater inputs into the north Atlantic, which reduced the AMOC (e.g. Björck *et al.*, 1997; Clarke *et al.*, 2004; Fleitmann *et al.*, 2008). The climate and landscape changes which occurred during the oscillations have been proposed as a driver of cultural development, but to what extent the oscillations affected human communities in terms of demography and settlement patterns is debated (e.g. Breivik *et al.*, 2018; Crombé, 2018; Griffiths and Robinson, 2018; Wicks and Mithen, 2014).

The climate in the early Holocene was generally cool and moist (Seppä *et al.*, 2005) and the vegetation was initially dominated by birch and pine (Åkesson *et al.*, 2015). This was followed by an increase in deciduous forest cover due to the continuous immigration of thermophilous tree taxa, although it has been shown that the typical Preboreal forest did not establish until after the PBO (Jessen *et al.*, 2015). The transition from the late Palaeolithic Ahrensburg culture to the early Mesolithic Maglemose culture has in Denmark been dated to about 11,500–11,000 cal BP (Jessen *et al.*, 2015). The Maglemosian subsistence has traditionally been described as focused on big game hunting in the forest (Aaris-Sørensen, 1998). The Preboreal fauna was characterized by big game such as aurochs (*Bos primigenius*), elk (*Alces alces*), giant deer (*Megaloceros giganteus*) and reindeer, which was present in the landscape throughout the Preboreal (Aaris-Sørensen *et al.*, 2007; Larsson, 2009). As the forest cover became more closed in the Boreal and early Atlantic chronozones, smaller animals such as wild boar (*Sus scrofa*), red deer (*Cervus elaphus*) and roe deer (*Capreolus capreolus*) became more common.

After the 8.2 kyr event, which defines the onset of the mid Holocene (Walker *et al.*, 2012), the climate was characterized by a long period of dry, warm and stable conditions called the Holocene Thermal Maximum (e.g. Seppä *et al.*, 2005). A mixed oak forest dominated the southern Scandinavian vegetation (Åkesson *et al.*, 2015), where red deer, roe deer and wild boar were abundant (Magnell, 2017). A transition towards a subsistence more reliant on fishing is seen during the Mesolithic, which is manifested by numerous fishing constructions and large shell middens (*kökkenmøddingar*) during the mid and late Mesolithic periods (Aaris-Sørensen, 1998; Fischer, 2005). The Mesolithic period ends at about 6000 cal BP, when agriculture was

introduced in southern Scandinavia.

Development of the Baltic Basin

The Baltic Ice Lake was formed in the southern part of the Baltic Basin at about 16,000 cal BP by the build-up of large amounts of meltwater in front of the receding Scandinavian Ice Sheet (Houmark-Nielsen and Kjær, 2003). The Baltic Ice Lake had its outlet through the Öresund Strait (Figure 2), and as long as the uplift of the threshold area was compensated by erosion of loose sediments, the lake was at level with the sea (Björck, 1995). At about 14,000 cal BP, the bedrock sill was exposed and erosion ceased. Due to the continued uplift of the threshold area, the Baltic Ice Lake was dammed above the sea level (Andrén *et al.*, 2011). Due to the N-S uplift gradient, areas south of the threshold isobase experienced a transgression, while areas to the north experienced a continued regression (Björck, 2008). When the ice margin receded north of Mt Billingen (Figure 2), situated in the South-Swedish highlands, at about 13,000 cal BP, it is believed that a first drainage of the Baltic Ice Lake occurred, which lowered the water level by about 10 m (Björck, 1979, 1995). Due to the drainage, the outlet of the Baltic Ice Lake shifted from the Öresund Strait to the lowlands north of Mt Billingen in south-central Sweden (Björck, 2008). During the Younger Dryas stadial, the ice sheet re-advanced south of Mt Billingen and the outlet was closed off, which led to rising water levels in the Baltic Ice Lake and eventually the Öresund threshold was transgressed and re-established as an outlet (Andrén *et al.*, 2011; Björck, 1995) (Figure 3). After the threshold was overflowed, areas south of the threshold experienced a continued transgression throughout the Younger Dryas. At the onset of the Holocene the ice margin once more receded north of Mt Billingen, which led to a second, catastrophic Baltic Ice Lake drainage of 25 m in just 1–2 years (Björck, 1995). Traces of the drainage can be seen as washed bedrock and deposits of coarse gravel and boulders in the Mt Billingen area (Strömberg, 1992). The drainage lowered the water level down to sea level, marking the transition from the Baltic Ice Lake to the Yoldia Sea.

The drainage exposed vast coastal areas in the southern Baltic Basin (Figure 4). In the southernmost parts of the Baltic Basin, the uplift had shifted to submergence as the forebulge moved northward, meaning that the lowest shoreline was formed immediately after the drainage, followed by a transgression (Björck, 1995). Further north, in southern Sweden, the land uplift was still larger than the sea level rise, which led to a continued regression during the Yoldia Sea Stage. The Yoldia Sea, with its outlet through the Närke Strait and the Vänern Basin (Figure 2), was characterized by a brackish phase. However, it was not until about 250 years after the onset of the Yoldia Sea Stage that the outlet area became wide enough to allow saline water to penetrate into the Baltic Basin (Andrén *et al.*, 1999; Björck,

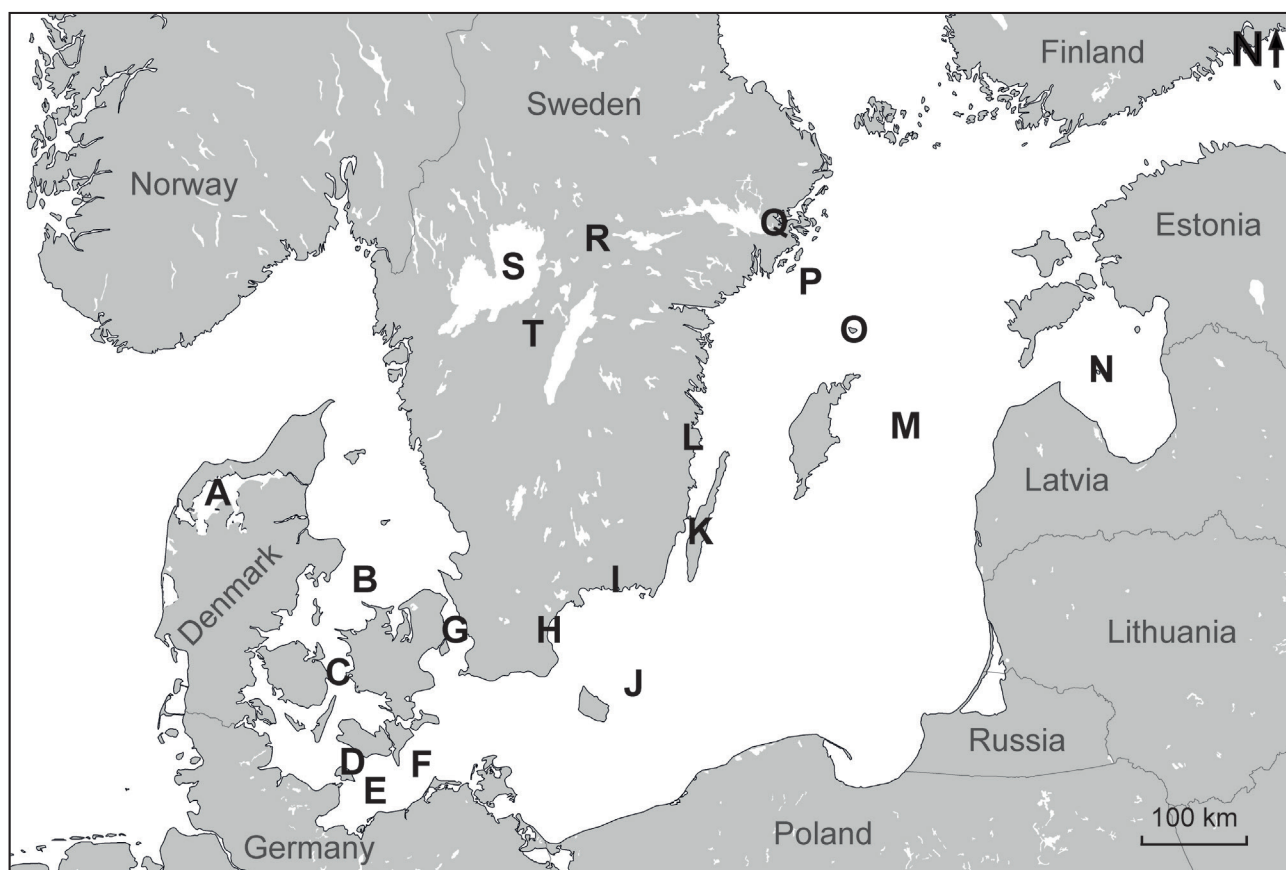


Figure 2. Map of The Baltic Basin and its surrounding areas. Sites mentioned in the text: (A) Limfjorden (B) Kattegat (C) Store Belt Strait (D) Fehmarn Belt Strait (E) Mecklenburg Bay (F) Darss Sill (G) Öresund Strait (H) Hanö Bay (I) Blekinge (J) Bornholm Basin (K) Öland Island (L) Oskarshamn (M) Gotland Basin (N) Ruhnu Island (O) Gotska Sandön Island (P) Landsort Deep (Q) Stockholm (R) Närke Strait (S) Vänern Basin (T) Mt Billingen. Base map © EuroGeographics.



Figure 3. Palaeogeographic map showing the extent of the Baltic Ice Lake just prior to the final drainage at 11,700 cal BP (Andrén *et al.*, 2011). Reprinted by permission from Springer Nature.

2008). The brackish phase has been inferred from the glaciomarine mollusc *Portlandia (Yoldia) arctica*, from which the Yoldia Sea is named (Torell, 1872), and from diatom and foraminifera records from *e.g.* the Landsort

Deep (Lepland *et al.*, 1999), the Gotland Basin (Andrén *et al.*, 2000a), and as far south as the Bornholm Basin (Andrén *et al.*, 2000b) (Figure 2). Due to the continued uplift of the outlet area, the straits west of the Vänern Basin became increasingly shallow and the saline intrusions ceased after about 100–150 years (Andrén *et al.*, 2011; Andrén and Sohlenius, 1995; Wastegård *et al.*, 1995). The narrowing and shallowing of the straits forced the water level in the Baltic Basin to rise above the sea level (Björck, 1987), which marks the onset of the next phase of the Baltic Basin development, the Ancylus Lake Stage.

The water level in the Ancylus Lake, named after the freshwater mollusc *Ancylus fluviatilis* (Munthe, 1887), rose in pace with the uplift of the outlet area, which led to a tilting of the water surface, and areas north of the outlet experienced a regression, whereas areas south of the outlet experienced a transgression (Björck, 2008). The rapid transgression inundated areas in the southern Baltic Basin that had previously emerged during the Yoldia Sea Stage (Björck, 1995) (Figure 5). In the Hanö Bay (Figure 2), stumps and stems dated to the Ancylus Lake Stage have been retrieved from the seafloor by scientific expeditions and by fishing vessels as trawler bycatch (Berglund *et al.*, 1986; Hansen, 1995; Hansson *et al.*, 2017a, submitted; Håkansson, 1968, 1972, 1974, 1976, 1982). Stumps and stems dating to the Ancylus Lake Stage have also been found outside the Lithuanian (Žulkus and Girininkas, 2012) and Polish coasts (Uści-

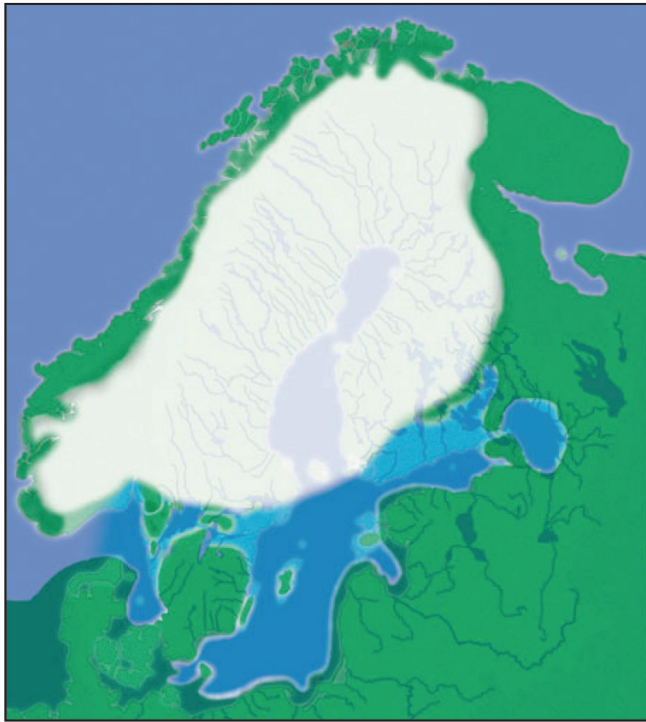


Figure 4. Palaeogeographic map showing the extent of the Yoldia Sea during its brackish phase at 11,100 cal BP (Andrén *et al.*, 2011). Reprinted by permission from Springer Nature.

nowicz, 2014) and in the Store Belt Strait (Fischer, 1995) (Figure 2). It has been estimated that the transgression lasted for approximately 500 years (Björck, 2008), and the final Ancylus Lake level is manifested as raised beaches in southern Sweden (*e.g.* Mikaelsson, 1978; Munthe, 1902), southern Finland (*e.g.* Tikkanen and Oksanen, 2002) and the Baltic states (*e.g.* Rosentau *et al.*, 2013; Veski 1998).

At about 10,300 cal BP, the water level in the Ancylus Lake was lowered due to the establishment of a new outlet in the southern Baltic Basin (Björck, 2008). This outlet, which was first proposed by von Post (1937), who named it the Dana River, ran through the Darss Sill, the Mecklenburg Bay, the Fehmarn Belt Strait and the Store Belt Strait (Figure 2). Björck (1995) proposed a rapid Ancylus regression of 10–15 m due to threshold erosion in the outlet area. However, Bennike and Jensen (1998), Bennike *et al.* (2000), Jensen *et al.* (1999) and Lemke *et al.* (1999) found no support for a rapid regression as their investigations pointed to calm conditions in the outlet area. Furthermore, Lemke *et al.* (2001) concluded that the Darss Sill threshold was too shallow to accommodate a regression of more than 5 m. This led Björck *et al.* (2008) to propose a much less dramatic regression scenario with an initially forced 5 m lowering due to erosion of the threshold, followed by a normal regression of about 5 m due to land uplift in the Baltic Basin region. Due to the relatively rapid global sea level rise and the small land uplift in the outlet area, it only took about 200–300 years before the sea was at level with the Ancylus Lake. This scenario resulted in a fairly calm and wide river system with levées and lakes through the Store Belt area, which has been noted by Bennike *et al.* (2004) and an extensive estuary in the Hesselø Bay area in southwestern Kattegat (Figure 2)



Figure 5. Palaeogeographic map showing the Ancylus Lake at its maximum extent at approximately 10,300 cal BP (Andrén *et al.*, 2011). Reprinted by permission from Springer Nature.

where this fluvial system ended up (Bendixen *et al.*, 2017a, 2017b), draining the whole Baltic Basin.

The first signs of brackish conditions in the Baltic Basin after the Ancylus Lake Stage have been recorded in the Hanö Bay (Berglund *et al.*, 2005) and the Bornholm Basin (Andrén *et al.*, 2000b) at about 9800 cal BP, indicating that the Baltic Basin was at level with the sea and that the long Dana River system allowed at least occasional saline intrusions, marking the onset of the Initial Littorina Sea. The establishment of the Dana River meant that a large part of the southern Baltic Basin experienced an initial regression. However, as the Baltic Basin was at level with the sea, areas in the southernmost Baltic Basin, where the uplift was lower than the global sea level rise, experienced a continued transgression (Andrén *et al.*, 2011). In southernmost Sweden, where the uplift more or less equalled the sea level rise, the water level was relatively stable during a period of about 1000 years (Hansson *et al.*, 2018, submitted).

The opening of the Öresund Strait at about 8500 cal BP, as a consequence of the ongoing eustatic sea level rise, allowed large amounts of saline water to enter the Baltic Basin, marking the start of the Littorina Sea (Andrén *et al.*, 2011), named after the marine mollusc *Littorina littorea* (Erdmann, 1868). The Littorina Sea was characterized by pronounced transgressions recorded across the Baltic Basin south of the Stockholm area (*e.g.* Berglund, 1964; Bitinas and Damušytė, 2004; Munthe, 1911; Muru *et al.*, 2017; Rosentau *et al.*, 2013) (Figure 2), possibly forced by large meltwater inputs from the decaying Antarctic and Laurentide Ice Sheets (Andrén *et al.*, 2011). The timing of the onset of the transgressions depended on the uplift rate; in Limfjorden, located



Figure 6. Palaeogeographic map showing the extent of the Littorina Sea during its most saline phase at approximately 6500 cal BP (Andrén *et al.*, 2011). Reprinted by permission from Springer Nature.

in the peripheral uplift area, the onset has been dated to just after 9000 cal BP (Petersen, 1981), in Blekinge (Berglund *et al.*, 2005) (Figure 2) and north-eastern Estonia (Rosentau *et al.*, 2013) the onset is dated to about 8500 cal BP, whereas in the Stockholm area, where sea level rise equalled land uplift, the onset is dated to about 7800 cal BP (Hedenström, 2001). At about 6000 cal BP, the global sea level stabilised and land uplift became the sole controlling factor of the water level in the Baltic Basin (Björck, 2008) (Figure 6). Since then, areas with a negative land uplift have experienced a continued transgression, whereas areas with a positive uplift have experienced an ongoing regression. Based on studies in Blekinge (Yu *et al.*, 2007) and on Ruhnu Island in the Gulf of Riga (Muru *et al.*, 2018) (Figure 2), the initial regression rate was slow, followed by a slightly increased rate between 4000–2000 cal BP and a new slowing down of the rate during the last 2000 years.

The Haväng area

Haväng is situated on the east coast of Skåne, south-eastern Sweden, where the Verkeån River runs into the Hanö Bay, in the southernmost part of a sandy grassland area called the Ravlunda Field, delimited by the Verkeån River to the south and the Julebodaån River to the north (Figure 7). The Ravlunda Field is named after the amber (Swedish: *bärnsten* or *rav*) commonly found washed up on the beaches in the area (Nilsson, 1961), and has since the 1940s, when the Swedish Armed Forces requisitioned the area, been used as an artillery firing ground. The Haväng area has a long human

history, as manifested by an approximately 5500 years old megalith tomb called *Havängsdösen*, situated on a hilltop just north of the Verkeån River. The tomb was excavated in 1869, after it was uncovered by a heavy storm a few decades earlier (Bagge and Kaelas, 1952). A permanent stone construction used for trout fishing called *Öradekaren*, situated about 500 m upstream from the mouth of the Verkeån River, is known from at least the 17th century, and continued fishing activities have taken place there until the 1980s (Juhlin Alftberg, 2010). In the river outlet, remains of a harbour construction, manifested as two stone piers and about 50 wooden poles, can be seen during periods of low water mark (Rodhe, 2013). In 1637, Jochum Beck started to mine and process alum shales at Andrarum, some 13 km upstream from Haväng (Jakobsson and Olsson, 2011). During the 18th century, under the leadership of Christina Piper, the factory developed into the largest industry in Skåne. The Haväng harbour was, for a rather short time, used to ship the alum products, before the harbour was discontinued in the early parts of the 18th century (Rodhe, 2013).

The bedrock in the Haväng area consists of a base of Precambrian crystalline rocks, which is overlain by Cambrian shales and sandstones south and northwest of the Verkeån River (Erlström *et al.*, 2004). Glaciolacustrine sediments, 5–60 m in thickness, cover the glacial till that rests on the bedrock. The glaciolacustrine sediments, deposited in a succession of local ice lakes situated between the Linderödsåsen Horst in the west and the receding ice sheet to the east, are characterized by plateaus at different altitudes, ice-contact slopes, drainage channels and dead-ice hollows (Malmberg Persson, 2000). The Verkeån River meanders through the glaciolacustrine deposits, forming an up to 50 m deep valley. The river, which drains a catchment area of about 150 km², has a mean annual streamflow of about 1.4 m³ s⁻¹, but with large seasonal variations as demonstrated by maximum and minimum values of 25 m³ s⁻¹ and 0.02 m³ s⁻¹, respectively (Anheden, 1967).

The Quaternary sediments in the Hanö Bay consist of a clayey diamicton covered by a thin layer of sand and clay (Björck *et al.*, 1990). On the seafloor east of Haväng, organic deposits and abundant wood remains are found down to a depth of 25 m b.s.l., deposited during times of lower water levels in the Baltic Basin when the Verkeån River extended across the exposed ground (Figure 7). This submerged, relict landscape can be divided into three sub-areas. Sub-area A constitutes the innermost part of the submerged landscape, extending 700 m from the shore, down to a depth of 12 m b.s.l. Organic deposits, with a maximum thickness of 3 m above the surrounding sandy seafloor, characterize the sub-area. Some of the organic deposits appear as crescentic ridges, 5–25 m wide, sloping towards the centre of the submerged landscape, while some deposits appear as elongated, 10–40 m wide, coast-parallel ridges (Figure 8). The stratigraphy of both types of ridges can be described as a compacted dark brown homogeneous fine detritus gyttja overlying a grey

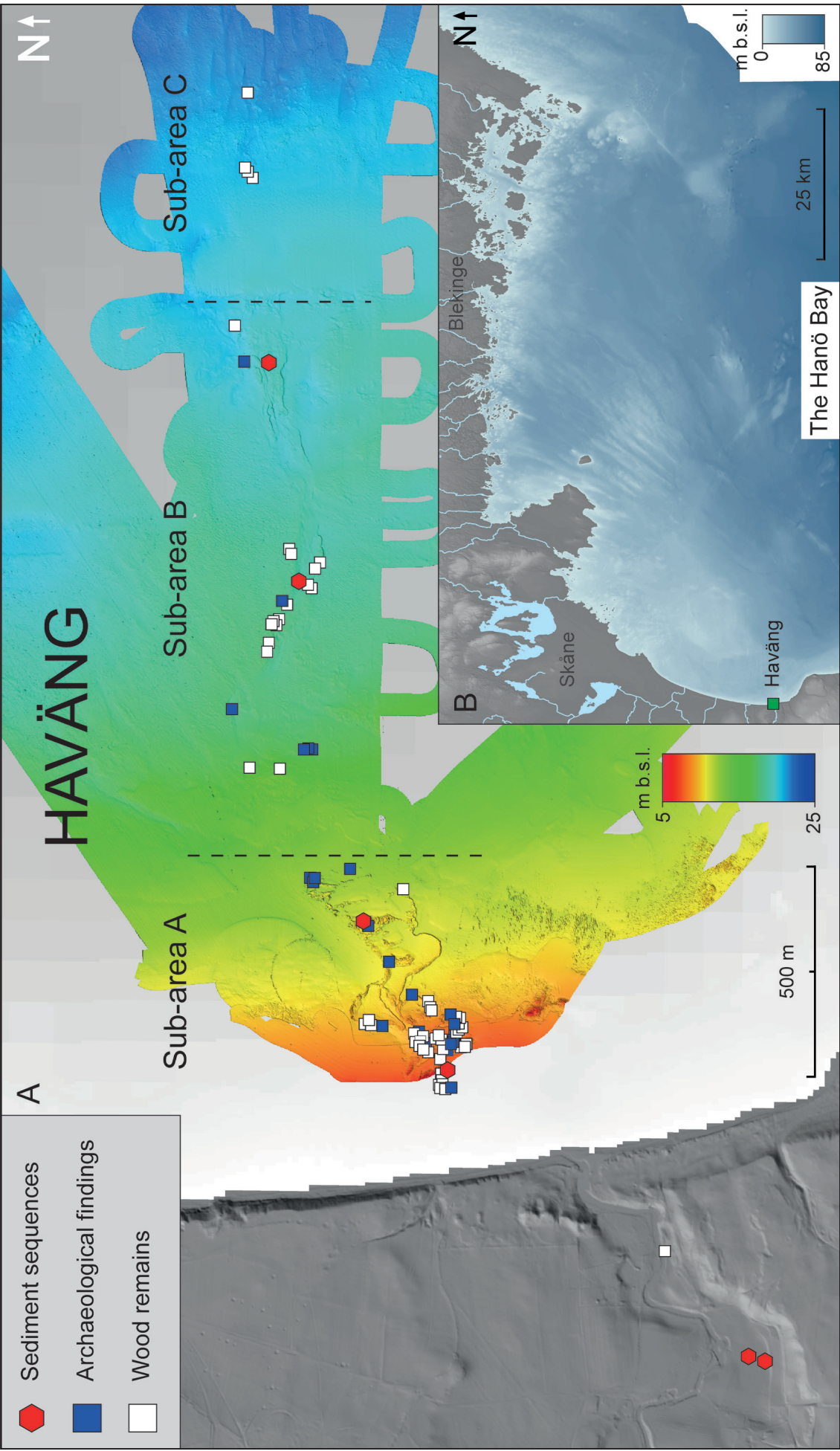


Figure 7. Overview of the Haväng study area. (A) Topographic and bathymetric composite map of Haväng. The subdivision of the study area and the locations of the sediment sequences (red hexagons), archaeological findings (blue boxes) and tree stumps and stems (white boxes) are marked. Not shown are the locations of the discrete organic sediment samples, obtained immediately adjacent to each sampled stump or stem. (B) Topographic and bathymetric composite map of the Hanö Bay region. The locations of Haväng and the main rivers and lakes are shown. Topography data © Lantmäteriet.

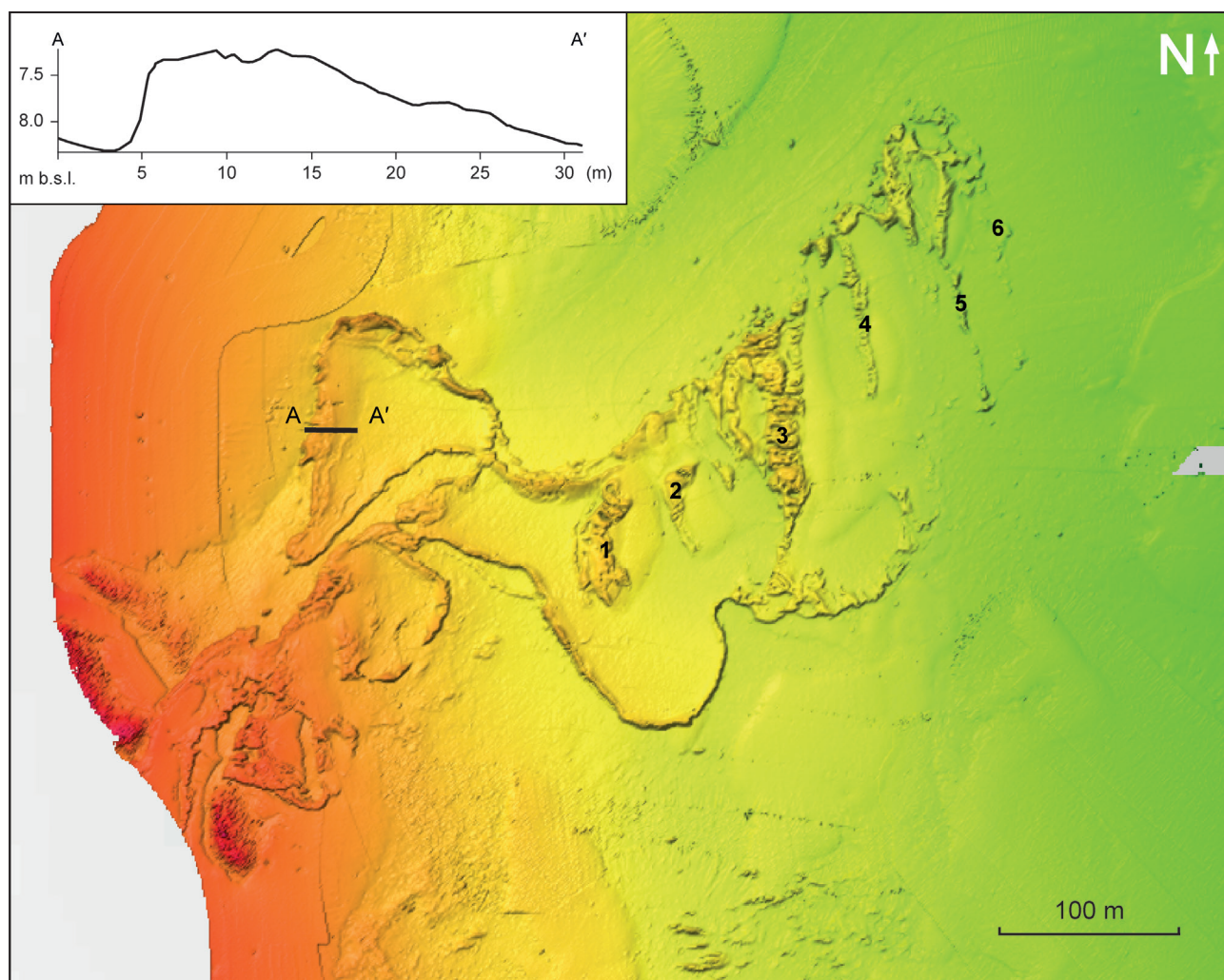


Figure 8. Bathymetric map of sub-area A of the submerged landscape at Haväng. Crescentic ridges dominate the western part of the sub-area, while six N-S elongated, coast-parallel ridges (marked 1–6) occur in the eastern part. The transect A-A' shows the general topography of the crescentic ridges, consisting of a steep outer slope and a gentle inner slope.

calcareous gyttja (Figure 9a). Abundant, well-preserved, rooted stumps and non-rooted stems are found protruding from the calcareous gyttja (Figures 9a and 9b), while some stumps and stems are found adjacent to the organic sediments (Figure 9c). Archaeological artefacts found embedded in the sediments, such as refuse material, worked animal bones and antlers and eight manifest fishing constructions, are evidence of extensive human activity in the Haväng area (Figures 9d and 9e).

Sub-area B constitutes the middle part of the submerged landscape, extending from 12 m b.s.l. down to a depth of approximately 20 m b.s.l. (Figure 7). Here, organic sediments described as a grey calcareous gyttja form two, 5–10 m wide, sub-parallel ridges, 30–50 m apart, in west-east orientation that outlines the margins of the former river. Between the ridges, organic deposits that constitute the middle part of the former river valley are overlain by sand. A detritus gyttja, rich in fragmented wood remains, is covering the calcareous gyttja in some parts of the sub-area. As in sub-area A, abundant rooted stumps and non-rooted stems are found protruding from the calcareous gyttja. Worked animal bones and antlers constitutes the archaeological artefacts in the sub-area. Additionally, a burned log (Figure

9f) and a hollow rooted pine stem are presumed to have been shaped by human activities. Sub-area C constitutes the outermost parts of the submerged landscape, stretching from 20 m b.s.l. down to 24 m b.s.l., about 3 km east of the coastline (Figure 7). The sub-area is dominated by clay, which in the westernmost part is covered by sand. Occasional thin organic deposits and a few rooted stumps and non-rooted stems can also be found in the sub-area, but no archaeological artefacts have so far been discovered.

The geology of the Haväng area was first described by De Geer in the 1880s (De Geer, 1889). Nilsson (1961) carefully described the formation and development of the Ravlunda Field since the last Ice Age in his text *Ravlundafältets geologi*. Nilsson sampled and analysed organic sediments, described as a compacted gyttja deposited in fresh water, situated just at, and just northeast of, the Verkeån River outlet. Pollen analysis revealed that the sediments were deposited about 8000–5000 years ago (Swedish: *ekblandskogstiden*), when a mixed deciduous forest dominated the south Swedish landscape. During the 1980s, the stratigraphy of the Hanö Bay was investigated (Björck and Dennegård, 1988; Björck *et al.*, 1990) and an interdisciplinary research project explored the submerged landscape

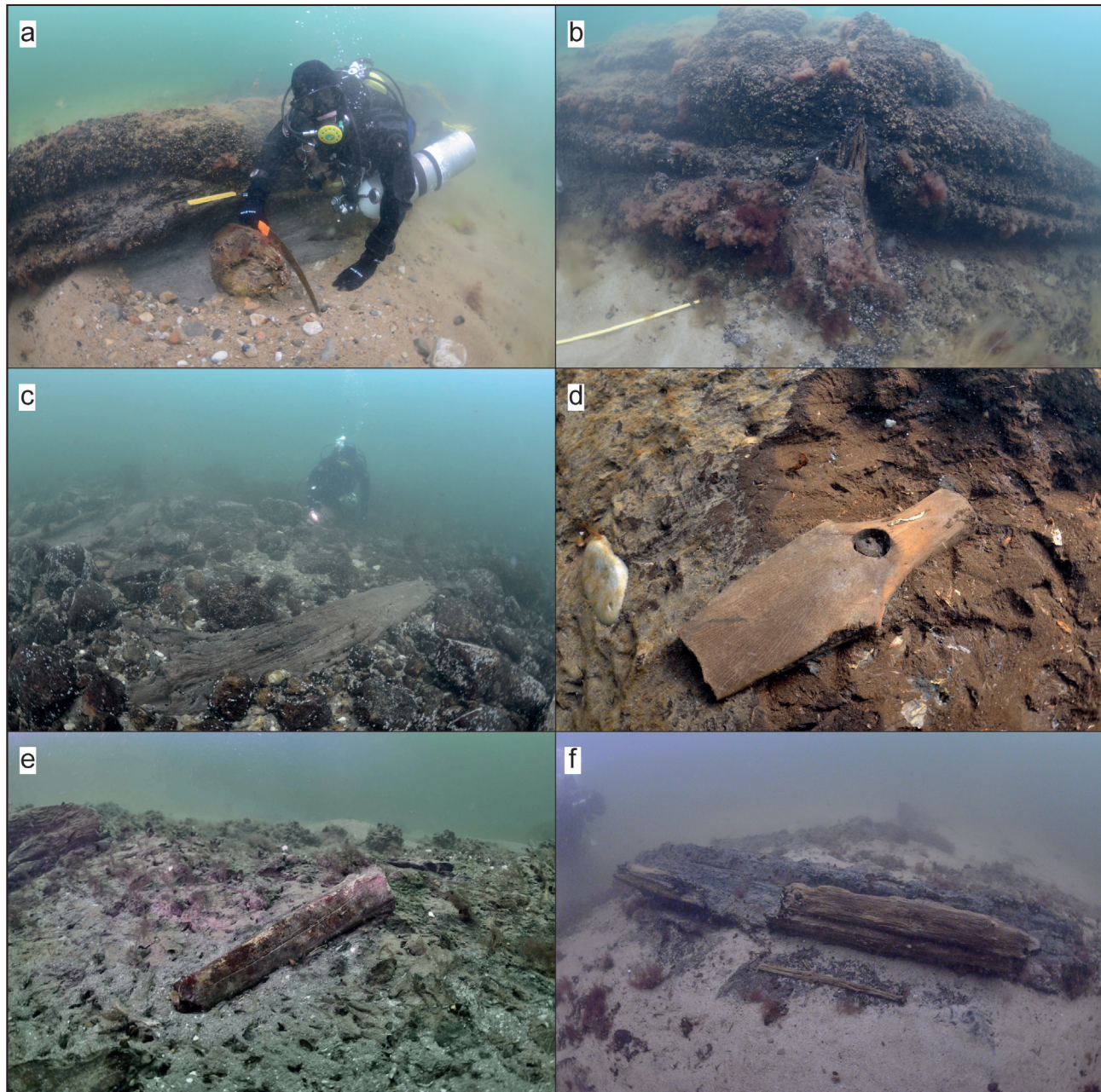


Figure 9. Photographs of the submerged landscape at Haväng. (a) Stratigraphy of the organic sediment ridges in sub-area A; a grey calcareous gyttja overlain by a dark brown fine detritus gyttja. A non-rooted pine stem (HAV098) protrudes from the calcareous gyttja at 7.6 m b.s.l. Diver in the photograph Anton Hansson. (b) A rooted pine stump (HAV100) protruding from an organic sediment ridge at 7.7 m b.s.l. (c) A non-rooted pine stem (HAV133) situated in a boulder-rich area, a few metres north of an organic sediment ridge at 3.9 m b.s.l. (d) An elk antler pick axe (HAV042) found in an organic sediment ridge at 5.6 m b.s.l. The imprint of the broken tip can be seen in the sediment. The pick axe measures 20 cm. (e) A metatarsal (HAV006) from an adult aurochs cow situated on top of the organic sediments at 15.4 m b.s.l. The bone shows fine cut marks from skinning. (f) A hollow and burnt pine stem (HAV026) located at 19.0 m b.s.l. The stem was possibly used as a log-fire. Photographs Arne Sjöström.

aiming at describing its formation and at searching for possible archaeological remains (Hansen, 1986, 1987). A bathymetric map, based on coarse single-beam echo sounder data and diving observations, was obtained, describing the landscape as a set of five coast-parallel ridges (Hansen, 1985). The ridges were proposed to have been formed by accumulation of peat between sand dunes parallel to the coastline during the Littorina transgression, but no archaeological artefacts were discovered (Hansen, 1995). Gaillard and Lemdahl (1994) studied terrestrial macroscopic remains from organic samples obtained during diving expeditions in the 1980s. They concluded that the landscape was

formed during the Ancylus Lake and Initial Littorina Sea Stages, and that the organic sediments were deposited in elongated shallow lakes or lagoons protected by beach ridges or sand dunes. In 2003, diving archaeologist Arne Sjöström started to explore the submerged landscape. In 2009 the public outreach project Havsresan, organised by Lund University, performed bathymetric mapping and diving surveys at Haväng. Since 2013, a team of collaborating archaeologists and geologists has performed detailed studies of the submerged landscape, which this thesis is a result of.

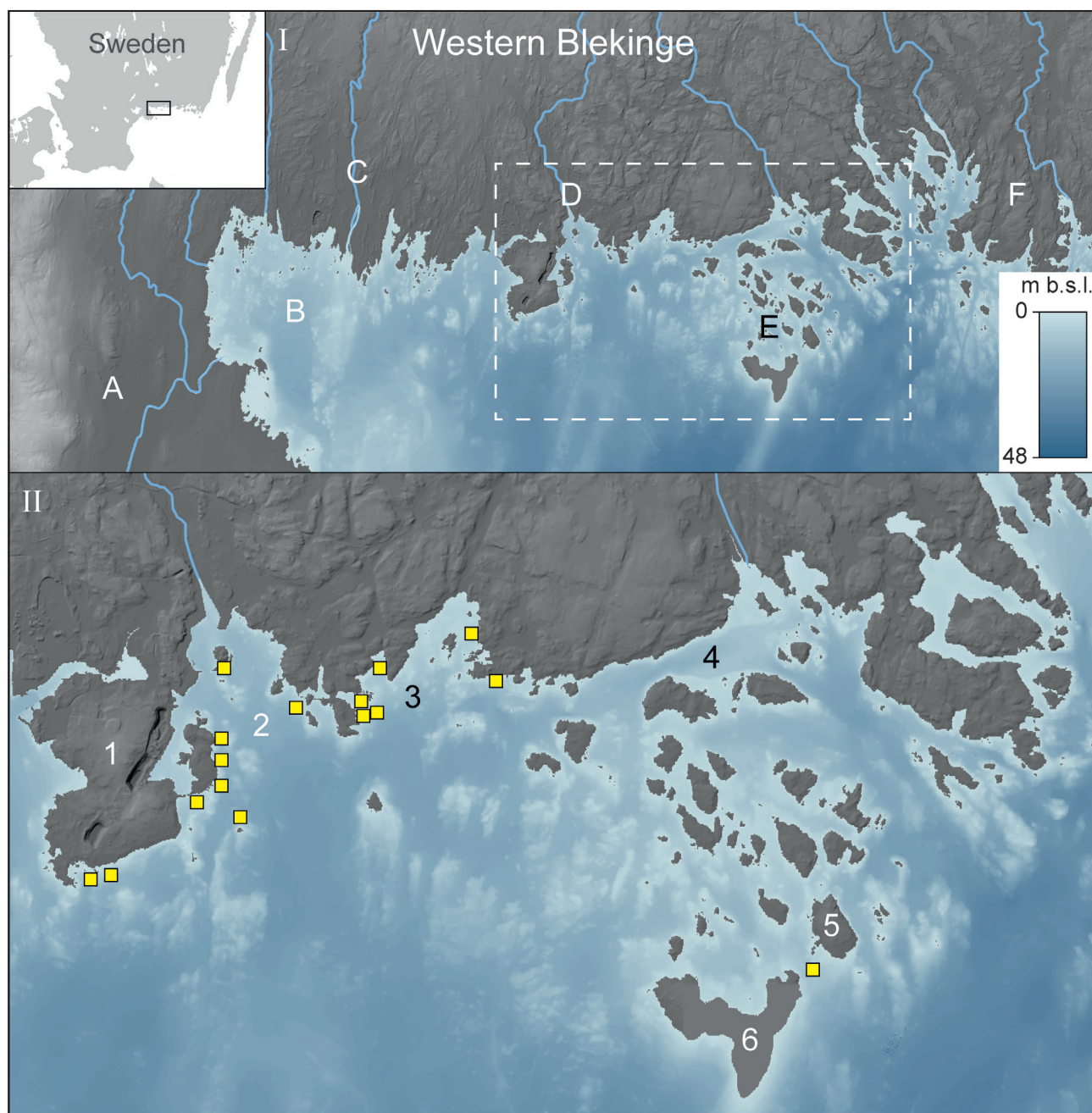


Figure 10. Overview of the western Blekinge study area. (I) Topographic and bathymetric composite map of western Blekinge. Sites mentioned in the text: (A) Listerlandet Peninsula (B) Pukavik Bay (C) Mörrumsån River (D) Karlshamn (E) Hällaryd Peninsula (F) Biskopsmåla Peninsula. (II) Enlargement of the Karlshamn-Hällaryd Peninsula area showing the locations of submerged stumps and stems (yellow boxes). Sites mentioned in the text: (1) Sternö Peninsula (2) Karlshamnsfjärden Bay (3) Svanevik Bay (4) Matvik Bay (5) Harö Island (6) Tärnö Island. Topography data © Lantmäteriet.

Western Blekinge

The province of Blekinge is situated in the northern part of the Hanö Bay region, in southeastern Sweden (Figure 10). The western part of Blekinge is here defined by the Listerlandet Peninsula to the west and the Biskopsmåla Peninsula to the east. East of Karlshamn, the Hällaryd Archipelago characterizes the coastal landscape. The bedrock topography is characterized by a relief dominated by ridges and intermediate valleys trending in N-S direction. Rivers and streams, including the large Mörrumsån River, flow in the valleys before they reach their outlets in the Hanö Bay. The bedrock is dominated by Precambrian crystalline rocks intersected by diabase dykes in a N-S direction (Persson, 2000), except on

the Listerlandet Peninsula, where the bedrock consists mainly of Cretaceous limestone (Persson, 1995). The Quaternary cover is dominated by till above the highest shoreline. Glaciofluvial sediments in the form of eskers occur in the valleys, which below the highest shoreline transform into delta formations and valley infills (Persson, 2000). Below the highest shoreline, the Quaternary cover is generally thin and dominated by till and glacial clay, which is partly overlain by post-glacial sand and peat. In the near-shore zone, exposed bedrock is common.

Diving surveys in western Blekinge during the last five years have revealed several remains of a submerged landscape across an extensive area (Figure 10) (Hansson

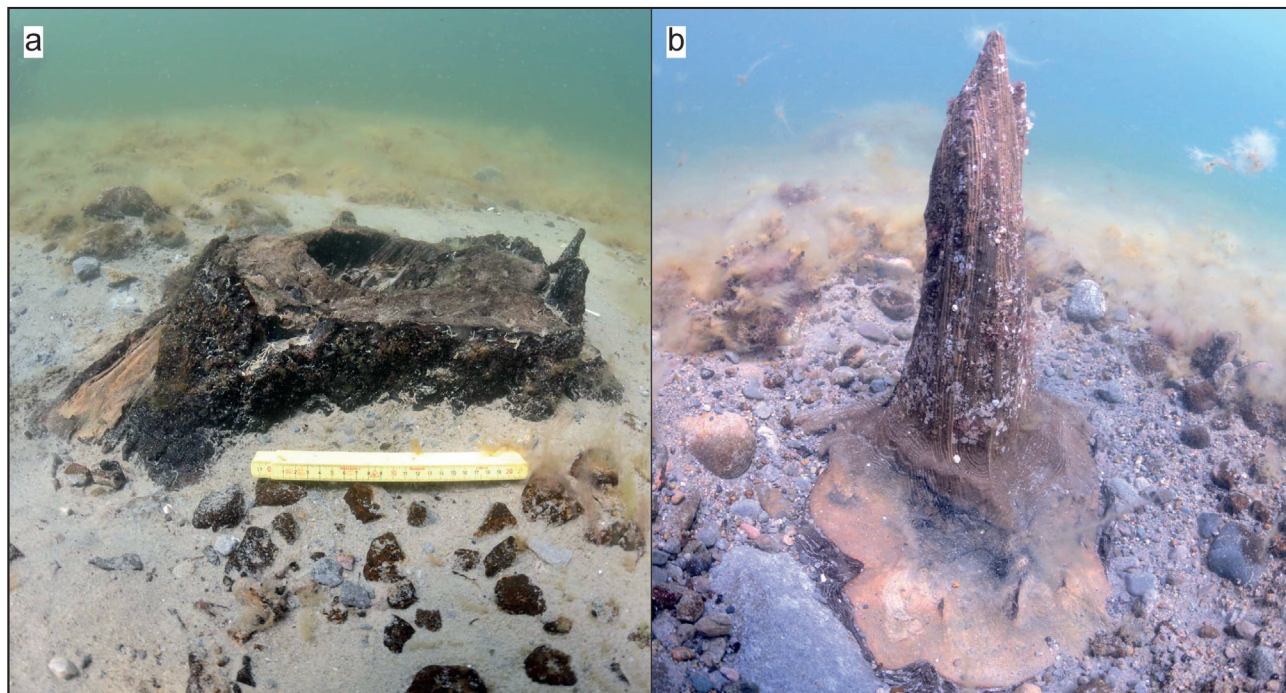


Figure 11. Photographs of the submerged landscape in western Blekinge. (a) A rooted birch stump found at 6.3 m b.s.l. in the Svanevik Bay. (b) A rooted pine stump found at about 10 m b.s.l. between the Tärnö and Harö Islands, in the outer Hällaryd Archipelago. Photographs Arne Sjöström.

et al., submitted; Holmlund *et al.*, 2017). To the south and to the east of the Sternö Peninsula, several areas with abundant rooted pine remains and organic sediments, situated at a depth of 5–15 m b.s.l., have been discovered by divers. Furthermore, in the inner part of the Karlshamnshäraden Bay, two more areas with pine remains have been discovered. In the western part of the Svanevik Bay, a rooted birch stump has been found at 6 m b.s.l. (Figure 11a), while further to the east, several areas with erosional ridges and rooted pine stumps appear, situated at a depth of 5–10 m b.s.l. In the outer parts of the Hällaryd Archipelago, between the Tärnö and Harö Islands, a large area with rooted pine stumps and non-rooted pine stems appear at 8–10 m b.s.l., just inside the top of a steep slope, which falls down to 15 m b.s.l. (Figure 11b). Finally, in the eastern part of the Pukavik Bay, a non-rooted pine stem has been found at a depth of 18 m b.s.l.

Blekinge has a rich tradition of Quaternary research, mainly focusing on the development of the Baltic Basin since the last deglaciation. Blekinge is ideal for sea-level research, as its coastline runs parallel with the uplift isobases, which means that the results from the many sheltered bays and basins are easily comparable. The research efforts started already in the 19th century (De Geer, 1882; Holst, 1899) and have since then continued more or less without interruption (*e.g.* Munthe, 1902, 1940; Sandegren, 1939; Nilsson, 1953; Berglund, 1964, 1966, 1971; Mikaelsson, 1978; Björck, 1979, 1981; Liljegren, 1982; Berglund and Björck, 1994; Yu *et al.*, 2003, 2004, 2005, 2007; Berglund *et al.*, 2005; Andrén *et al.*, 2007). However, this research has mainly focused on the Late Glacial and mid- to late Holocene periods, from where evidence of past water level fluctuations can be found above the present-day

sea level.

The first archaeological excavations in Blekinge took place during the late 19th century and the first decades of the 20th century (*e.g.* Wibling, 1895, 1900; Erixon, 1913; Lönnberg, 1930; Bagge and Kjellmark, 1939). Several Mesolithic and Neolithic sites along the coastline were excavated, often in connection to the contemporary shoreline displacement research. During recent years, the excavations of Stone Age sites have been driven by contract archaeology, specially manifested in excavations in connection with large road and housing constructions in westernmost Blekinge (*e.g.* Kjällquist and Friman, 2017; Rudebeck and Kjällquist, 2016).

Material and methods

Fieldwork

Surveillance and sampling of the submerged landscapes in the Hanö Bay have been performed by diving geologists and archaeologists. Diving campaigns have been ongoing at Haväng since 2003 during periods of favourable weather conditions and unrestricted access to the military area, either by entering the water from the shore or by diving from a boat with an assisting crew. In Blekinge, fieldwork mainly took place during the summers of 2015 and 2016 in cooperation with the Swedish Maritime Archaeological Society (MAS). In order to obtain sample positions, a wire connecting the diver to a floating GPS buoy was used. Due to drift of the buoy, the sample positions were manually corrected according to the bathymetric map, and the final posi-



Figure 12. Sampling of a non-rooted pine stem (HAV093) with a hand-powered saw at Haväng. The sample was found at 4.9 m b.s.l. and protrudes from the organic sediments seen to the left. Photograph Arne Sjöström.

tions of the samples were determined with a maximum horizontal error of a few metres. The vertical position of the samples was measured by a diving computer and the obtained depths were corrected for deviations from the mean water level. Underwater sampling of trees was performed with a handsaw at the thickest part of the visible stems, where the largest number of annual rings is expected (Figure 12). Discrete organic sediment samples were obtained immediately adjacent to the sampled trees with a trowel and placed in a glass jar or plastic sample bag. For larger organic sediment samples, a spade was used. Each sample site was extensively photographed in order to create a 3D photogrammetry model. Archaeological findings of smaller size, such as bones and antlers, were brought back to the surface, whereas larger findings, such as the stationary fishing constructions, were documented, sub-sampled and left *in situ*.

Bathymetric and topographic data

Echo sounding is a type of sonar used to obtain water depths in order to construct bathymetric data sets. An echo sounder measures the time interval between emission and return of transmitted sound pulses, which is used to calculate the water depth. Echo sounding can be performed either by a single pulse or by an array of multiple pulses. Contrary to single beam techniques, a multibeam echo sounder emits a simultaneous array (normally 120°–150°) of sound pulses, which enables the production of extremely high resolution bathymetric data sets (Colbo *et al.*, 2014). The multibeam echo sounding technique provides data sets with a horizontal error of a small percentage of the water depth and a vertical error of less than one per cent of the water depth. The backscatter signal produced by the sound pulses can also be used to infer geological characteristics of the seafloor (Brown and Blondel, 2009).

The bathymetric data set for the Hanö Bay was compiled by Aquabiota AB within the project MARMONI and consists of single-beam and multibeam echo sounder measurements performed in the 1990s and 2000s

(Wijkman *et al.*, 2015). The spatial resolution of the data set is 10 m per pixel, except in areas with military restrictions, where the spatial resolution is 100 m per pixel. At Haväng, multibeam echo sounding measurements covering the extent of the submerged landscape were performed in 2009, 2012 and 2014, respectively. The measurements were performed by MMT (2012) and the Swedish Maritime Administration (2009 and 2014). The obtained data set was processed in the QPS Fledermaus 7.1 software, creating a bathymetric data set with a spatial resolution of 0.25 m per pixel. Topographic data consisting of LiDAR measurements with a spatial resolution of 2 m per pixel were provided by the Swedish Mapping, Cadastral and Land Registration Authority (Lantmäteriet). The topographic data were subsequently down-sampled in order to create a seamless Digital Elevation Model (DEM) data set by merging the bathymetric and topographic data sets. In *Papers III* and *IV*, the DEM was altered in order to reconstruct the early Holocene shorelines according to the results from the shoreline displacement records. In addition, in *Paper III*, a flow accumulation algorithm was used to reconstruct the early Holocene river network below present-day sea level in western Blekinge.

Sediment sequences

Six sediment sequences were obtained at Haväng, four from the submerged landscape and two from a small basin situated about 500 m upstream from the Verkeån River outlet, in order to reconstruct the palaeo-environment and water level fluctuations during the early Holocene. Three of the sequences were retrieved with a vibro corer from the vessel *R/V Ocean Surveyor* in 2009 and 2014, two terrestrial sequences were sampled with a Russian-style peat corer in 2015 and 2016, while one short sediment sequence was sampled with a metal box and a spade by divers in 2016. The obtained stratigraphies were described and subsequently investigated with a number of methods in order to reconstruct their depositional environments. Loss-on-ignition was used to estimate the organic matter content (Bengtsson and Enell, 1986), magnetic susceptibility was measured in order to assess the minerogenic component of the sequences, total element contents were measured with an X-ray fluorescence instrument in order to obtain additional information about the depositional environments and measurements of the total carbon and nitrogen content were used to assess the origin of the organic matter (Meyers, 1994). Pollen analysis was performed in order to reconstruct the local vegetation. Samples were prepared according to the methodology of Berglund and Ralska-Jasiewiczowa (1986) and *Lycopodium* spore tablets used for pollen concentration estimations were added to the samples (Stockmarr, 1971). Diatom analysis was performed in order to assess the aquatic environment at the time of deposition. The samples were prepared according to the methodology of Battarbee *et al.* (2001).

Dating methods

The ^{14}C -dating method is used to determine the age of organic material and is based on the decay of the radioactive ^{14}C isotope. The isotope has a half-life of 5730 ± 40 years, which means that it is possible to date objects that are up to approximately 50,000 years old. In this thesis, ^{14}C dating has been used to date terrestrial macroscopic plant remains obtained from sediment sequences and discrete organic sediment samples, cellulose extracted from five consecutive annual rings from dendrochronologically analysed stumps and stems, bulk samples from other wood remains and collagen extracted from animal bones and antlers. The samples were measured at the radio-carbon laboratories at Lund and Uppsala Universities. The obtained ages were calibrated to calendar years using the INTCAL13 data set (Reimer *et al.*, 2013) and the Oxcal 4.2.4 software (Bronk Ramsey, 2009). In total, 50 samples from Haväng and 13 samples from western Blekinge have been dated (Table A1). In order to constrain the obtained ages, modelling of the individually calibrated ages was performed in the Oxcal 4.2.4 software. ‘Wiggle-match’ dating (D_sequence) was performed on some of the dendrochronologically analysed trees by modelling two or more ^{14}C ages with a known amount of years between the dated samples, obtained either from the same tree or by dendrochronological cross-dating between two or more trees (Bronk Ramsey, 2008; Bronk Ramsey *et al.*, 2001). ^{14}C ages obtained from rooted stumps were modelled with the U_sequence (Bronk Ramsey, 2008), assuming a constant deposition, in order to constrain the timing of the Ancylus Lake transgression. P_sequence modelling (Bronk Ramsey, 2008) was used to create age models for the sediment sequences in order to assess the sediment deposition rate.

The subject of dendrochronology was founded by Andrew E. Douglass in the early 20th century as a way of studying climate and weather by measuring the width of annual rings in trees (Fritts, 1976). Dendrochronology enables exact calendar year dating of wood material with a sufficient number of annual rings. At Haväng, tree-ring chronologies were obtained from the sampled pine trees in order to construct local chronologies used for assessing water level fluctuations and other environmental changes during the early Holocene. Individual trees were analysed by measuring the annual growth rings with a precision of 0.01 mm on at least two radii. The radii were cross-dated and subsequently merged into ring-width series. The ring-width series from all sampled trees were then cross-dated using statistical and visual methods (Pilcher, 1990), and matching series were merged into chronologies.

Summary of papers

Author contributions are listed in Table 1.

Paper I:

A submerged Mesolithic lagoonal landscape in the Baltic Sea, southeastern Sweden - Early Holocene environmental reconstruction and shore-level displacement based on a multiproxy approach. Hansson, Nilsson, Sjöström, Björck, Holmgren, Linderson, Magnell, Rundgren and Hammarlund: 2018, Quaternary International 463.

In the inner part of the submerged landscape at Haväng, a sediment sequence obtained at a depth of 8 m b.s.l. was studied with a number of methods in order to reconstruct the local environment at the time of deposition. The 3.6 m long sediment sequence consists of a dark brown homogenous, compacted fine detritus gyttja with a high organic matter content. Seven ^{14}C datings from terrestrial macroscopic plant remains yielded ages in the range of 9100–8600 cal BP, *i.e.* from the Initial Littorina Sea Stage, indicating a sediment accumulation rate of about 1 cm yr^{-1} . A principal component analysis of the element content revealed a different element composition in the uppermost 100 cm compared to the rest of the sequence. The pollen record obtained from the sequence was divided into two zones. Zone 1 (350–88 cm) is dominated by *Alnus*, *Betula*, *Corylus* and *Pinus* and has a high concentration of pollen grains. Zone 2 (88–0 cm) is also dominated by *Alnus*, *Betula*, *Corylus* and *Pinus*, but is defined by the appearance of *Tilia*. In zone 2, the pollen concentration is considerably lower than in zone 1. The diatom record was divided into two zones. Zone 1 (350–75 cm)

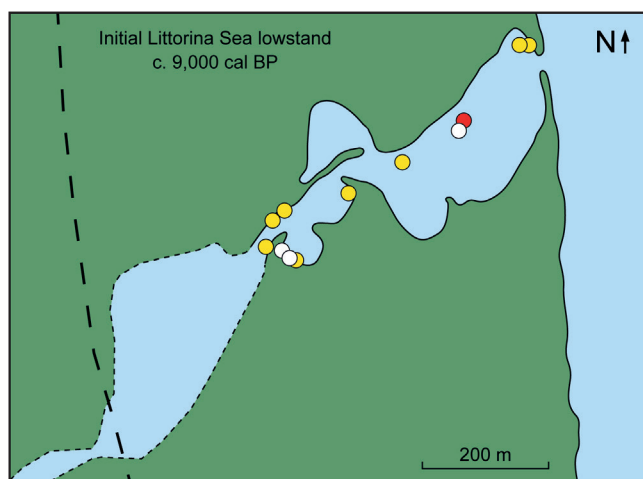


Figure 13. Shoreline reconstruction of the Haväng area during the Initial Littorina Sea lowstand at about 9000 cal BP. The reconstructed extent of the lagoon is based on the outline of the organic sediment ridges in sub-area A. The locations of the sediment sequence (red circle), bones and antlers (white circles) and stationary fishing constructions (yellow circles) are marked. The long dashed line indicates the present coastline. The short dashed lines indicate the outline of the organic sediments mapped by divers where the bathymetric data is missing. Figure modified from Hansson *et al.* (2018).

is dominated by freshwater taxa, but a weak brackish signal was found throughout. Zone 2 (75–0 cm) is also dominated by freshwater taxa, but an increase in indifferent or brackish taxa was recorded. The sediment sequence was interpreted to have been deposited in a stable lagoonal environment (Figure 13). The sediment accumulation rate and the organic matter content indicate a highly productive aquatic environment, but probably with a substantial terrestrial organic detritus input as well. The lagoonal gyttja sediments are found down to a depth of 12 m b.s.l., which is interpreted as the minimum water level during the Initial Littorina Sea Stage. The vegetation was dominated by a relatively open forest with *Betula* and *Alnus* along the river shores, while *Pinus* and some deciduous tree species occupied the surrounding landscape.

The pollen concentration, diatom assemblage and elemental content records show changing conditions in the uppermost metre of the sequence, which is interpreted as a destabilisation of the lagoonal environment caused by the onset of the Littorina Sea transgression, when the shoreline moved towards land and finally transgressed the sample position at about 8500 cal BP. Several archaeological artefacts have been found embedded in the organic sediments. Most of the artefacts encountered are of organic character, such as pine

torches, wood sticks and animal bones and antlers. The bones and antlers are worked or have butchering marks originating from human activity. Of special interest is a discarded elk antler pick axe, dated to about 8700 cal BP (Figure 9d). Eight stationary fishing constructions made of hazel wood have been found in the area, dating to 9200–8400 cal BP, the hitherto oldest known in northern Europe, indicating that lagoonal and river mouth fishing was of great importance to the early Mesolithic communities in the area (Figure 13). The permanent constructions indicate mass-exploitation and hints at a more sedentary lifestyle during the early Mesolithic than previously thought.

Paper II:

Shoreline displacement and human resource utilization in the southern Baltic Basin coastal zone during the early Holocene: New insights from a submerged Mesolithic landscape in south-eastern Sweden. Hansson, Björck, Heger, Holmgren, Linderson, Magnell, Nilsson, Rundgren, Sjöström and Hammarlund: 2017, The Holocene.

Three sediment sequences and several rooted stumps and non-rooted stems were obtained at depths of 4 to

Table 1. Author contributions to the papers.

Author's contribution	Paper I	Paper II	Paper III	Paper IV
Concept and study design	Hansson Hammarlund	Hansson Hammarlund	Hansson Nilsson	Hansson
Fieldwork	Sjöström Hansson Nilsson Linderson	Sjöström Hansson Nilsson Hammarlund Linderson	Sjöström Nilsson Hansson Linderson	Hansson Hammarlund Brunlid Nilsson Rundgren Linderson Nilsson
Lithological and chronological analyses	Hansson	Hansson	Hansson	Hansson Brunlid Nilsson
Pollen analysis	Hansson	Hansson	---	Brunlid Nilsson
Diatom analysis	Holmgren	Holmgren	---	---
Osteological analysis	Magnell	Magnell	---	Magnell
Macrofossil analysis	---	Heger	Hansson	---
Dendrochronological analysis	---	Hansson	Hansson	---
GIS landscape reconstructions	---	---	Landeschi	Hansson
Data interpretation	Hansson Hammarlund Rundgren Nilsson Björck Linderson Sjöström Magnell	Hansson Hammarlund Rundgren Nilsson Björck Linderson Sjöström Magnell	Hansson Nilsson Hammarlund Sjöström	Hansson Magnell Boethius Rundgren Hammarlund Brunlid Nilsson Lagerås
Writing	Hansson Nilsson Hammarlund Magnell Rundgren	Hansson Nilsson Hammarlund Magnell Rundgren	Hansson Nilsson Landeschi Hammarlund	Hansson Boethius Magnell Lagerås
Comments on manuscript	Björck Sjöström Linderson	Björck Sjöström Linderson	Björck	Rundgren Nilsson Hammarlund

21 m b.s.l. from the submerged landscape at Haväng in order to reconstruct the local environment and water level changes during the Yoldia Sea and Ancylus Lake Stages. The outermost, 1.4 m long, sequence, situated at 18.7 m b.s.l., was ^{14}C dated to 11,200–10,800 cal BP and consists of a minerogenic lower part overlain by an organic upper part. The pollen record is totally dominated by *Pinus*, whereas the diatom analysis, with the exception of one frustule, found no diatoms. At 17.5 m b.s.l., a 3.5 m long sequence was obtained, consisting of coarse minerogenic sediments in the lowermost part, followed by interbedded silty gyttja and fine clastic sediments in the major, middle part and coarse minerogenic sediments in the uppermost part of the sequence. The sequence spans from 11,200 to 10,500 cal BP, with a sediment accumulation rate of 5–6 mm yr⁻¹ in the fine-grained middle part. The pollen record is dominated by *Pinus* and *Betula*, with a continuous presence of

Corylus, *Filipendula*, *Salix* and *Poaceae*. The diatom record consists solely of freshwater taxa. The third, 0.3 m long, sequence was obtained at 5 m b.s.l., capturing the transition from the underlying grey calcareous gyttja to the dark brown fine detritus gyttja and was ^{14}C dated to 10,200–9500 cal BP. Based on these results, it was concluded that the Verkeån River extended across the exposed soils during the Yoldia Sea and Ancylus Lake Stages. The fine-grained sediments and the diatom assemblages indicate a wide and shallow, slow-flowing, nutrient-rich riverine environment. Findings of beaver (*Castor fiber*) bones suggest that parts of the river were dammed, creating an environment characterized by ponds and wetlands. After the area was exposed, it took some time for the vegetation to establish on the sandy soils as reflected by the initially extreme dominance by *Pinus*, mostly transported from areas upstream, in the pollen record, followed by a successive establishment of a more diverse flora along the river. The recovered tree material indicate an open woodland dominated by pine, and microscopic charcoal particles found in the sediments show that the woodland was affected by repeated fires.

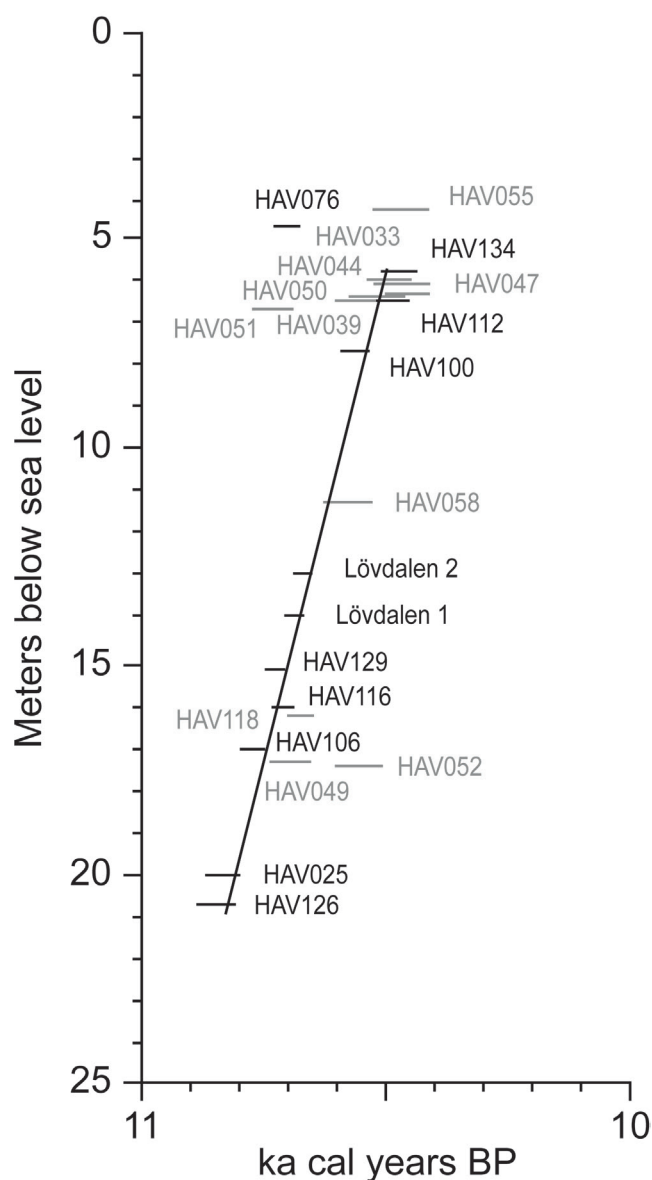


Figure 14. Plot showing the age-depth relation of rooted (black lines) and non-rooted (grey lines) trees at Haväng. Assuming a linear transgression, modelling of the ^{14}C ages from the rooted trees was performed in order to estimate the transgression rate. Sample HAV076 was omitted from the modelling. Figure from Hansson *et al.* (2017).

An interpolation between the Baltic Ice Lake levels at Oskarshamn and the Mecklenburg Bay (Figure 2) indicates that the final Baltic Ice Lake level at Haväng was situated at approximately 16 m a.s.l. Consequently, after the Baltic Ice Lake drainage the water level at Haväng was approximately 9 m b.s.l. The deepest rooted pine stump at Haväng is located at 20.7 m b.s.l., indicating that the minimum water level during the Yoldia Sea lowstand was 24–25 m b.s.l. The ^{14}C age of nine rooted pine stumps was modelled with the U_sequence in the Oxcal 4.2.4 software. The U_sequence assumes a constant rate of deposition, but here the constant deposition was substituted by a constant water level rise, in accordance with an assumed linear Ancylus Lake transgression. The model results show that the transgression started just before 10,800 cal BP and lasted until about 10,300 cal BP, indicating a transgression rate of 4 cm yr⁻¹ (Figure 14). The proposed transgression scenario is supported by 11 wiggle-match dated non-rooted trees, yielding an age-depth relation in accordance with the model results. Based on the innermost sediment sequence, showing uninterrupted lacustrine sedimentation, it was concluded that the maximum level of the Ancylus Lake did not reach above 5 m b.s.l.

Several organic archaeological artefacts, such as discarded pine torches and tree stumps that exhibit scars and features indicating utilization for pine-torch production, reflect human exploitation of the woodland ecosystem. Furthermore, a hollow and burned pine stem found at 19 m b.s.l. is interpreted as the possible remains of a log-fire, used as a night fire at campsites. Findings of several worked aurochs, beaver and red deer bones and antlers indicate the location of nearby archaeological sites and the importance of terrestrial resources. This should be seen in the perspective of the younger findings of stationary fishing constructions at Haväng, showing the importance of aquatic resources

(Paper I).

Paper III:

A revised early Holocene shoreline displacement record for Blekinge, southern Sweden, and implications for underwater archaeology. Hansson, Hammarlund, Landeschi, Sjöström and Nilsson: submitted.

The new shoreline displacement record from Haväng in combination with recent publications from geoarchaeological excavations at Norje Sunnansund connected to a major road construction, highlighted the need for a refinement of the early Holocene shoreline displacement in Blekinge. Surveillance and sampling were therefore performed by divers in the submerged landscapes in western Blekinge during the summers of 2015 and 2016. Rooted stumps, non-rooted stems and organic sediments were sampled at depths of 5 to 15 m b.s.l. and ^{14}C dating was performed. The revised shoreline displacement record is mainly based on the corresponding record from Haväng (*Papers I and II*), adjusted to the different land uplift rate by interpolation and extrapolation with other shoreline displacement records from the southern Baltic Basin. During the Yoldia Sea lowstand, at 10,800 cal BP, the level was approximately at 20 m b.s.l., based on the levels at Haväng and the Arkona Basin. The maximum level of the Ancylus Lake was approximately 3 m a.s.l. based on the levels at Haväng and Olsäng, the latter a raised beach complex in eastern Blekinge. Wiggle-match dated pine stumps and stems from the seafloor and archaeological artefacts from Norje Sunnansund correlate well with the proposed timing of the Ancylus Lake transgression. During the subsequent Initial Littorina Sea Stage, a lowstand level of about 4 m b.s.l. is proposed, several metres lower than concluded by previous studies. This level is based on an extrapolation between the lowstand levels at Haväng and in the Arkona Basin, and on the extent of the transgression north and south of Blekinge, both indicating a lowstand level of about 4 m b.s.l. Furthermore, a slope feature found at 5 m b.s.l. in the inner, calmer part of the archipelago has been interpreted as a submarine bar, formed by wave activity just below the contemporary sea level during the Initial Littorina Sea Stage, when the water level was relatively stable over a long period. The timing of the subsequent Littorina Sea transgression, which started at about 8500 cal BP, is in agreement with the archaeological evidence from Norje Sunnansund and Ljungaviken, situated in the westernmost part of Blekinge. The refined shoreline displacement record fills the gap between the previously established Late Weichselian and mid- to late Holocene records (Berglund *et al.*, 2005; Björck, 1979) (Figure 15).

The revised shoreline displacement record was used to reconstruct the palaeo-landscape during the Yoldia Sea lowstand, the Ancylus Lake transgression phase, the Ancylus Lake maximum and the Initial Littorina Sea lowstand. A DEM was altered by subtracting or adding

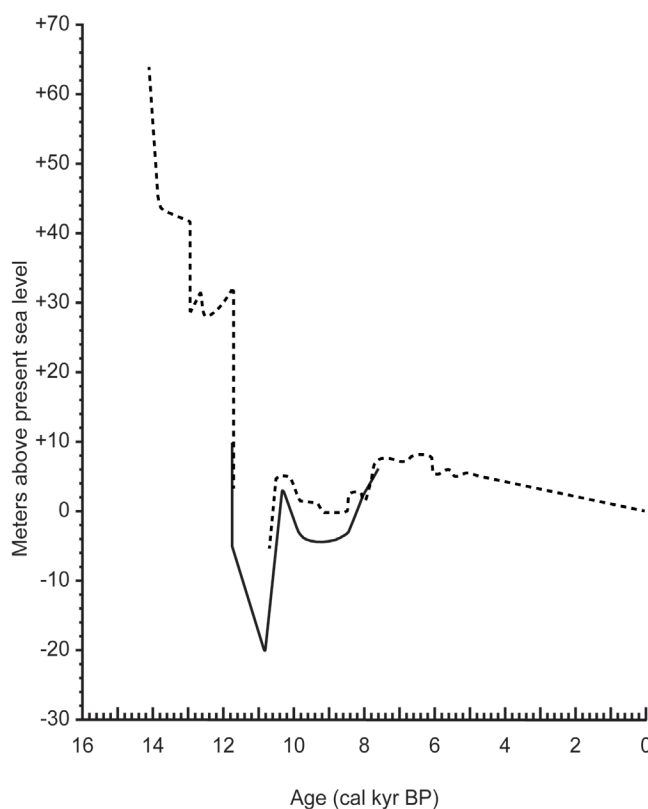


Figure 15. The revised shoreline displacement reconstruction from Blekinge (solid line) bridging previously published shoreline displacement records for the Late Weichselian (Björck, 1979) and the mid- to late Holocene (Berglund *et al.*, 2005) (dashed lines). Figure from *Paper III*.

the value of each of the four reconstructed shoreline levels mentioned above to the present-day DEM values. Furthermore, the courses of eight rivers in the study area were reconstructed below the present-day sea level in order to highlight areas of high archaeological potential. During the Yoldia Sea lowstand, vast areas were exposed. To the west, in the Pukavik Bay, four rivers ran into the ancient Lake Kladdsjön, which had a single outlet river that ran into the Yoldia Sea in a small bay. To the east, another river had its outlet in a protected bay on the Tärnölandet Peninsula. The protected bay areas, together with the inlet and outlets areas of Lake Kladdsjön constitute areas of high archaeological potential, as during the Preboreal, such locations are known to have been important for the mobile foragers. During the subsequent Ancylus Lake transgression phase, much of the previously exposed landscape became submerged. The Pukavik Bay turned into a shallow lagoon and wetland area, where four rivers, including the larger Mörrumsån River, had their outlets. This area was probably one of the most important archaeological hot spots during this period. During the Ancylus Lake maximum, about 10,300 cal BP, the water level was situated about 3 m a.s.l. and consequently, the low-lying areas along the present Mörrumsån River outlet became a small archipelago. Archaeological findings found along the Mörrumsån River above the present-day sea level hints at the great potential of underwater excavations in the area. During the Initial Littorina Sea lowstand, earlier findings indicate that the archipelago was inhabited, and its large

islands and protected waters were probably ideal for humans. Furthermore, our proposed lowstand level means that large submerged areas, with great archaeological potential, have yet to be explored.

Paper IV:

Shoreline displacement, coastal environments and human subsistence in the Hanö Bay region during the Mesolithic. Hansson, Boethius, Hammarlund, Lagerås, Magnell, Nilsson Brunlid and Rundgren: manuscript.

The Hanö Bay region, situated in southeastern Sweden, has recently been the focus of several geoarchaeological research projects covering the early Holocene. Individually, the excavations at Haväng and Norje Sunnansund have revealed well-preserved organic archaeological objects, which have given new insights into the lifestyle of humans during the early Mesolithic. Together with new GIS-modelled shoreline reconstructions based on shoreline displacement records from the Hanö Bay, the new geoarchaeological and zooarchaeological results from the region are used to describe the subsistence and settlement strategy development of the south-Scandinavian Mesolithic communities. Shoreline reconstructions, based on the shoreline displacement records from Haväng and western Blekinge, were created by manipulating a DEM of the study area. Due to the uneven land uplift, the DEM had to be tilted in order to reconstruct synchronous shorelines. This was performed by dividing the DEM into segments representing a water level change of 0.1 m parallel to the uplift isobase. Each segment was then manipulated according to the shoreline displacement interpolated between the records from Haväng and western Blekinge. Five maps were produced showing the position of the shoreline during the Yoldia Sea lowstand, the Ancylus Lake transgression phase, the Ancylus Lake maximum, the Initial Littorina Sea lowstand and the Littorina Sea transgression phase.

Vast coastal areas became exposed during the Yoldia Sea lowstand (Figure 16a). The shoreline reconstruction shows that a large bay was formed east of the Haväng site. Based on the present-day bathymetry, it seems that the rivers in eastern Skåne had their outlets in this bay. There are only a few archaeological settlements preserved from the Yoldia Sea Stage, and these were small, seasonal camps indicating a society based on small mobile groups using different sites for hunting, fishing and gathering. During the subsequent Ancylus Lake transgression phase, large areas became inundated (Figure 16b). At Haväng, the Verkeån River created a rich coastal environment that attracted big game and, consequently, humans. Several worked bones and antlers indicate that the subsistence included hunting of aurochs and beaver, but the importance of fishing is yet uncertain. The dominance of pine and grasses and sedges in the pollen record and the presence of aurochs in the landscape indicate an open pine woodland in the coastal areas. Few archaeo-

logical settlements from the time of the Ancylus Lake maximum have been discovered, which might be due to the constant shoreline movements, preventing the development of long-time coastal settlements at single locations (Figure 16c). During the Initial Littorina Sea Stage (Figure 16d), there is evidence of permanent settlements from both Haväng and Norje Sunnansund. Stationary fishing constructions and the development of food preservation indicate a high reliance on freshwater fish in the diet. This development towards a delayed-return subsistence and a sedentary lifestyle corresponds to the development of productive aquatic environment during the Initial Littorina Sea Stage, when the coastline was relatively stable during an extended period. The bone remains from Norje Sunnansund indicate a year-round presence in this coastal landscape, which raises questions regarding the development of territoriality during the Mesolithic. After marine conditions were established in the Baltic Basin (Figure 16e), findings from several settlements in the Hanö Bay region suggest a shift towards a marine-based subsistence, although freshwater and terrestrial resources were still exploited. The dominance of pine and deciduous tree taxa in the pollen record and a decline in the number of aurochs bones indicate a development towards a more closed forest. To what extent the early Holocene climate oscillations affected the human populations in the Hanö Bay region is uncertain. Evidence from Norje Sunnansund suggests that humans exploited a more extensive sea ice cover for seal hunting during the 9.3 kyr event, while several settlements in Skåne show no occupation decline during the 8.2 kyr event. Due to the relatively short duration of the events, it is often difficult to establish an absolute connection between the events and the dated findings. This study highlights the correlation between water level changes and settlement development during the Mesolithic. Furthermore, this study shows that a combination of zooarchaeological and palaeo-ecological research can provide highly resolved, multi-faceted palaeo-environmental records.

Discussion

The complexity of the submerged landscape at Haväng

The submerged landscape at Haväng is a complex coastal environment characterized by the imprint of several water level fluctuations, shifting depositional environments and erosive forcing. The early Holocene water-level changes that enabled the formation of organic deposits also led to erosion. It is therefore difficult to determine which landscape features that have maintained their original form and what features that have been reshaped by erosion. Adding to this complexity, a mixture of stumps and stems, organic sediments and archaeological artefacts of different ages are found in the same context on the seafloor (Figure

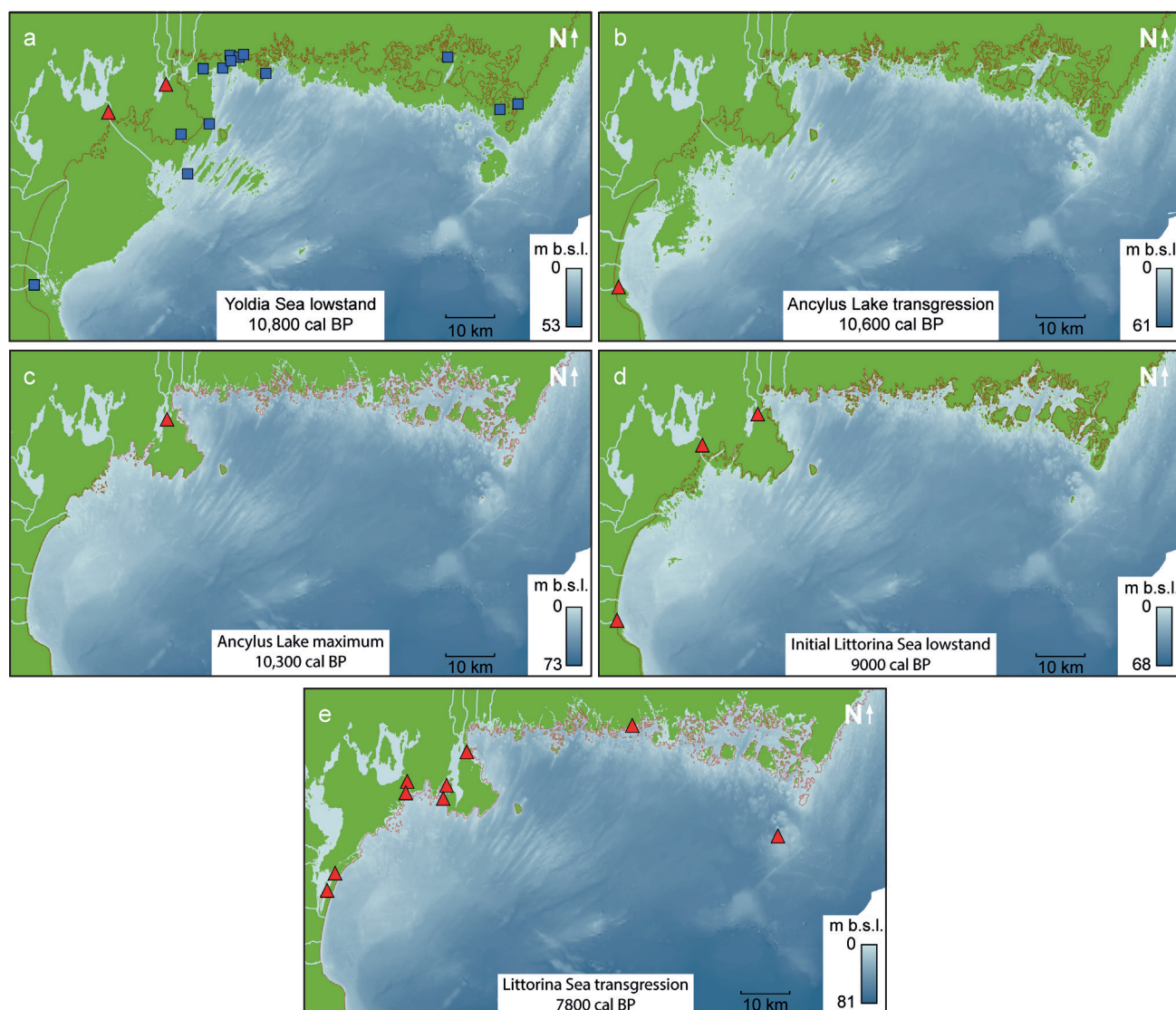


Figure 16. Shoreline positions in the Hanö Bay during (a) the Yoldia Sea lowstand, (b) the Ancylus Lake transgression phase, (c) the Ancylus Lake maximum, (d) the Initial Littorina Sea lowstand and (e) the Littorina Sea transgression phase. The locations of settlements (red triangles) and submerged wood remains (blue boxes) are marked. Topography data © Lantmäteriet. Figure modified from *Paper IV*.

17). When the investigations started, it was unclear if the stumps and stems originated from one or both of the Yoldia Sea and Initial Littorina Sea lowstand periods, and whether organic sediments of the same type found at different depths were of the same age. It took about a year of surveillance diving, sampling and dating of wood remains and organic sediments in order to get a basic understanding of the chronology of the components that constitute the submerged landscape, before detailed environment and shoreline displacement reconstructions could be performed. The importance of the diving expeditions for the outcome of this thesis cannot be stressed enough. Apart from sampling stumps, stems and archaeological artefacts, the diving efforts have been vital for understanding the stratigraphy and morphology of the landscape, knowledge that would have been missed if only sediment sequences and bathymetric maps would have been used for landscape and environmental reconstructions. Therefore, it is also of importance that the divers have geological and archaeological experience.

The interpretation of the depositional environment is comparably straightforward in sub-areas B and C, where the channel-shaped ridges and fine-grained organic sediments are clear indicators of a riverine environment (Figure 7). The width of the channel is approximately 30–50 m, which is considerably wider than the modern Verkeån River. This can be explained by the low gradient in sub-area B, which together with damming, as evident from beaver bones found in the archaeological material, created a wide and shallow slow-flowing stream, characterized by wetlands and ponds. In the outermost part of sub-area B, the channel widens and the northern channel ridge splits into a set of ridges (Figure 18), which were probably formed when the rising water level successively flooded the river shores at the onset of the Ancylus Lake transgression.

Sub-area A has a complex morphology consisting of crescentic organic sediment ridges in the inner part and coast-parallel organic sediment ridges in the outer part (Figure 8). It is clear that together, these features



Figure 17. Photograph showing the complex stratigraphy of the submerged landscape at Haväng. Washed out boulders from the glaciation, a rooted pine stump dated to about 10,500 cal BP and organic sediments partly covering the stump dated to about 9000 cal BP are found at the same depth. Diver in the photograph Anton Hansson. Photograph Arne Sjöström.

outline the outer limits of the lagoonal system during the Initial Littorina Sea Stage, but the inner structures and the relation between the different organic sediment ridges are still not fully understood. At a first glance, the crescentic ridges resemble the remains of a meandering river, which consequently led to an initial interpretation of the coast-parallel organic sediment ridges as oxbow lakes formed in the meandering system (Hansson *et al.*, 2017b). However, when studying these assumed meander loops (crescentic ridges) in detail one recognizes that they tilt inward and that they consist of the same type of fine detritus gyttja as found in the 'oxbow lakes' (coast-parallel ridges) (Figure 8). Based on these observations, the area was reinterpreted as a lagoon, where the crescentic organic sediment ridges outline the shape of the former lagoon shores. The organic sediments were deposited in the entire lagoon, but inside the crescentic organic sediment ridges, a layer of sand covers the organic sediments. This also means that the coast-parallel ridges most likely are not depositional features, but instead, their shape is due to later erosion. In total, six coast-parallel ridges occur in sub-area A, but their age distribution is not yet fully known (Figure 8). One possibility is that longshore currents have eroded parts of the gyttja sediments during the early parts of the Littorina Sea transgression, when the shoreline was just above the gyttja surface. However, why these currents did not erode the sediments that remain as the coast-parallel ridges as well is not clear. Another possibility is that the ridges were deposited between coast-parallel sand bars formed by the Littorina Sea

transgression. The bars would then have been eroded during the latter stages of the transgression and/or the subsequent regression. However, the lowermost part of the dated coast-parallel ridge was deposited before the onset of the transgression, and furthermore, sand grains were only found in the uppermost 20 cm in the studied ridge, disputing that the ridges were formed by sand bars. The processes that formed these coast-parallel ridges, and whether they reflect the depositional environment or later erosion processes, is still unknown. A first step towards a better understanding of these ridges is to establish whether they are synchronous or if they were deposited in a succession.

Indicators for water level lowstands

Above the present-day water level, the elevation of raised beaches (*e.g.* Mikaelsson, 1978; Munthe, 1911; Tikkanen and Oksanen, 2002) and the connection and isolation of basins from the sea (*e.g.* Björck, 1979; Corner *et al.*, 1999; Long *et al.*, 2011; Yu, 2003) are established methods for determining past water level changes. However, below the present-day water level, the determination of past fluctuations is most often less accurate. For a long time, submerged tree stumps have been used as indications of past lower water levels (*e.g.* Wilcke, 1850; Reid, 1913; Ramsay, 1926; Isberg, 1927; Nilsson, 1961; Berglund *et al.*, 1986), but as many of the remains were found washed up on the shore or were caught in fishing nets, their *in situ* positions have

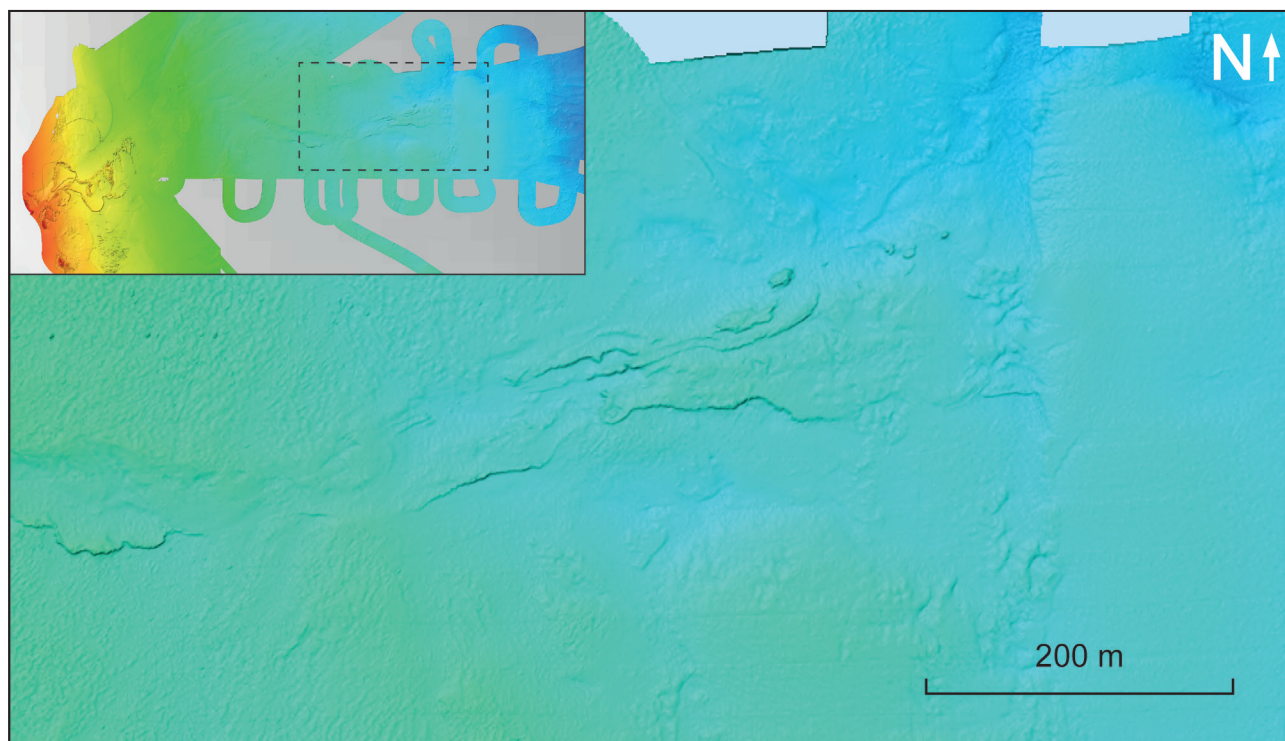


Figure 18. Bathymetric map of the eastern part of sub-area B at Haväng. The northern ridge split into a set of ridges at about 18 m b.s.l.

not been known and consequently, no accurate determination of the past lowstands were presented. Other methods used for determination of past fluctuations below the present water level include the identification of coastal facies in sediment stratigraphies (e.g. Bendixen *et al.*, 2017b; Bennike and Jensen, 1998; Uścinowicz, 2006), and the study of coral reefs, mainly found in tropical areas (e.g. Bard *et al.*, 1996; Fairbanks, 1989).

At Haväng, rooted stumps and non-rooted stems were used for reconstruction of the Yoldia Sea lowstand level and the timing of the subsequent Ancylus Lake transgression. In theory, a submerged rooted tree stump reveals that the contemporaneous shoreline was situated somewhere below the stump, but not how much lower. In order to constrain the lowstand level, rooted stumps from a large area need to be identified. After extensive diving surveys in sub-area C at Haväng, the deepest rooted stump was found at 20.7 m b.s.l. (Figure 19). It is possible that trees did grow at greater depths, but due to erosion or embedding by covering sediments, they have not been found. Such potential stump finds would, if found, lower the obtained lowstand level. Still, when considering the Haväng area as a whole, there is a large abundance of stumps and stems above 20.7 m b.s.l. (Figure 7) not affected by erosion or covered by sediments, whereas no trees have been found below 20.7 m b.s.l., suggesting that the deepest growing tree indeed has been found. Another uncertainty to take into account is the position of the tree in relation to the contemporaneous water level at the time of death. Satellite images of present-day sandy coastlines on the south coast of Skåne and on the islands of Gotska Sandön and Öland (Figure 2) in the Baltic Sea show that adult pine trees grow at least 2–3 m above the normal Baltic Sea level, indicating that the lowstand

level was situated at least 2–3 m below 20.7 m b.s.l., and that the tree likely died due to the rise in groundwater, when the water level reached about 2–3 m below the tree. If accounting for these uncertainties, the use of rooted tree stumps for determination of lowstand levels is a highly accurate method.

Submarine bars are depositional features formed by wave and current action in the energy dissipation zone just below the water level (King, 1972). Such bars are particularly well developed in areas with stable water levels and without tidal effects, such as in the Baltic Sea. Depending on the length and gradient of the shore slope, one to three bars are formed from 1 m b.s.l. and downwards (Leont'ev, 2004). Modern submarine bars have been described from e.g. the Mediterranean (King, 1972) and the Baltic Sea, e.g. the Curonian Spit (Zilinskas and Jarmalavicius, 2007). However, these features have not been used to infer past water level changes. In western Blekinge, a roughness analysis



Figure 19. The deepest rooted pine stump found at Haväng (HAV126), located in sub-area C at 20.7 m b.s.l. Photograph Arne Sjöström.

(Wilson *et al.*, 2007) indicated a steep slope feature at approximately 5 m b.s.l. in the protected Matvik Bay area, located in the inner Hällaryd Archipelago (Figure 10). This feature has not been dated, and therefore not constrained to a specific period, but its position about 1 m below the proposed lowstand level of 4 m b.s.l. suggests a formation during the Initial Littorina Sea Stage, when the water level was relatively stable during an extended period (Hansson *et al.*, submitted). If formed during the Initial Littorina Sea Stage, the bar was situated about 1 m b.s.l., and the proposed formation was by wave activity in a calm and narrow bay where glaciofluvial material was readily available. The narrow bay setting prevented larger waves to erode the feature and hampered the formation of deeper bars. Furthermore, since the Initial Littorina Sea Stage the water level has never been as low (Berglund *et al.*, 2005), which has protected the bar from later erosion by wave activity. However, using submarine bars as a standalone indicator for past water levels, especially without any chronological constraints is a rather useless method. Apart from the problem of dating, the major uncertainty lies in the uncertain depth of the bar below the contemporaneous water level, as there is a possibility of erosion of bars situated above and below, which would give an erroneous water level estimation. However, if used together with more robust water level indicators, submarine bars could help constrain the uncertainty of the reconstructed level.

Stationary fishing constructions are mounted in the bottom sediments of rivers, lagoons or the sea (*e.g.*

Fischer, 2007). Numerous constructions dated to the mid- to late Mesolithic and the Neolithic have been found in Danish waters, typically consisting of wickerwork fences made of hazel rods with a basketry trap of willow (Fischer, 2007). In order to allow maintenance of these constructions, they were placed in shallow areas where the water depth was not more than a few metres (Fischer, 2007; Mortensen *et al.*, 2015). This means that, if found *in situ*, the constructions can provide information on past water level fluctuations. However, it is likely that the constructions were frail and easily destroyed by wave action (if located in the sea), since finds of fragmented fishing constructions greatly outnumber the number of undestroyed traps found (Fischer, 2007), meaning that most of the constructions were not discovered in their *in situ* position. Regarding the fishing constructions at Haväng (Figures 20 and 21), eight of which have been found across sub-area A (Figures 7 and 13), their preservation is due to embedment by organic sediments, meaning that the fishing constructions either were displaced, possibly by floods or storms, and drifted to their places of deposition, or somehow abandoned and covered by organic sediments in their original positions. At least one of the fishing constructions at Haväng shows signs of being preserved *in situ*. The two ^{14}C dated fishing constructions, situated at 12 m b.s.l. and 6 m b.s.l., have an age-depth relation in agreement with the reconstructed shoreline displacement (Figure 22), indicating that fishing constructions can be used for estimation of lowstand levels, although the uncertainty of their positions in relation to the contemporaneous water level



Figure 20. A stationary fishing construction (HAV027) made of hazel rods found at 6.3 m b.s.l. embedded in organic sediments. The legs of the ruler measure 1 m each. Photograph Arne Sjöström.



Figure 21. Close-up of a stationary fishing construction (HAV027) made of hazel rods found at 6.3 m b.s.l. embedded in organic sediments. Diver in the photograph Beesham Soogrim. Photograph Arne Sjöström.

lead to an error of several metres.

Shoreline displacement reconstructions

Several types of archives have been used for the reconstruction of shoreline changes at Haväng, such as wood remains, sediment stratigraphy and archaeological artefacts. At Haväng, the water level lowstands are, as discussed above, well recorded, whereas the highstand levels have been more difficult to distinguish. During periods when the water level was situated above the present-day level, the position of the shoreline has not been recorded in the submerged landscape. In order to obtain shoreline level information for these periods, interpolations between levels from sites north and south of Haväng have been used to estimate the corresponding level at Haväng. Interpolated levels do not have the same accuracy as levels obtained on-site and they should only be seen as estimates of the level. For example, the interpolated Ancylus Lake maximum level at Haväng was calculated to 2 m b.s.l. (Hansson *et al.*, 2018), whereas later studies of the stratigraphy covering the transition from the Ancylus Lake Stage to the Initial Littorina Sea Stage indicated that the maximum level did not exceed 5 m b.s.l. (Hansson *et*

al., 2017a), meaning that the interpolations most likely have an error of at least a few metres.

Submerged rooted stumps are reliable indicators of past water level fluctuations, as they must have grown above the past water level and have most likely died by drowning in direct connection to the transgression. The timing of the transgression can be well constrained when working with rooted trees (positioned *in situ*) using a combination of ^{14}C dating and dendrochronology. However, obtaining the year of death of a tree is complicated by erosion of the stumps and stems, as the outermost annual rings are most often missing from the salvaged trees. This means that the age of the tree could be several hundred years younger than the obtained dates show, but in most cases, the number of missing rings can be estimated to between 50 and 75. The number of estimated missing rings is subsequently subtracted from the obtained calibrated ages. Furthermore, when reconstructing the Ancylus Lake transgression, the record was shifted about 60 years towards the present in order to account for the fact that the trees probably died when water level was 2–3 m below the base of the tree due to the rise in ground water level during the transgression. Even when considering the dating difficulties mentioned above, the tree ages are generally more precise than ages obtained from most other shoreline displacement archives. By plotting all the dated tree samples together with the reconstructed shoreline displacement, it is evident that the non-rooted stems, which were not used in the reconstruction of the Ancylus Lake transgression, in general exhibit an age-depth relation in accordance with the timing of the Ancylus Lake transgression (Figure 22). This means that at Haväng, the non-rooted stems have been deposited close to their *in situ* position.

The Haväng sediment sequences have been used to infer whether their deposition occurred in a transgressive or regressional setting. The sequences dated to the Yoldia Sea and Ancylus Lake Stages were deposited in a riverine environment and consequently plot above the reconstructed shoreline displacement record (Figure 22). The Initial Littorina Sea Stage sequence, which consists of lagoonal sediments, has been used to constrain the level of the Initial Littorina Sea Stage lowstand (Figure 22). As the water level in the lagoon was at level with the Baltic Basin and the water depth in the lagoon was at least 1–2 m, the deposition of the organic sediments occurred at least 1–2 m below the water level of the Baltic Basin. Consequently, the lowstand level was determined to 2 m above the level of the top of the outermost coast-parallel organic sediment ridge. Among the discovered archaeological objects, only the stationary fishing constructions can be used for shoreline reconstructions, as discussed above. The recovered bones and antlers are refuse material from settlements, which were placed or thrown in the river and lagoon, meaning that their depth positions are not representative of the contemporaneous water level. However, the location of the refuse material indicates proximity to the former shoreline or lagoon/river

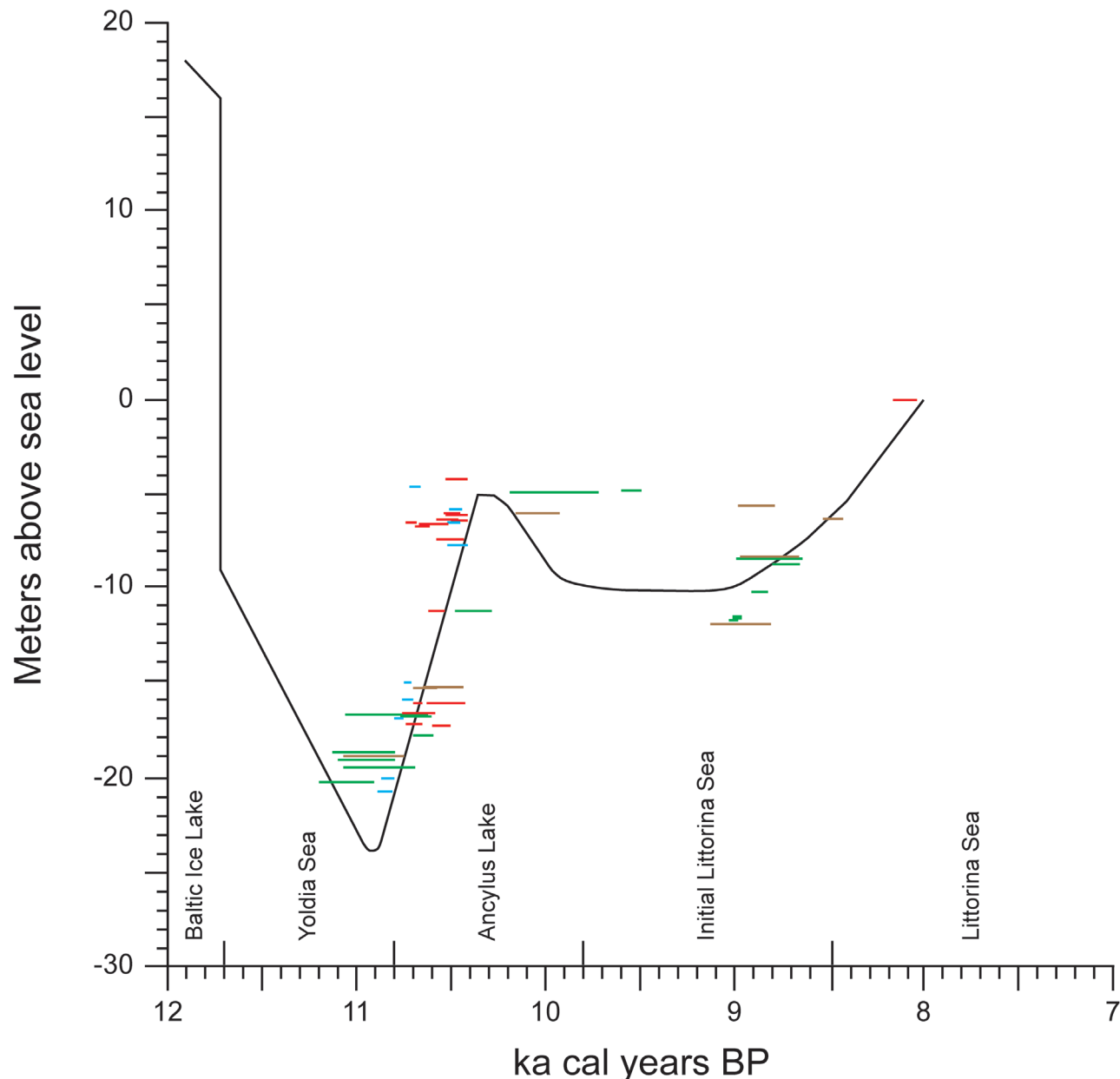


Figure 22. Shoreline displacement reconstruction for the early Holocene at Haväng. Calibrated ^{14}C ages (Table A1) from all dated samples at Haväng; rooted stumps (blue), non-rooted stems (red), archaeological artefacts (brown) and organic sediments (green), are represented by coloured bars.

bank. Together, the combination of these archives have contributed to a robust reconstruction of the shoreline displacement in the Hanö Bay during the early Holocene, which have increased our understanding of the Baltic Basin lowstand phases.

Potentials and limitations of the tree-ring material

A great effort has been put into sampling and analysis of tree-ring series in the stumps and stems from Haväng and western Blekinge. In total, 79 trees were sampled at Haväng, while 8 trees were sampled in western Blekinge (Table A2). In addition, ring-width measurements from 38 trees at Haväng, sampled during the 1980s and in 2009, were available for the dendrochronological analysis. The initial aim of the tree-ring analysis was not only to reconstruct the shoreline displacement,

as discussed above, but also to reconstruct local climate changes during times of tree-growth in the presently submerged coastal areas (*cf.* Edvardsson, 2013). However, due to the nature of the dendrochronological material, the latter has not been possible. The tree-ring pattern is a reflection of many factors, such as temperature, precipitation, wind stress, soil stability and forest dynamics, which determine the width of each ring (Schweingruber, 1996). The trees sampled at Haväng have been growing in a sandy, unstable substrate, meaning that the tree-ring pattern to a large extent is influenced by changing local conditions rather than more regional precipitation and temperature variations. The local tree-ring signal, together with the often low number of rings (<75) (Table A2), have made cross-dating of the samples difficult, and many samples have not been possible to match. Furthermore, damage to the living trees, *e.g.* by deer rubbing their velvet antlers and post-depositional compaction of the wood remains



Figure 23. A non-rooted pine stem (HAV055) located at 4.2 m b.s.l. The sample has been compacted by overlying sediments, which has disturbed the tree-ring pattern. Photograph Arne Sjöström.

(Figure 23) have also contributed to non-representative tree-ring records in a palaeoclimate perspective.

Three main chronologies from Haväng have been constructed based on cross-dating of individual tree-ring series. Chronology 30110019 (Figure 24a) contains 23 samples and spans 229 years. Wiggle-match dating yielded an age span of 10,700–10,600 to 10,500–10,400 cal BP. Chronology 30110029 (Figure 24b) contains 14 samples and spans 216 years. Wiggle-match dating yielded an age span of 10,850–10,800 to 10,650–10,600 cal BP. Chronology 30110039 (Figure 24c) contains 5 samples and spans 189 years. Wiggle-match dating yielded an age span of 10,850–10,750 to 10,700–10,600 cal BP. The trees that were used for construction of the chronologies have been stacked, sorted according to the ending year and subsequently grouped based on the depth of each sample below the present sea level. By examining the older chronology 30110029 and the younger chronology 30110019, it is evident that, with a few exceptions, the samples show an age-depth dependency. As the samples used to construct the chronologies are non-rooted, this shows that the non-rooted trees generally have not drifted far from their growth positions after they died. The gradients of the ending-year distributions can be used as an independent means of estimating the rate of the Ancylus Lake transgression, although these estimates are somewhat uncertain as the exact growth positions of the trees are unknown and their years of death are uncertain. However, by drawing a straight line through the ending years of samples with preserved sapwood (as their outermost rings are close to the year of death) in chronology 30110019 (Figure 24a), a transgression rate estimate is obtained, which is 10–20% higher than the rate obtained by the more robust age-modelling approach based exclusively on rooted stumps (Figure 14). Contrary to the wiggle-match dating, dendrochronology has the advantage of calendar-year age determination, but more rooted samples with preserved sapwood/bark would be needed to allow more robust conclusions.

The few trees obtained from Blekinge indicate a higher potential for obtaining a regional, and hence climatic,

signal in the tree-ring pattern than from the trees at Haväng. This is most likely due to the fact that the substrate and forest dynamics in western Blekinge were of a different character than at Haväng. The submerged trees in western Blekinge seem to have been growing in a proper forest setting with more stable substrate conditions, as opposed to the unstable and sandy soils at Haväng. In order to fully explore the palaeoclimatic potential of the submerged trees in the Hanö Bay, the future focus should be on the trees from Blekinge, although sampling and cross-dating of at least 100 trees will probably be needed to obtain robust chronologies.

On the preservation of submerged landscapes

How is it possible that submerged landscapes can withstand destruction for up to more than 100,000 years, and what factors govern their preservation? Submerged landscapes have been found in a wide range of contexts, from coastal and intertidal zones to deeper waters offshore, in areas with varying geological and bathymetric conditions (Flemming *et al.*, 2017c). There are several parameters in play in order for a submerged landscape to withstand destruction to become preserved to today. The burial and survival are dependent on interactions between environmental factors, coastal configuration and geodynamics, biological interactions and geochemical processes. In the short-time perspective, an artefact needs to be protected from destructive wave activity during the time of inundation, either by a protective sediment cover or by weak wave activity. However, even during times of rapid transgression, an object would have been exposed to wave activity for at least several decades. When inundated, topographic features such as rock outcrops, lagoons, sand spits and estuaries could provide shelter for the artefacts (Masters and Flemming, 1983). In the longer perspective, sites situated in deeper waters, below the storm wave base, are less prone to destruction than sites located in more shallow waters, and therefore it is possible that sites found in shallow waters are only seen during a brief period between exposure and erosion (Flemming *et al.*, 2017c).

In the Baltic Sea region, the predominant wind direction is from the west, which leads to less exposure to both mean and extreme wave activity along the east-facing coasts compared to the west-facing coasts (Rosentau *et al.*, 2017; Tuomi *et al.*, 2011). Consequently, the conditions for preservation of submerged landscapes are generally favourable in the Hanö Bay and in the south-western Baltic Basin. At Haväng, the preservation of the submerged landscape and its artefacts is dependent on the aquatic environment in which the landscape was once formed. The submerged landscape consists of riverine and lagoonal sediments, which have been able to withstand wave and current erosion, whereas the surrounding terrestrial environment has not been preserved. The undulating glaciolacustrine landscape seen today above the present sea level likely

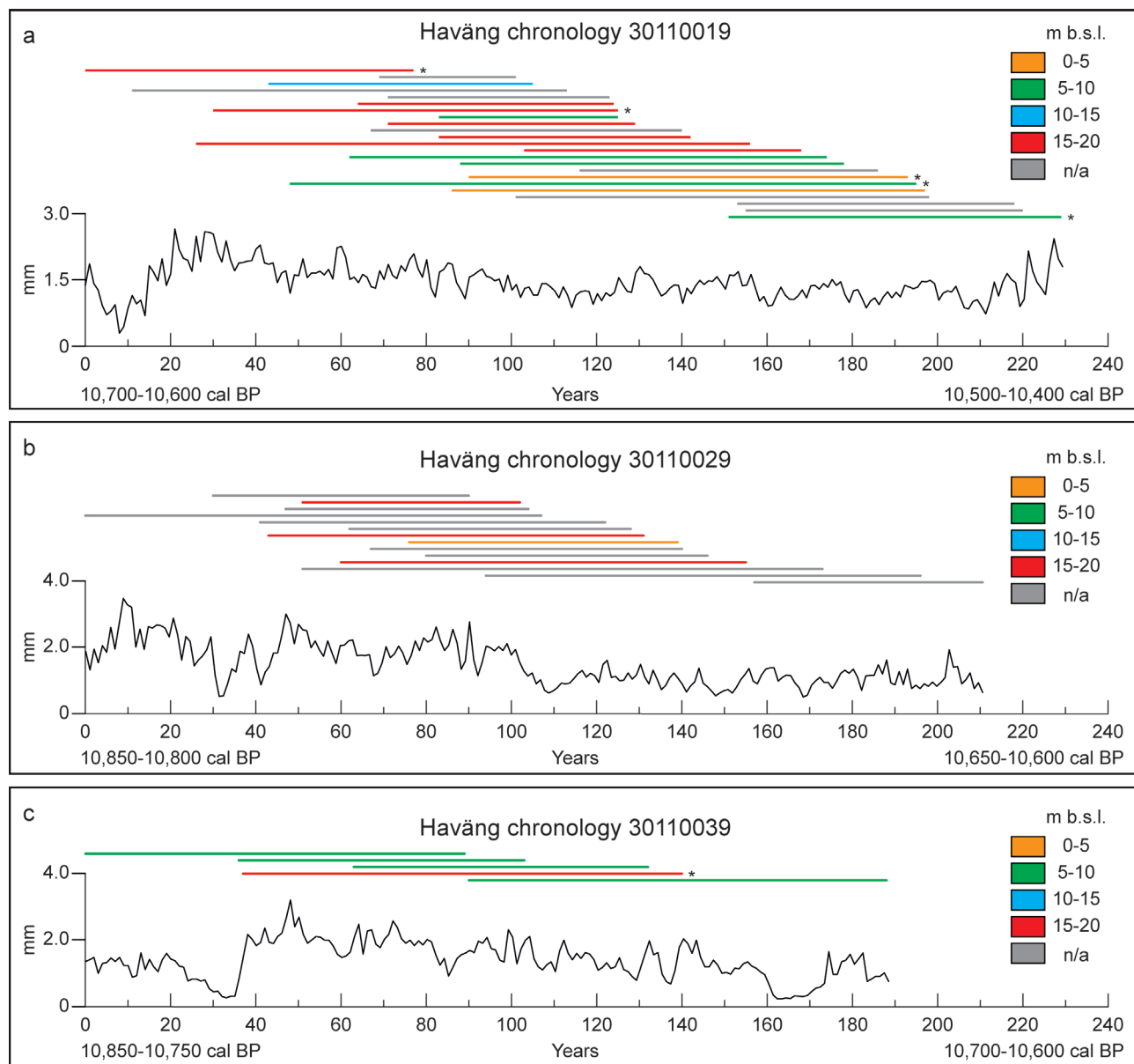


Figure 24. Ring-width chronologies constructed from trees sampled at Haväng. The samples are stacked, sorted by ending year and grouped into four categories based on the depth below sea level of each sample (orange 0–5 m, green 5–10 m, blue 10–15 m, red 15–20 m). Ring-width measurement from samples obtained from previous studies lack depth information. Samples marked with asterisks have sapwood preserved.

extended out on the exposed soils during the lowstand periods. The easily erodible glaciolacustrine sediments were then eroded during the Ancylus Lake and Littorina Sea transgressions. It is possible that the organic sediments were covered by the surrounding sandy and silty deposits during the Littorina Sea transgression, protecting them from destructive processes. The fine detritus gyttja deposited during the Initial Littorina Sea Stage has a stiff character, in fact so stiff that it prevented the vibro corer from penetrating the sediments at several locations. This stiffness could imply compaction by a now eroded sediment cover. The site would then have become uncovered by waves and currents at some point in time, transporting the covering sediments seawards. However, in the deeper parts of the submerged landscape, the rooted stumps suggest that little or no net accumulation of sediments has taken place since inundation. Instead, a few ‘spider stumps’ (Figure 25) have had their root systems exposed by

erosion, showing that the soil surface was situated, at least locally, about a metre above the present seafloor.

Most of the archaeological artefacts have been found embedded in the fine detritus and calcareous gyttjas, which have acted as protective covers already before inundation of the landscape. However, a few bones have been found situated on top of the sediments, indicating either a landscape that has undergone neither erosion nor deposition since inundation or that the artefacts were covered by protecting sediments and subsequently found in the (short) time between exposure and destruction. The fishing constructions, situated on top of the organic sediment ridges, are exposed to erosive wave and current activity. Due to sand drift, the constructions are sometimes exposed and sometimes covered, which tears on the wooden material. One fishing construction has been almost completely destroyed since its discovery.



Figure 25. A 'spider stump' found at Haväng. Erosion has exposed the root system of the tree, indicating that the soil surface was situated, at least locally, above the present seafloor. Diver in the photograph Beesham Soogrim. Photograph Arne Sjöström.

The stumps and stems are, in most cases, found protruding from the organic sediments, indicating that the preservation depends on a protective cover. However, there are exceptions where stumps and stems have been preserved without protection by organic sediments, indicating that several factors need to be considered in order to understand the process of wood preservation. Stumps and stems from the Ancylus Lake Stage have been preserved, but no stumps or stems from the Initial Littorina Sea Stage have been found, indicating that the transgression rate is an important preservation factor. During the Ancylus Lake transgression, the water rose by approximately 4 cm year⁻¹ (Hansson *et al.*, 2017a), whereas during the early parts of the Littorina Sea transgression, the rate was considerably lower. Since it is assumed that the trees died prior to inundation, the rate of transgression will determine how long the trees are exposed to terrestrial decay processes, which in turn will determine if the trees can withstand erosive forces under water. Consequently, the comparably slow transgression rate during the Initial Littorina Sea Stage most likely meant that the trees were more or less totally decomposed before the water level reached their growth positions. After inundation, the lack of shipworms, due to the brackish conditions in the Baltic Basin, is vital for the preservation of the wood remains. However, increased water temperatures in the Baltic Sea, as an effect of climate change, are aiding the shipworms to adapt to lower salinity, which will cause severe problems not only for stumps and stems, but also for shipwrecks and other wooden structures (Perez-Alvaro, 2016).

The submerged landscape in western Blekinge has a different character than the one at Haväng. In western Blekinge, the archipelagic setting means that leeward areas are sheltered from wave erosion, whereas areas facing the sea are more exposed. The wood remains are generally found in sheltered areas and their preservation does not seem to be related to a protective sediment cover, contrary to the situation at Haväng. The tree preservation is sometimes aided by instantaneous inundation, as seen east of Sternö (Figure 10), where stems appear to have fallen to the seafloor during

scree events. Even though the submerged landscape in western Blekinge is less explored than at Haväng, it seems that the landscape does not only reflect aquatic environments. Instead, terrestrial palaeo-surfaces have been preserved in some areas, which have the potential of preserving settlement sites, rather than 'just' refuse material.

In conclusion, the submerged landscapes at Haväng and in western Blekinge show that preservation depends on a complex interplay between deposition and erosion, on a range of scales. Factors such as transgression rate and protective sediment covers are important but evidently not critical for preservation of artefacts in sheltered areas. An overarching factor important for the survival of the submerged landscapes is the prevailing wind regime protecting the Hanö Bay from extreme wave activity. Despite these favourable conditions, the future of the submerged landscapes in the Hanö Bay is not certain. As mentioned above, the invasion of shipworms into the Baltic Basin poses a real threat to the wooden remains. When diving in the Haväng area, we see destruction of the sediment ridges caused by anchoring boats and fishing nets (Figure 26), and the military activities in the area tear on the landscape. In theory, all Swedish archaeological sites and culture landscapes, above and below the water surface, are protected by the Swedish culture heritage law (*Kulturmiljölagen*) (Riksantikvarieämbetet, 2014). However, submerged landscapes such as at Haväng are difficult to protect as they consist of a mix of cultural and natural heritages and to determine what should be protected is not obvious. Should only the immediate area surrounding the fishing constructions and the other known artefacts be protected, or should the entire landscape be protected, based on the high potential for finding more exceptional artefacts in the area? One way of protecting these submerged landscapes is by establishing marine national parks and nature reserves, but so far, only a few exists in Sweden. One example is the nature reserve at Sternö (Figure 10), which comprises an area with submerged stumps and stems down to a depth of about 20 m b.s.l. east of the Sternö Peninsula (Olsén, 2014). However, the knowledge about



Figure 26. Destruction of a sediment ridge, either by an anchoring boat or by fishing nets. A rope has sliced off the top part of the ridge. Diver in the photograph Beesham Soogrim. Photograph Arne Sjöström.

submerged landscapes, and their exceptional geoarchaeological potential, is still low among legislators, but recent media attention and research output, such as this thesis, will hopefully increase this awareness, which could lead to a better legislative protection of submerged landscapes in the near future.

Reflections on combining geology and archaeology

Quaternary geologists and archaeologists are, to a great extent, interested in similar topics, such as climate and landscape reconstructions and human-environment interaction, and by approaching a site from both disciplines, I believe the final result can be greatly enhanced, as the outcome of the geoarchaeological studies at Haväng have proven. For example, working in a geoarchaeological environment has led to some interesting discussions regarding the role of humans in the early Holocene landscape. Geologists tend to view humans as passive inhabitants in the landscape prior to the introduction of agriculture about 6000 years ago, and in most cases a geologist argues that natural processes have shaped the observed remains or phenomena, whereas an archaeologist tends to interpret the same remains or phenomena as a result of human activity. These opposing views have been played out in discussions regarding forest fires and the origin of damages and scars on wood remains from Haväng. Most often this has resulted in a compromise, where both natural and human related interpretations have been presented. When reconstructing the landscape and vegetation, the geoarchaeological approach has proven fruitful. Worked animal bones and antlers do not only indicate human activity but the animals themselves can add to the knowledge of the past landscape. For example, aurochs bones indicate that the landscape must have been relatively open in order to accommodate these large ruminants, while beaver bones indicate that parts of the riverine landscape were dammed wetlands. The food preferences of the discovered animals do also facilitate the reconstruction of the past vegetation.

The multidisciplinary approach has enabled interesting offshoots from the core aims of this thesis, of value for both geologists and archaeologists. In cooperation with the Centre for GeoGenetics at Copenhagen University, we are currently working with analysing ancient sediment DNA from organic sediments sampled at 16.4 m b.s.l. at Haväng, dating to the Ancylus Lake Stage. DNA deposited in frozen and non-frozen sediments can be extracted in order to obtain genetic data from past environments (Haile *et al.*, 2007) and sediment DNA has been used to reconstruct *e.g.* past vegetation, fauna and human dispersal (*e.g.* Jørgensen *et al.*, 2012; Olajos *et al.*, 2018; Slon *et al.*, 2017; Smith *et al.*, 2015). At Haväng, we are particularly interested in investigating microorganism DNA as a human indicator and DNA from the marine mammal fauna, as these groups have not been represented in the osteolog-

ical material. Another study in progress is lipid-based palaeo-temperature reconstructions (*e.g.* Peterse *et al.*, 2012; Tierney, 2012) based on the highly resolved sediment sequences from Haväng.

After having been working with the archaeological aspect of the Haväng site, it is quite clear that the human communities affected the landscape they lived in, and I think it is time to re-evaluate the importance of human impact on the landscape during the early Holocene. Maybe we should start to look at the Mesolithic communities as managers of the landscape, meaning that they promoted the growth of certain taxa that they were in need of, while consequently, unimportant taxa were suppressed. For example, hazel was used both as a food source (hazelnuts) and as building material for the fishing constructions and the humans were consequently in need of healthy hazel stands. Another example is the management of pine trees. Some pine stems show scars and features, which would have made the wood rich in tar (Figure 27), that could be connected to the production of pine torches found on the seafloor at Haväng. The stationary fishing constructions in themselves indicate a relatively large population, as large amounts of fish could be caught. At the contemporary Norje Sunnansund settlement, situated at the Listerlandet Peninsula, evidence of a subsistence based on large-scale fishing and mammal hunting strongly suggests that the settlement was inhabited year-round (Boethius, 2018). Haväng and Norje Sunnansund have many common features, such as their coastal location and a large scale fish-based subsistence, which suggest that also Haväng could have been inhabited year-round. Together, the two settlements contain evidence of the subsistence chain, as Haväng shows the fish catching process, while Norje Sunnansund shows the processing



Figure 27. A hollow pine stump found in sub-area B at Haväng, possibly indicating pine-torch production. Photograph Arne Sjöström.

and preservation of the catch (Boethius, 2016). Furthermore, keeping and maintaining such attractive fishing waters as the lagoon at Haväng also raises questions regarding the development of territoriality during the Mesolithic.

Outlook - submerged landscapes in the Baltic Sea

Various types of submerged landscapes have been discovered in the southern Baltic Basin since the earliest parts of the 20th century (Figure 1). In Denmark, there is a long underwater archaeology tradition, and at present around 1500 sites, most of them from the late Mesolithic, have been found (e.g. Fischer, 1993a, 1995, 2011). Although flint finds are most common, preservation of organic objects such as wood, bones and antlers is found at many sites. Numerous fragmented and complete stationary fishing constructions from the late Mesolithic and early Neolithic have been discovered indicating a subsistence dominated by fish (e.g. Fischer, 2005, 2007; Pedersen, 1997). Furthermore, rooted pine stumps dated to about 10,100 cal BP have been recovered from the Store Belt Strait along the former Dana River (Fischer, 1997) (Figure 28). In the Öresund Strait, worked flint was discovered in the 1930s at Pilhaken, outside the Saxån River outlet south of Landskrona (Larsson, 2017) (Figure 28). Several later excavation campaigns have revealed three early Mesolithic settlements consisting of organic artefacts such as bones, hazelnuts and burned wooden sticks situated at the Saxån River palaeo-river mouth (Fischer, 1993b; Larsson, 1999). On the southern coast of Skåne, outside the Kabusa and Nybroån River mouths (Figure 28), a submerged landscape with preserved organic sediments and stumps and stems has been discovered by the 'Haväng research team' (Figure 29). Pollen analysis of the organic sediments dates the landscape to the

Initial Littorina Sea Stage, but most likely the stumps and stems date to the Yoldia Sea Stage. Further investigations of the area are ongoing.

Submerged landscapes in German waters have been discovered in e.g. the Kiel and Wismar Bays (Figure 28). In the Kiel Bay, findings of an oak trunk at 6 m b.s.l. led to further excavations in the immediate area where flint tools and organic artefacts such as worked animal bones, leister prongs and human bones, dated to the Ertebølle period, were discovered in organic sediments (Goldhammer and Hartz, 2017). $\delta^{13}\text{C}$ values of the human bones showed signs of a marine-based diet. In the Wismar Bay, the seafloor is partly covered by organic sediments, outlining the shape of relict riverbanks and shorelines. Here, excellent preservation conditions enabled the discovery of various organic and lithic remains from several Late Mesolithic sites (Jöns and Harff, 2014; Lübke *et al.*, 2011). Fish bones from the oldest site show a diet dominated by freshwater fish, followed by a transition towards a reliance of marine fish at the younger sites (Lübke *et al.*, 2011). From one of the younger sites, parts of a fishing construction and leister prongs, dated to about 7000 cal BP, were recovered (Hartz and Lübke, 2006).

No submerged archaeological sites have been found along the Polish and Lithuanian coasts, but several areas with abundant wood remains hint at the archaeological potential. Outside the northern part of the Curonian Spit, in Lithuania (Figure 28), rooted and non-rooted pine remains, dated to 11,100–10,500 cal BP, have been discovered down to a depth of about 30 m b.s.l. (Žulkus and Girininkas, 2012). In the Gdansk Bay (Figure 28), alder and oak trunks were recovered from 16–17 m b.s.l. (Uścińowicz *et al.*, 2011). The trunks were found in organic sediments overlain by sand and were dated to about 8000 cal BP. Further to the east, in the Vistula Lagoon (Figure 28), alder stumps found a few m b.s.l. have been dated to between 6000–3500 cal BP (Łęczyński *et al.*, 2007).



Figure 28. Map of the southern Baltic Basin. The locations of submerged landscapes mentioned in the text are marked: (A) Kiel Bay (B) Store Belt (C) Wismar Bay (D) Pilhaken (E) Kriegers Flak (F) Kabusa and Nybro (G) Gdansk Bay (H) Vistula (I) Curonian Spit. Base map © EuroGeographics.

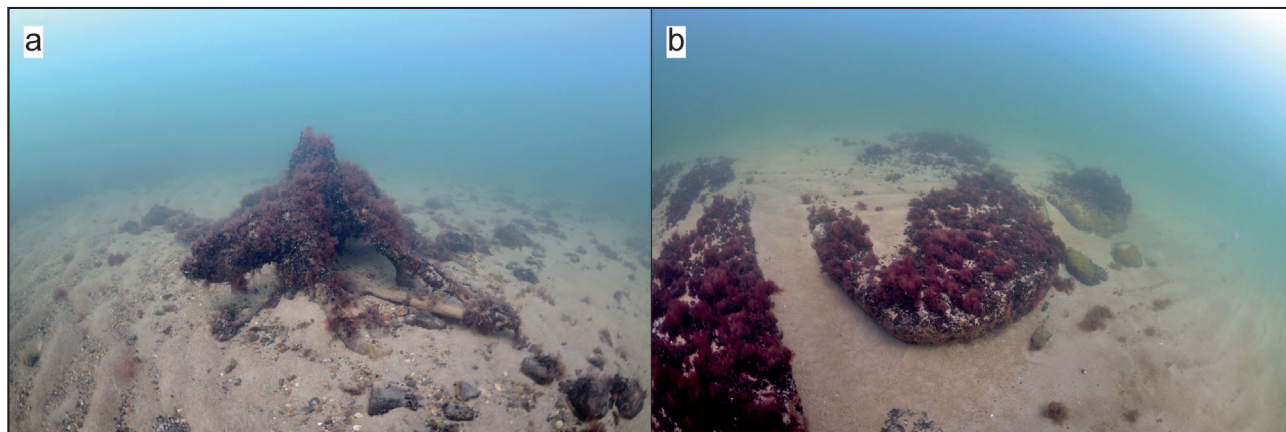


Figure 29. Photographs of the submerged landscape outside the Kabusa and Nybroån River mouths. (a) A rooted pine stump outside the Kabusa River mouth. (b) Organic sediments outside the Nybroån River mouth. Photographs Arne Sjöström.

All of the submerged landscapes from the southern Baltic Basin mentioned above show similarities with the submerged landscapes in the Hanö Bay. Sites located at river-mouths and lagoons have a comparably high chance of being preserved due to the organic embedding of wooden objects, bones and antlers. The archaeological sites in Denmark and Germany, contrary to the Hanö Bay, contain abundant flint remains, which is most likely an effect of the lack of proper archaeological excavations at Haväng. Stationary fishing constructions were evidently common in the southern Baltic Basin during the Mesolithic, and were used in both marine and freshwater settings. Based on these similarities between the sites, the question then arises: is it possible to apply predictive modelling for location of further submerged sites? This issue has been a long-standing goal within the research community (Flemming *et al.*, 2017c). Based on the many submerged sites in Danish waters, Fischer (1995) developed the *fishing site location model*, predicting the location of sites based on the ideal location for using standing fishing gears, which has had regional success. However, the location of a site was not only determined by geography, but vegetation patterns and complex social and cultural factors were also involved in choosing a settlement location (Groß *et al.*, 2018; Grøn, 2012), and in a global perspective, there is no efficient model applicable to a wide range of environments (Benjamin, 2010; Flemming *et al.*, 2017c). In the southern Baltic Basin, submerged archaeological sites are most commonly found in organic sediments in connection to palaeo-channels and river mouths, which consequently are key features for the discovery of further submerged landscapes. Multibeam echo sounding surveys outside present-day river mouths can locate areas with preserved organic sediments, which after mapping can be thoroughly investigated by diving archaeologists and geologists. Although these coastal sites were attractive for human populations, they might be overrepresented due to their good preservation in the organic sediments, while sites located inland are not discovered/preserved. However, new acoustic techniques for locating knapped flint are under development (Grøn, in press), which could facilitate the discovery of submerged inland sites.

Due to the fluctuating and dynamic shoreline history in the southern Baltic Basin, it is possible to find submerged landscapes and archaeological sites from the whole Holocene; in southernmost Sweden, submerged landscapes can be found from the early and mid-Mesolithic about 11,700 to 8000 years ago, while along the German and Polish coasts submerged landscapes can be found from the Mesolithic, Neolithic and up to present due to the land submergence (*e.g.* Lampe, 2005; Uścinowicz, 2006). Furthermore, terrestrial sediments from *e.g.* the Kriegers Flak (Figure 28), dated to about 41,000–36,000 cal BP (Anjar *et al.*, 2010), indicate the possibility of finding submerged landscapes dating to the late Pleistocene in the Baltic Basin. The Hanö Bay region and Lithuania are the only areas in the Baltic Basin so far with remains dated to the Yoldia Sea Stage. However, the Yoldia Sea lowstand levels in the southernmost Baltic Basin were positioned at 40 to 50 m b.s.l., which make the discovery and excavation of potential coastal sites more difficult. Surveying and excavation of these deep areas will in the near future be easier due to the rapid development of remotely operated underwater vehicles (ROV). By compiling the lowest water levels at several locations in the southern Baltic Basin; Oskarshamn 0 m b.s.l. (Svensson, 1991), Blekinge 20 m b.s.l. (Hansson *et al.*, submitted), Haväng 25 m b.s.l. (Hansson *et al.*, 2017a), Arkona Basin 40 m b.s.l. (Bennike and Jensen, 1998), Gdansk Bay 50 m b.s.l. (Uścinowicz, 2006), Lithuania 50 m b.s.l. (Živilė Gelumauskaitė, 2009), Pärnu 2 m b.s.l. (Habicht *et al.*, 2017), Tallinn 0 m b.s.l. (Muru *et al.*, 2017), a map of the ‘lowest shoreline’ has been produced (Figure 30). The ‘lowest shoreline’ is not synchronous, but the map shows the parts of the seafloor in the Baltic Basin which at some point in time have been exposed, and where the discovery of submerged landscapes is possible.

Summary and conclusions

The world under the sea is key for our understanding of past landscapes and cultures. This thesis advances our knowledge about the coastal landscapes during the early Holocene and highlights the great potential of underwater research by combining several disciplines.

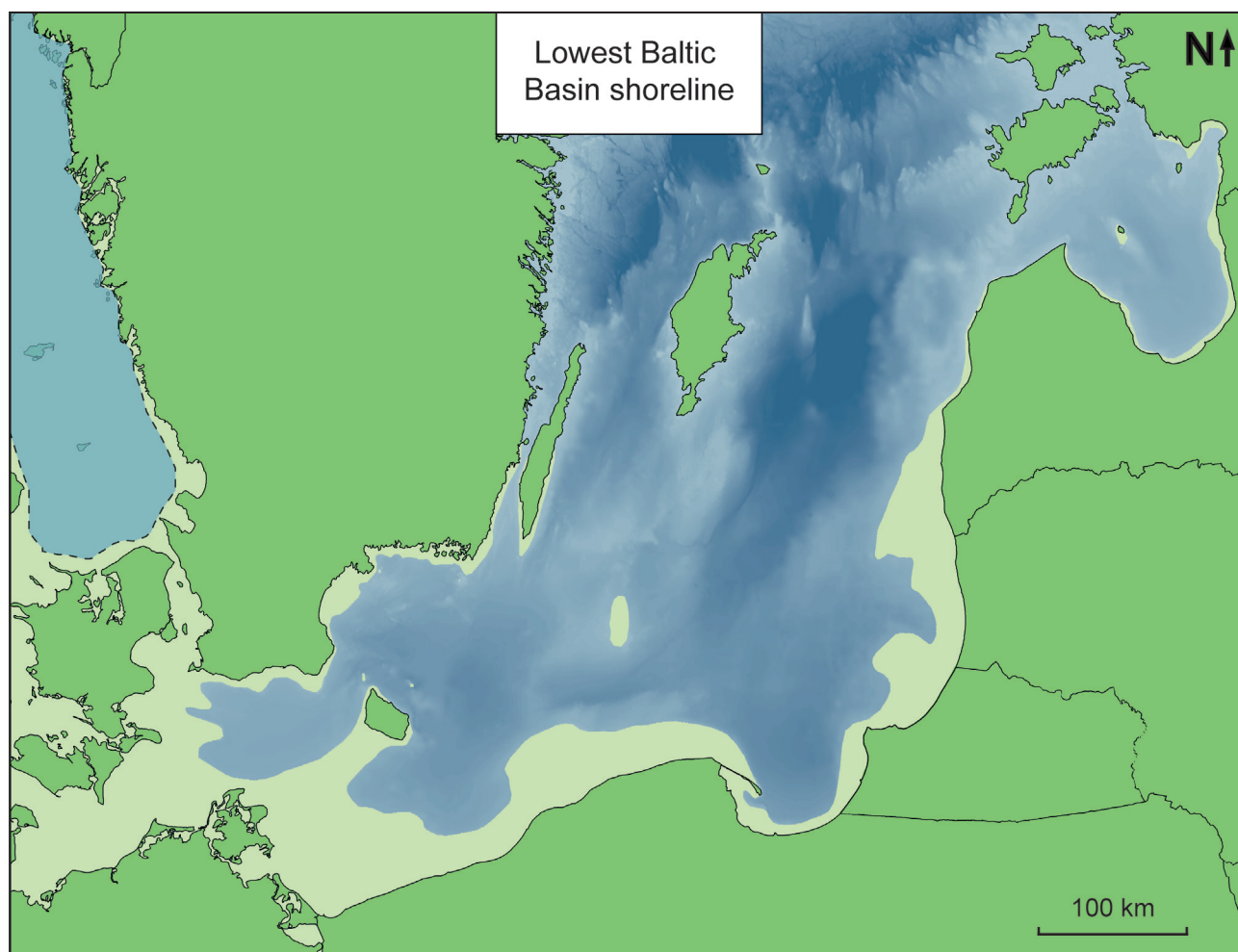


Figure 30. The lowest Baltic Basin shoreline. The map shows an estimation of the areas of the present Baltic Basin seafloor that at some point, since the last deglaciation, have been exposed, *i.e.* areas where it is possible to locate submerged landscapes. The reconstruction is based on the lowest shoreline levels at Oskarshamn, Blekinge, Haväng, the Arkona Basin, the Gdansk Bay, Lithuania, Pärnu and Tallinn and interpolations between the above-mentioned sites. The estimation of the lowest shoreline of Kattegat has been marked by a dashed line. Base map © EuroGeographics. Bathymetry data © EMODnet.

The research carried out at Haväng has refined the local shoreline displacement and shed new light on the way of life during the Mesolithic. Furthermore, these results have been put in a regional context, showing the interplay between landscape changes and subsistence strategy development in southern Scandinavia. The main conclusions from the studies in this thesis are presented below:

- The research from Haväng has refined the local early Holocene shoreline displacement history. Based on submerged rooted tree stumps it is concluded that the Yoldia Sea lowstand level was 24–25 m b.s.l., and that the subsequent Ancylus Lake transgression started at about 10,800 cal BP and lasted for approximately 500 years with a mean rate of 4 cm yr⁻¹. The maximum level of the Ancylus Lake was determined to approximately 5 m b.s.l. During the subsequent Initial Littorina Sea lowstand, the water level was determined to about 10 m b.s.l., based on the occurrence of lagoonal sediments.
- During the Yoldia Sea Stage, the Verkeån River extended across the exposed coastal areas. The landscape was characterized by an open wood-

land dominated by pine and grasses. After the onset of the Ancylus Lake transgression, the river developed into a shallow, slow-flowing nutrient-rich stream characterized by ponds and wetlands. The area developed into a highly productive lagoon with a slight brackish influence during the subsequent Initial Littorina Sea Stage. Now, a more closed forest with both deciduous and coniferous trees established. After the onset of the Littorina Sea transgression, the lagoonal environment was disturbed by the approaching shoreline and was finally inundated at about 8000 cal BP. At the height of the Littorina Sea transgressions, at about 6000 cal BP, the water level was approximately 4 m a.s.l. and the Verkeån River valley turned into a protected bay.

- At the onset of the Mesolithic period, the humans in the Hanö Bay region were mobile hunters, fishers and gatherers with a subsistence strategy which included hunting of aurochs and beaver. During the Initial Littorina Sea Stage (Maglemose), a shift towards a subsistence relying on large-scale freshwater

fishing can be seen. The findings of stationary fishing constructions suggest a development towards a sedentary lifestyle with a year-round presence in the coastal landscape. The findings at Haväng show the importance of river-mouth sites and raises questions regarding the development of territoriality and human impact on the surrounding landscape during the early Holocene.

- By combining geology and archaeology, detailed shoreline displacement records can be obtained, which are vital for reconstructions of past landscape changes. GIS-based landscape and river network reconstructions can greatly aid the predictive modelling for the discovery of further submerged sites by locating past shorelines and river mouths.
- Submerged landscapes are excellent natural and cultural archives of great importance for geological and archaeological research. Coastal settlements contribute greatly to our understanding of the subsistence strategies during the Mesolithic and act as an important complement to the more abundant inland archaeological sites. The study of the submerged landscape at Haväng has proven that a geoarchaeological approach can maximise the research output, providing detailed information on shoreline fluctuations, landscape dynamics and coastal human societies. The unique longevity of approximately 3000 years at the Haväng site enables studies of the coastal development over relatively long periods during the early Holocene. Continued research at Haväng and other newly discovered submerged landscapes will bring further insights into the complex interplay between the coastal landscape, water level changes and the human population during the early Holocene.

Svensk sammanfattning

Under istider, när stora mängder havsvatten var bundet i inlandsisar, var den globala havsnivån lägre än idag och stora delar av kontinentalsockeln torrlagd. Den senaste istiden (cirka 115 000–12 000 år sedan) var inget undantag, då torrlagda områden utvecklades till ekologiskt rika kustområden som möjliggjorde människans spridning över världen. När inlandsisarna smälte steg havsnivån och dessa landskap dränktes. I dag finns rester och lämningar från dessa landskap och dess invånare väl bevarade på havsbotten. I södra Östersjön, där stora områden tidvis har varit torrlagda, är arkeologiska lämningar vanliga på havsbotten. De flesta fynden har gjorts utanför de danska och tyska kusterna, medan de tidig-holocena (11 700–8200 år sedan) undervattenslandskapen vid Haväng i östra Skåne och utanför kusten i västra Blekinge i Hanöbukten är unika för Sverige.

Det övergripande målet med den här avhandlingen är att öka förståelsen för dessa tidig-holocena kustlandskap och dess invånare samt de havsnivåförändringar som torrlade, och sedan dränkte, landskapen.

Högupplöst batymetridata, organiska lagerföljder, provtagning av träd och arkeologiska fynd av dykare och GIS-baserade landskapsrekonstruktioner har använts i detta multidisciplinära projekt för att undersöka Hanöbuktens tidig-holocena havsnivåförändringar, kustlandskapets miljöutveckling och mänskliga resursutnyttjande.

Baserat på åldern och djupet av organiska lagerföljder och rotfasta stubbar från Haväng har de tidig-holocena havsnivåförändringarna rekonstruerats. Den lägsta nivån i Yoldiahavet har bestämts till 24–25 meter under nuvarande havsyta (m.u.n.h.) medan den påföljande Ancylustransgressionen varade cirka 500 år, från 10 800 till 10 300 år sedan, då Ancylussjön steg med ungefär 4 cm per år. Den högsta nivån i Ancylussjön var ungefär 5 m.u.n.h. innan nivån sjönk till som lägst 10 m.u.n.h. i det påföljande tidiga Littorinahavet (cirka 9000 år sedan). Littorinahavet nådde sin högsta nivå på ungefär 4 meter över nuvarande havsyta för cirka 6000 år sedan.

Under Yoldiahavets och Ancylussjöns tid (11 700–9800 år sedan) var Havängsområdet ett relativt öppet kustlandskap med en gles tallskog. Verkeån var vid den här tidpunkten en långsamt rinnande och näringsrik å med inslag av våtmarker och dammar. Benfynd med slaktmärken från uroxer och bäver visar att de människor som bodde i området åtminstone delvis livnärde sig på jakt. När Ancylussjön övergick i det tidiga Littorinahavet utvecklades Verkeåns mynning till en näringsrik lagun och det omkringliggande landskapet var präglat av en tät blandskog. Fynd av flera stationära fiskfällor, daterade till 9000–8400 år sedan, visar att stora mängder fisk kunde fångas och att den mänsk-

liga dieten därför till stor del var baserad på fisk. Detta tyder i sin tur på att människorna kan ha befunnit sig, mer eller mindre bofast, i Havängsområdet året om. Havängsområdet dränktes sedan slutligen av Littorinatransgressionen för cirka 8000 år sedan.

Baserat på den nya strandlinjeförskjutningskurvan från Haväng har det tidigare delvis osäkra tidig-holocena strandlinjeförskjutningsförloppet i Blekinge förfinats. Detaljerade GIS-modellerade paleogeografiska rekonstruktioner av kustlinjens läge och åarnas lopp under dagens havsyta visar på flera tidig-holocena åmynningsområden med hög arkeologisk potential i västra Blekinge.

Undervattenslandskapen har bevarats tack vare generellt skyddade förhållanden i Hanöbukten där den erosiva vågpåverkan är relativt begränsad. Träden och de arkeologiska lämningarna har skyddats av täckande organiska gyttjeavlagringar vilket visar att områden som låg vid laguner och åmynningar har stor chans att bevaras. Trots att dessa landskap bevarats i tusentals år finns det många hot mot deras fortlevnad. Införandet av marina naturreservat är ett sätt att öka skyddet för dessa värdefulla lämningar.

Resultaten från denna avhandling visar att undervattenslandskap kan vara utmärkta arkiv för både naturliga och mänskliga organiska lämningar, samt att ett geoarkeologiskt angreppssätt kan ge detaljerad information om havsnivåförändringar, landskapsdynamik och mänskliga kustersamhällen. Resultaten från Hanöbukten visar i vilken typ av miljö undervattenslandskap kan bevaras, vilket underlättar i sökandet av nya lämningar på havsbotten. Fortsatta undersökningar i Havängsområdet och i andra nyfunna undervattensområden kommer att öka förståelsen för dessa komplexa kustlandskap och dess invånare.

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Table A1. Calibration results and sample details of ¹⁴C dates used in this study, 50 from Haväng and 13 from western Blekinge. The ¹⁴C ages were calibrated using the OxCal 4.2.4 software (Bronk Ramsey, 2009) and the INTCAL13 calibration dataset (Reimer *et al.*, 2013).

Sample number	Site	Depth (m b.s.l.)	Material	Taxa	Lab number	¹⁴ C age (cal yr BP)	Calibrated age (cal yr BP, 1 σ)	D_sequence modelled ('wiggle-match') age corrected for sampled rings (cal yr BP, 1 σ)	U_sequence modelled age corrected for sampled rings (cal yr BP, 1 σ)	P_sequence modelled age (cal yr BP, 1 σ)	Rooted
HAV046	Haväng	0.0	Wood	<i>Pinus</i>	LuS-10926	7315±45	8180–8050	---	---	---	No
HAV055	Haväng	4.2	Wood	<i>Pinus</i>	LuS-11806	9355±50	10,660–10,510	10,530–10,410	---	---	No
HAV076	Haväng	4.6	Wood	<i>Pinus</i>	LuS-11411	9440±50	10,730–10,590	10,720–10,660	---	---	Yes
HMC3	Haväng	4.8	Macro	Mixed terrestrial remains	LuS-12198	8580±60	9600–9490	---	---	---	---
HMC2	Haväng	4.9	Macro	Mixed terrestrial remains	LuS-12197	8930±50	10,190–9940	---	---	---	---
HMC1	Haväng	4.9	Macro	Mixed terrestrial remains	LuS-12196	8820±55	10,120–9710	---	---	---	---
HAV042	Haväng	5.6	Bone	<i>Alces alces</i> , pick axe	LuS-11011	7975±35	8980–8780	---	---	---	---
HAV134	Haväng	5.8	Wood	<i>Pinus</i>	LuS-12028	9340±45	10,650–10,500	---	10,510–10,440	---	Yes
HAV033	Haväng	6.0	Wood	<i>Pinus</i>	LuS-11401	9375±50	10,670–10,520	10,540–10,450	---	---	No
HAV004	Haväng	6.0	Bone	<i>Cervus elaphus</i> , antler	Ua-48208	8892±62	10,160–9920	---	---	---	---
HAV044	Haväng	6.1	Wood	<i>Pinus</i>	LuS-11403	9285±50	10,570–10,410	10,530–10,410	---	---	No
HAV027	Haväng	6.3	Wood	<i>Corylus</i> , fishing construction	Ua-48213	7718±55	8550–8440	---	---	---	---
BLE33	Svanevik	6.3	Macro	Mixed terrestrial remains	LuS-12392	1790±35	1805–1628	---	---	---	---
HAV047	Haväng	6.4	Wood	<i>Pinus</i>	LuS-11404	9235±50	10,490–10,300	10,500–10,410	---	---	No
HAV050	Haväng	6.4	Wood	<i>Pinus</i>	LuS-11407	9435±50	10,720–10,590	10,580–10,460	---	---	No
BLE03	Svanevik	6.4	Wood	<i>Betula</i>	LuS-11812	9245±50	10,504–10,298	---	---	---	Yes
BLE34	Svanevik	6.4	Macro	Mixed terrestrial remains	LuS-12393	9325±50	10,647–10,434	---	---	---	---
BLE35	Svanevik	6.4	Macro	Mixed terrestrial remains	LuS-12394	9320±50	10,641–10,431	---	---	---	---
HAV039	Haväng	6.5	Wood	<i>Pinus</i>	LuS-11402	9390±50	10,690–10,570	10,600–10,500	---	---	No
HAV048	Haväng	6.5	Wood	<i>Pinus</i>	LuS-11405	9495±50	11,070–10,670	10,740–10,680	---	---	No
HAV112	Haväng	6.5	Wood	<i>Pinus</i>	LuS-11560	9355±55	10,660–10,510	---	10,520–10,450	---	Yes
BLE36	Svanevik	6.5	Macro	Mixed terrestrial remains	LuS-12395	9375±50	10,674–10,523	---	---	---	---
HAV078	Haväng	7.4	Wood	<i>Pinus</i>	LuS-11807	9305±45	10,580–10,430	---	---	---	No
HAV100	Haväng	7.7	Wood	<i>Pinus</i>	LuS-11558	9345±55	10,660–10,500	10,520–10,410	10,590–10,530	---	Yes
HAV002	Haväng	8.3	Bone	<i>Cervus elaphus</i> , tibia	Ua-48207	7939±53	8970–8650	---	---	---	---
BLE10	Tärnö	8.4	Wood	<i>Pinus</i>	LuS-11813	9435±50	10,721–10,588	---	---	---	Yes
HAC6b	Haväng	8.5	Macro	Mixed terrestrial remains	LuS-10962	8000±45	9000–8780	---	---	8990–8630	---
HAC6a	Haväng	8.5	Macro	Mixed terrestrial remains	LuS-10880	7900±35	8770–8630	---	---	8780–8630	---
HAC4	Haväng	8.7	Macro	Mixed terrestrial remains	LuS-10676	8025±55	9010–8780	---	---	8800–8650	---

Sample number	Site	Depth (m b.s.l.)	Material	Taxa	Lab number	¹⁴ C age (cal yr BP)	Calibrated age (cal yr BP, 1 σ)	D _{sequence modelled} ('wiggle-match') age corrected for sampled rings (cal yr BP, 1 σ)	U _{sequence modelled} age corrected for sampled rings (cal yr BP, 1 σ)	P _{sequence modelled} age (cal yr BP, 1 σ)	Rooted
BLE22	Tärnö	8.9	Wood	<i>Pinus</i>	LuS-12379	9570±50	11,077–10,768	---	---	---	Yes
BLE23:1	Tärnö	9.1	Wood	<i>Pinus</i>	LuS-12380	9490±50	11,063–10,660	107,93–10,704	---	---	No
BLE23:2	Tärnö	9.1	Wood	<i>Pinus</i>	LuS-12381	9445±50	10,736–10,589	10,670–10,581	---	---	No
BLE24	Tärnö	9.5	Wood	<i>Pinus</i>	LuS-12382	9440±50	10,729–10,588	---	---	---	No
BLE25:1	Tärnö	9.5	Wood	<i>Pinus</i>	LuS-12383	9540±65	11,072–10,728	10,805–10,706	---	---	No
BLE25:2	Tärnö	9.5	Wood	<i>Pinus</i>	LuS-12384	9445±50	10,736–10,589	10,750–10,651	---	---	No
BLE26	Tärnö	9.7	Wood	<i>Pinus</i>	LuS-12385	9345±50	10,654–10,500	---	---	---	Yes
HAC3	Haväng	10.3	Macro	Mixed terrestrial remains	LuS-10675	8040±115	9090–8660	---	---	8910–8820	---
HAV058	Haväng	11.3	Wood	<i>Pinus</i>	LuS-11410	9335±50	10,650–10,440	10,620–10,530	---	---	No
HAV059	Haväng	11.3	Macro	Mixed terrestrial remains	LuS-11564	9215±45	10,480–10,280	---	---	---	---
HAC2	Haväng	11.6	Macro	Mixed terrestrial remains	LuS-10674	7950±55	8980–8660	---	---	9010–8960	---
HAC1	Haväng	11.7	Macro	Mixed terrestrial remains	LuS-10673	8020±120	9030–8650	---	---	9010–8960	---
HAC7	Haväng	11.8	Macro	Mixed terrestrial remains	LuS-10881	8085±45	9090–8980	---	---	9030–8980	---
HAV083	Haväng	12.0	Wood	<i>Corylus</i> , fishing construction	Ua-38145	8086±60	9130–8800	---	---	---	---
HAV129	Haväng	15.1	Wood	<i>Pinus</i>	LuS-11563	9340±50	10,650–10,500	---	10,750–10,710	---	Yes
HAV007	Haväng	15.4	Bone	<i>Castor fiber</i> , fibula	Ua-48209	9396±57	10,700–10,570	---	---	---	---
HAV006	Haväng	15.4	Bone	<i>Bos primigenius</i> , metatarsus	LuS-10393	9330±65	10,650–10,430	---	---	---	---
HAV116	Haväng	16.0	Wood	<i>Pinus</i>	LuS-11808	9550±45	11,070–10,750	10,760–10,700	10,730–10,690	---	Yes
HAV117	Haväng	16.2	Wood	<i>Betula</i>	LuS-11561	9320±50	10,640–10,430	---	---	---	No
HAV118	Haväng	16.2	Wood	<i>Pinus</i>	LuS-11809	9450±45	10,740–10,590	10,700–10,650	---	---	No
HAV143	Haväng	16.8	Macro	Mixed terrestrial remains	LuS-10879	9485±45	11,060–10,610	---	---	---	---
HAV023	Haväng	16.8	Wood	<i>Pinus</i>	Ua-48210	9453±60	10,760–10,580	---	---	---	No
HAV144	Haväng	16.8	Macro	Mixed terrestrial remains	LuS-10878	9470±45	10,770–10,600	---	---	---	---
HAV106	Haväng	17.0	Wood	<i>Pinus</i>	LuS-11559	9580±55	11,080–10,780	---	10,800–10,750	---	Yes
HAV049	Haväng	17.3	Wood	<i>Pinus</i>	LuS-11406	9440±50	10,730–10,590	10,740–10,650	---	---	No
HAV052	Haväng	17.4	Wood	<i>Pinus</i>	LuS-11409	9405±50	10,700–10,580	10,600–10,500	---	---	No
HHC1	Haväng	17.9	Macro	Mixed terrestrial remains	LuS-11094	9405±50	10,700–10,580	---	---	---	---
HGC2	Haväng	18.8	Macro	Mixed terrestrial remains	LuS-11557	9610±60	11,130–10,790	---	---	---	---
HAV026	Haväng	19.0	Wood	Log-fire	Ua-48212	9543±59	11,070–10,740	---	---	---	---
HGC1	Haväng	19.2	Macro	Mixed terrestrial remains	LuS-11093	9605±45	11,100–10,790	---	---	---	---
HHC2	Haväng	19.6	Macro	Mixed terrestrial remains	LuS-11120	9500±50	11,070–10,680	---	---	---	---

Sample number	Site	Depth (m b.s.l.)	Material	Taxa	Lab number	¹⁴ C age (cal yr BP)	Calibrated age (cal yr BP, 1 σ)	D _{sequence} modelled ('wiggle-match') age corrected for sampled rings (cal yr BP, 1 σ)	U _{sequence} modelled age corrected for sampled rings (cal yr BP, 1 σ)	P _{sequence} modelled age (cal yr BP, 1 σ)	Rooted
HAV025	Haväng	20.0	Wood	<i>Pinus</i>	Ua-48211	9582±59	11,090–10,780	---	10,870–10,800	---	Yes
HHC3	Haväng	20.2	Macro	Mixed terrestrial remains	LuS-11121	9695±50	11,200–10,900	---	---	---	---
HAV126	Haväng	20.7	Wood	<i>Pinus</i>	LuS-11562	9620±50	11,140–10,800	---	10,890–10,810	---	Yes

Table A2. Sample details of the dendrochronological samples, 79 from Haväng and 8 from western Blekinge. Sample details marked with asterisk are estimated/uncertain values. Samples without depth information have been found on the beach or sampled at museums.

Site	Sample ID	Dendro ID	Depth (m b.s.l.)	Species	Rooted	Number of rings	Pith	Sapwood	Wane
Verkeån	HAV046	11347	0.5	<i>Pinus</i>	No	52	1	10*	No
Haväng	HAV032	11349	3.8	<i>Pinus</i>	No	73	3	34	Yes*
Haväng	HAV133	11422	3.9	<i>Pinus</i>	No	128	1	---	No
Haväng	HAV031	11348	4.0	<i>Pinus</i>	No	104	3	49	No
Haväng	HAV055	11362	4.2	<i>Pinus</i>	No	180	1	25	No
Haväng	HAV076	11371	4.6	<i>Pinus</i>	Yes	66	1	---	No
Haväng	HAV127	11415	4.6	<i>Pinus</i>	No	52	1	---	No
Haväng	HAV093	11394	4.9	<i>Pinus</i>	No	151	1	---	No
Haväng	HAV084	11390	5.5	<i>Pinus</i>	No	18	1	---	No
Haväng	HAV090	11391	5.5	<i>Pinus</i>	No	16	1	---	No
Haväng	HAV091	11392	5.5	<i>Pinus</i>	No	37	1	25	No
Haväng	HAV134	11423	5.8	<i>Pinus</i>	Yes	98	20	---	No
Haväng	HAV033	11350	6.0	<i>Pinus</i>	No	72	1	---	No
Haväng	HAV034	11351	6.0	<i>Pinus</i>	No	117	1	37	No
Haväng	HAV035	11352	6.0	<i>Pinus</i>	No	6	1	---	Yes
Haväng	HAV092	11393	6.0	<i>Pinus</i>	No	62	1	8	No
Haväng	HAV044	11354	6.1	<i>Pinus</i>	No	164	10*	---	No
Haväng	HAV095	11395	6.3	<i>Pinus</i>	No	113	1	---	No
Svanevik	BLE03	11420	6.3	<i>Betula</i>	Yes	79	60*	---	Yes
Haväng	HAV047	11356	6.4	<i>Pinus</i>	No	83	1	57	No
Haväng	HAV050	11359	6.4	<i>Pinus</i>	No	139	5*	46	No
Haväng	HAV039	11353	6.5	<i>Pinus</i>	No	51	10*	---	No
Haväng	HAV048	11357	6.5	<i>Pinus</i>	No	70	5*	---	No
Haväng	HAV112	11404	6.5	<i>Pinus</i>	Yes	97	1	---	No
Haväng	HAV051	11360	6.7	<i>Pinus</i>	No	68	5*	---	No
Haväng	HAV060	11364	6.8	<i>Pinus</i>	No	115	7	40	Yes
Haväng	HAV135	11424	7.1	<i>Pinus</i>	No	103	5	---	No
Haväng	HAV079	11373	7.3	<i>Pinus</i>	No	168	1	58	No
Haväng	HAV078	11372	7.4	<i>Pinus</i>	No	71	1	51	No
Haväng	HAV113	11405	7.5	<i>Pinus</i>	No	129	1	36	No
Haväng	HAV114	11406	7.5	<i>Pinus</i>	No	108	1	---	No
Haväng	HAV098	11396	7.6	<i>Pinus</i>	No	91	1	1	No
Haväng	HAV071	11368	7.7	<i>Populus</i>	No	67	5*	---	No
Haväng	HAV100	11397	7.7	<i>Pinus</i>	Yes	140	1	---	No
Haväng	HAV065	11365	8.1	<i>Pinus</i>	No	35	1	---	No
Haväng	HAV073	11369	8.3	<i>Pinus</i>	No	98	1	---	No
Haväng	HAV074	11370	8.3	<i>Pinus</i>	No	83	1	25	No
Tärnö	BLE10	11419	8.4	<i>Pinus</i>	Yes	49	1	---	No
Tärnö	BLE22	11431	8.9	<i>Pinus</i>	Yes	37	50*	---	No
Tärnö	BLE23	11432	9.1	<i>Pinus</i>	No	149	60*	---	No
Tärnö	BLE24	11433	9.5	<i>Pinus</i>	No	93	30	---	No
Tärnö	BLE25	11434	9.5	<i>Pinus</i>	No	148	1	---	No
Tärnö	BLE27	11436	9.5	<i>Pinus</i>	No	38	1	---	No
Tärnö	BLE26	11435	9.7	<i>Pinus</i>	Yes	37	50	---	No
Haväng	HAV058	11363	11.3	<i>Pinus</i>	No	71	1	---	No

SUBMERGED LANDSCAPES IN THE HANÖ BAY

Site	Sample ID	Dendro ID	Depth (m b.s.l.)	Species	Rooted	Number of rings	Pith	Sapwood	Wane
Haväng	HAV137	11437	14.5	<i>Pinus</i>	No	85	1	20*	No
Haväng	HAV129	11416	15.1	<i>Pinus</i>	Yes	138	1	27	No
Haväng	HAV116	11407	16.0	<i>Pinus</i>	Yes	52	10	---	No
Haväng	HAV117	11408	16.2	<i>Betula</i>	No	69	10	---	Yes
Haväng	HAV118	11409	16.2	<i>Pinus</i>	No	96	5	---	No
Haväng	HAV107	11401	16.3	<i>Pinus</i>	No	71	1	---	No
Haväng	HAV119	11410	16.3	<i>Pinus</i>	Yes	78	1	23	No
Haväng	HAV120	11411	16.4	<i>Pinus</i>	No	24	1	---	Yes*
Haväng	HAV131	11417	16.4	<i>Pinus</i>	No	65	1	---	No
Haväng	HAV132	11418	16.4	<i>Pinus</i>	No	89	4	---	No
Haväng	HAV109	11402	16.9	<i>Pinus</i>	No	89	1	---	No
Haväng	HAV110	11403	16.9	<i>Pinus</i>	No	153	1	34	No
Haväng	HAV104	11398	17.0	<i>Pinus</i>	No	61	1	---	No
Haväng	HAV105	11399	17.0	<i>Pinus</i>	No	55	10	---	No
Haväng	HAV106	11400	17.0	<i>Pinus</i>	Yes	29	1	---	No
Haväng	HAV049	11358	17.3	<i>Pinus</i>	No	104	1	25	No
Haväng	HAV052	11361	17.4	<i>Pinus</i>	No	107	1	43	Yes
Haväng	HAV070	11367	17.5	<i>Salix</i>	No	5	1	---	No
Haväng	HAV068	11366	18.7	<i>Pinus</i>	No	29	1	---	No
Haväng	---	11374	18.7	<i>Salix</i>	No	19	1	---	No
Haväng	---	11375	18.7	<i>Pinus</i>	No	66	1	---	No
Haväng	---	11376	18.7	<i>Salix</i>	No	24	7*	---	No
Haväng	---	11377	18.7	<i>Salix</i>	No	51	1	---	No
Haväng	---	11378	18.7	<i>Salix</i>	No	18	1	---	No
Haväng	---	11379	18.7	<i>Pinus</i>	No	83	1	---	No
Haväng	---	11380	18.7	<i>Salix</i>	No	18	1	---	No
Haväng	---	11381	18.7	<i>Salix</i>	No	44	5*	---	No
Haväng	---	11382	18.7	<i>Salix</i>	No	22	1	---	No
Haväng	---	11383	18.7	<i>Pinus</i>	No	17	1	---	No
Haväng	---	11384	18.7	<i>Pinus</i>	No	27	3	---	No
Haväng	---	11385	18.7	<i>Pinus</i>	No	60	1	---	No
Haväng	---	11386	18.7	<i>Salix</i>	No	22	1	---	Yes
Haväng	---	11387	18.7	<i>Pinus</i>	No	49	5*	---	No
Haväng	---	11388	18.7	<i>Salix</i>	No	17	3*	---	No
Haväng	---	11389	18.7	<i>Salix</i>	No	20	1	---	Yes
Haväng	HAV025	11355	20.0	<i>Pinus</i>	Yes	88	1	---	No
Haväng	HAV122	11412	20.7	<i>Pinus</i>	No	99	1	---	Yes
Haväng	HAV125	11413	20.7	<i>Pinus</i>	No	102	5	51	No
Haväng	HAV126	11414	20.7	<i>Pinus</i>	Yes	38	1	---	No
Haväng	---	11421	---	<i>Fagus</i>	No	73	10	---	Yes*
Haväng	---	11425	---	<i>Pinus</i>	No	140	1	---	No
Haväng	---	11426	---	<i>Pinus</i>	No	77	10	---	No