Impact of southern Baltic sea-level changes on landscape development in the Verkeån River valley at Haväng, southern Sweden, during the early and mid Holocene

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Cover picture: Lindgrens länga, on the edge of the Öradekar site. Photo: Anette Nilsson Brunlid.

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Abstract: In the Hanö bay off the coast at Haväng in SE Scania, southern Sweden, a submerged and well-preserved Mesolithic landscape is found, including remains of trees, river and lagoon sediments, and archaeological artefacts such as an antler pick axe and stationary fishing constructions. The landscape was formed during the Yoldia Sea (11,700-10,800 cal BP) and Initial Littorina Sea (9800-8500) low-water phases of the Baltic Basin. The landscape was subsequently drowned during the Ancylus Lake (10,800-9800 cal BP) and the Littorina Sea (8500-6000 cal BP) transgressions. The present study complements previous work by focusing on landscape development in the part of the Haväng area that is located inside the modern coastline but was influenced by the early to mid-Holocene sea-level fluctuations within the region. The study sites, Öradekaren and Havängsgården, are located approximately 500 m from the coastline, in close proximity to the Verkeån River. Sediment sequences were analysed for pollen and macrofossils in order to reconstruct the development of the vegetation. Sedimentological, geochemical and geophysical methods were used, for example, X-ray fluorescence and magnetic susceptibility, in order to reconstruct the hydrological development at the sites from approximately 11,000 to 6000 cal BP. The analyses revealed a lacustrine environment in both sites, with fluctuating lake levels that from time to time was in connection to the Verkeån River. Within the time period of this study, two major transgressions occurred in the area. The Ancylus transgression peaked at approximately 10,300 cal BP but never reached the two localities, but the profound decline of *Pinus* pollen in the pollen record at this time reflects the drowning of the predominantly pine-rich forests growing in what today is the Hanö Bay. Another transgression starting at about 9 000 cal BP, peaked at about 5 m a.s.l. between 7500-6000 cal BP. This is above the elevation of the two localities, but due to the narrow river valley, damming of the Verkeån River occurred by sediment ridge build up during the transgression. A sheltered lagoonal environment developed and the freshwater signature was preserved. Erosion and redeposition of older sediments occurred at the Havängsgården, but the Öradekar site remained a relatively deep and sheltered basin. The vegetation surrounding the sites displayed both aquatic and moisture demanding plants in and near the Öradekar Lake and *Pinus* and various deciduous trees on the drier grounds. After 6000 cal BP the landscape changed, the lakes were overgrown and turned into fens, the number of trees declined and more open ground covered by grasses and herbs developed. This suggests increased human impact on the landscape, including grazing of the recently developed fens at the study sites. This study showed that the impact of the sea level fluctuations during the Littorina Sea was recognised by lagoonal development, drowning parts of the river valley but no traces of saline influences in the study area were found.

Keywords: Sea-level change, Littorina Sea, Baltic Sea, Ancylus Lake, environmental reconstruction, Holocene

Supervisors: Mats Rundgren, Anton Hansson

Subject: Quaternary Geology

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Inverkan av havsnivåförändringar i södra Östersjön på landskaps-utvecklingen i Verkeåns dalgång vid Haväng, södra Sverige, under tidig- och mellan-holocen

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Sammanfattning: I Hanöbukten utanför Haväng i sydöstra Skåne finns välbevarade undervattenslämningar från ett mesolitiskt landskap med rester av träd och sediment avsatta i å- och lagunmiljö. Arkeologiska fynd av bland annat stationära fiskeredskap och en hackyxa av horn har gjorts. Landskapet formades under lågvattenperioderna under Yoldiahavet (11 700-10 800 cal BP) och Littorinahavets första fas (9800-8500 cal BP). Landskapet dränktes senare under Ancylussjöns (10 800-9800 cal BP) och Littorinahavets (8500-6000 cal BP) transgressioner. Denna undersökning kompletterar tidigare studier i området genom att fokusera på landskapsutvecklingen i Havängsområdet som ligger innanför dagens kustlinje men som påverkades av regionens havsnivåförändringar under tidig- till mellan-holocen. De två undersökta lokalerna, Öradekaren och Havängsgården är belägna nära Verkeån, ca 500 m från dagens kustlinje. Sediment från sedimentborrkärnor analyserades för pollen och makrofossil för att rekonstruera vegetationsutvecklingen. Sedimentologiska, geokemiska och geofysiska metoder användes för att förklara de hydrologiska förändringarna på de två lokalerna från ca 11 000-6000 år sedan. Resultatet från analyserna visade att båda lokalerna hade en lakustrin miljö med fluktuerande vattennivåer som tidvis var i kontakt med Verkeån. Under tidsperioden i denna studie inträffade två stora transgressioner i området. Ancylus-transgressionen nådde sin högsta nivå ca 10 300 cal BP, men nådde aldrig lokalerna. Däremot avspeglas dränkningen av tallskogarna som växte utanför Haväng i pollendiagrammet, tallpollensignalen blir märkbart mindre under denna tid. Ytterligare en transgression inträffade med början ca 9000 cal BP och nådde sin högsta nivå (ca 5 m.ö.h.) mellan 7500-6000 cal BP. Detta är höjdmässigt ovanför lokalerna men på grund av den smala ådalen dämdes Verkeån upp genom uppbyggnad av sedimentbarriärer i takt med havsnivåökningen. Erosion och deposition av äldre sediment inträffade vid Havängsgården när Littorina-transgressionen och efterföljande regression passerade lokalen men Öradekarens relativt djupa skyddade lakustrina miljö påverkades inte. Akvatisk flora och fuktkrävande växter växte i och runt Öradekarsjön. På de torrare markerna dominerade tall och lövträd. Efter ca 6000 cal BP förändrades landskapet och sjöarna växte igen och blev kärr. Antalet träd minskade och ett mer öppet landskap med gräs och örter bredde ut sig. Detta indikerar ökad mänsklig påverkan genom bland annat användningen av kärren som betesmark. Studien har visat att havsnivåförändringarna under Littorinatid påverkade de två lokalerna i dalgången men på grund av bildandet av en lagun bibehölls den lakustrina miljön trots havsnivåns läge.

Nyckelord: Havsnivåförändring, transgression, Haväng, Littorina, holocen.

Handledare: Mats Rundgren och Anton Hansson

Ämnesinriktning: Kvartärgeologi

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1 Introduction

Coastal areas surrounding the southern Baltic Sea experienced extensive sea level changes from the end of the last glaciation, about 16,000 years ago (Houmark-Nielsen & Kjaer 2003) until today. Several high and low stands (the Baltic Ice Lake, Yoldia Sea, Ancylus Lake and the Littorina Sea) shaped the coastal landscape. The complicated relationship between changes of the isostatic rebound, after the final retreat of the ice, and local and global (eustatic) sea level change have left remains of sunken landscapes in several areas in the southern Baltic Sea, for example in Denmark (Fisher 1997), outside the coast of Scania, southern Sweden (Hansson 2018) and Germany (Lampe 2005; Hartz et al. 2014). The now often completely inundated land areas reveal remains of trees, some still rooted and archaeological artefacts *in situ*. Sediment cores retrieved offshore at these sites display sediment sequences which when analysed, reveal information about, for instance, past sea-level changes, climate and vegetation.

After the final retreat of the Scandinavian ice sheet, the barren landscape in southern Scandinavia was first colonized by pioneer plants such as herbs and grasses (Iversen 1973; Kolstrup 1982; Noe-Nygaard & Heiberg 2001). About 15,000 years ago the climate changed and warmer summer temperatures enabled shrubs such as willow (*Salix* spp.) and the dwarf species of birch (*Betula nana*), to become established members of the flora. After a shorter colder period (Older Dryas) the climate changed again to milder temperatures (Björck & Möller, 1987). The Younger Dryas stadial, around 12,900 to 11,700 ago (Lowe et al. 2008), is named after the arctic and alpine herb *Dryas octopetala*. This recession to arctic climate meant that only the most cold adaptive species survived. From the onset of the Holocene at around 11,700 cal BP (Walker et al. 2009), the climate became warmer, allowing plants like sea buckthorn (*Hippophaë rhamnoides*) and juniper (*Juniperus communis*) to become established. Shortly thereafter trees like *Betula* (*B. pubescens* and *B. pendula*) and pine (*Pinus sylvestris*) immigrated, soon followed by hazel (*Corylus avellana*). *Pinus* grew on drier sandy soils whereas *Corylus avellana* thrived in the more nutrient-rich soils. The warmer climate further allowed other deciduous species to spread from about 10,000 cal BP, like elm (*Ulmus glabra*) (Åkesson et al. 2015), followed by alder (*Alnus glutinosa*), oak (*Quercus robur*) and linden or lime (*Tilia cordata*) at about 9000 cal BP (Berglund et al. 2008). A climate optimum ranging from about 8000 to 4000 cal BP in Sweden and the Baltic region is recognized by for example Seppä et al. (2005), Jessen et al. (2005) and Heikkilä & Seppä (2010), with summer temperatures about 2,5°C above present. Slightly warmer temperatures have been reconstructed for Latvia, 2,5 to 3,5°C, compared to Fennoscandia (Heikkilä & Seppä 2010).

The aim of this thesis is to reconstruct the environmental development in the Haväng area, situated at the mouth of the Verkeån River, in south eastern Scania through parts of the Holocene. Past sea-level low stands from the Yoldia Sea stage and the Initial Littorina Sea stage, from about 11,700-10,200 and 9800-8000 cal BP, have left well-preserved, long lost landscapes outside the Haväng coastline in Hanö Bay. The extensive underwater remains of trees and organic sediment ridges containing archaeological artefacts, have been partially studied giving evidence of human habitation and foraging in a lagoonal environment with pine forests covering the nearby area. The Littorina transgression peaked at about 4 m a.s.l. in the Haväng area (Hansson et al. 2018). The influences of this and other sea-level high stands have not been studied further inland. Did the proposed lagoonal conditions, found outside in Hanö Bay, apply further inland and did the Littorina Sea leave any traces of salinity in the river valley? This study will address the following questions based on palaeoecological, geochemical and geophysical analyses of sediment sequences from two sedimentary basins located upstream in the modern river valley, within 500 m from the present coastline. Since some of the sea-level high stands did not reach present inland areas and thus not cause erosion of previous sediments, the time period covered by these sediment sequences is expected to be longer than that studied based on sediment sequences collected in the Hanö Bay.

1. To what extent did past sea levels, in the beginning to the middle of the Holocene, from around 11,700 cal BP to approximately 6000 cal BP, impact the study areas?
2. How did the vegetation and hydrological conditions in the river valley respond to climate development and changes in the relative sea level during this time?

1.1 Geographical setting

The Verkeån River runs today through a hummocky landscape north of Kivik in SE Scania, in the south of Sweden, on its way to the Baltic Sea (Fig. 1). From the low stands of the Yoldia Sea to the onset of the Littorina Sea, around 11,700 to 8500 cal yr BP, the Verkeån River had at times a meandering path further out in what today is the Hanö bay. This is according to Nilsson (1961) the reason for the relatively deep river valley in Haväng today, cut down by the river as it continued much further outside Haväng, leaving evidence of a former river course on the sea floor by remains of organic deposits outlining the former fluvial and lagoonal system (Hansson et al. 2018).

Today the Haväng area is a nature reserve, created to protect the special biological and geological characteristics in the area (Länsstyrelsen 1975). It consists of a small river, the Verkeån River, primarily pasture grounds and the beaches of Hanö Bay in the Baltic Sea. The landscape is undulating, formed over

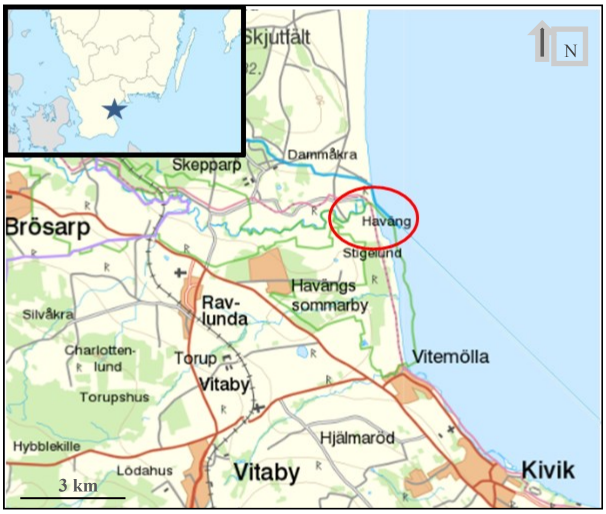

Fig. 1. Upper left; map of southern Sweden, and part of Denmark (in grey). Haväng is marked with a star. Main map: Haväng is marked with an ellipse. Modified after Lantmäteriet and Google Maps 2018.

time by a combination of the retreating glacial ice, the transgressions and regressions of the sea and local aeolian and fluvial conditions (Malmberg Persson, 2000), (Fig. 2). A ridge of predominantly glaciofluvial and aeolian sand runs parallel to the coastline, and the Verkeån River cuts through the ridge on its way to the Baltic Sea. In some older literature and maps, Verkeån River is named Skepparpsån. The river's streamflow varies with season, between 0.2 and 25 m^3/s (Anheden 1967). The catchment area is about 150 km^2 (Malmberg Persson 2000). The river is an important breeding area for trout (*Salmo trutta*).

The open grounds are accompanied by lush vegetation of deciduous trees like beech and alder on the river banks, which brings shade to the meandering Verkeån River (Niss 2007). A rare sand steppe vegetation with sand carnation (*Dianthus arenarius*) and sand lily (*Antherium liliago*) is found on the adjacent hills (Persson & Sandell 2014). The pasture grounds closest to the river are moist and home to different grasses, sedges and moisture-loving taxa like *Carex* and *Filipendula ulmaria* can be found (Niss 2007). The Öradekar site, one of the two sites studied in this thesis, is situated in a pasture ground adjacent to the river.

Åmark (1984) identified four different stratigraphical units of Quaternary deposits in the area between Ravlunda in the west to Vitemölla in the south east. The bedrock is covered from bottom to surface by an approximately 20 m thick lower till, then a lower, up to 60 m thick sand layer, then another till (<3 m thick) followed by an upper sand layer about 15 m thick. The upper sand layer is according to Åmark (1984) deposited by glaciofluvial processes but does also consist of coastal beach deposits. The area around the Verkeån River and the coastline consists of flood-plain deposits, glaciofluvial and aeolian deposits (Malmberg Persson 2000) (Fig. 2).

Previous palaeoecological studies in the area have primarily focused on the submarine landscape remains in the Hanö Bay, outside the coast of Haväng. But, for example Nilsson (1961), applied pollen analysis to a sediment sequence retrieved from the mouth of the Verkån River. He found pollen from aquatic plants and pollen reflecting a mixed deciduous forest with the presence of pine. The gyttja was dated to between about 3100 and 6500 cal BP. The same deposit was also sampled by Gaillard & Lemdahl (1994) and dated to about 6000 cal BP. There was no evidence of brackish or saline impact in the gyttja, suggested by Nilsson (1961) as being deposited in a fresh water lagoonal environment where the groundwater kept in pace with the rising sea level.

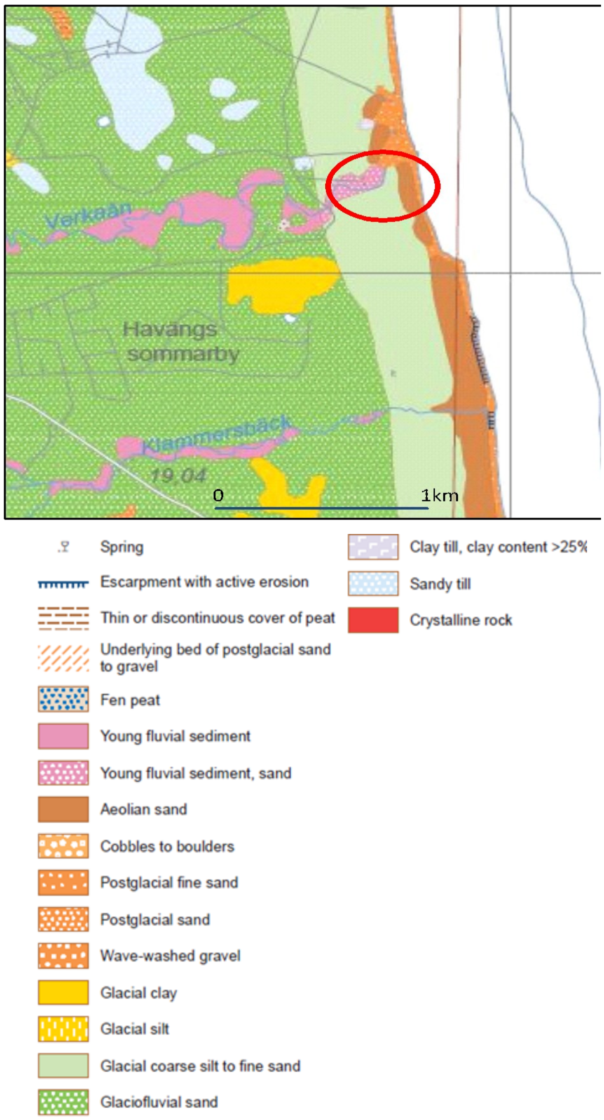

Fig. 2. Map of Quaternary deposits from the Swedish Geological Survey, 2018. Study areas are located within the red ellipse.

Gaillard & Lemdahl (1994) studied offshore organic deposits proposed as being formed in ancient lagoons which were created behind sand dunes or beach ridges during different sea-level stages, from the Ancylus transgression to the Littorina transgression. Gaillard & Lemdahl (1994) state that no plant or faunal remains found in the studied sediments belonged to definitely marine or brackish species, suggesting a lacustrine or waterlogged environment protected from the sea by ridges. Hansson et al. (2018) describe in more detail how these ridges, more likely make up the outline of lagoons which were connected to the river. During the Yoldia Sea stage, approximately 24 m b.s.l., the river incised down into a river valley, which was later redesigned by deposition and erosion in connection with the Ancylus transgression and later the Littorina sea-level fluctuations. Hansson et al. (2018) presented diatom evidence of a slightly brackish influence in the lagoons. The submerged landscape in Hanö Bay is the focus for a doctoral research project at Lund University. The project is a dual venture addressing both archaeological and geological aspects. This thesis is linked to this doctoral project by studying the impact of sea-level variations, vegetation and hydrological changes, using similar analytical methods, further inland.

1.2 Development of the Baltic Sea during and after the last deglaciation

The coastline surrounding what is today the Baltic Sea has experienced various environmental and geomorphological changes. In the studied area in the south of Sweden, the Baltic Ice Lake flooded the landscape at the end of the last glaciation. The retreat of the ice began in the south and the ice margin moved towards the north. The isostatic uplift, generated by the unloading of the pressure that the ice created, was greater in the south at this time, thus lifting the threshold that constituted the drainage of the meltwater through the Öresund strait (Andrén et al. 2011). The damming of the water from the ongoing melting of the ice sheet began when the erosion of the uplifted threshold, reached the bedrock in the Öresund strait.

A major transgression in the south of Sweden followed, but was interrupted by the supposed first drainage of the Baltic Ice Lake when the retreating ice reached the Swedish lowlands north of Mt. Billingen and an outlet was created through south central Sweden to the North Sea. (Björck 1995). At the beginning of the Younger Dryas stadial about 12,800 cal BP, the ice once again started to grow and closed the passage of water flowing from the Baltic Ice Lake at Mt. Billingen. The transgression that followed lasted to about 11,700 cal BP, at the onset of the Holocene, when the ice margin retreated from Mt. Billingen once more. The second drainage of the Baltic Ice Lake is thought to be catastrophic, with a lowering of the water level by approximately 25 m during just a few years (Björck 2008). A shoreline displacement curve for Haväng has been proposed by Hansson et al. (2018), suggesting a drop from about 14 m a.s.l. to about 24 b.s.l. This means a transformation at the study sites from a relatively deep water environment to dry inland.

The passage of water through the straits in south central Sweden eventually allowed saline water to reach the Baltic basin, and the Yoldia Sea stage was formed (Mörner 1995). The ongoing isostatic uplift was faster than the eustatic sea-level rise, creating more dry land in the southern Baltic basin. The Verkeån River formed a new meandering path because of the new dry land and made a new connection to the sea further out into the Hanö Bay. The uplift in south central Sweden caused the water way from south central Sweden to the North Sea to shallow up and, as a consequence, the Baltic basin became once again a fresh water lake, the so-called Ancylus Lake stage 10,700 to 9800 cal BP (Andrén et al. 2011). Southern Sweden experienced a transgression (Andrén et al. 2011), which drowned the landscape at Haväng. The rapidity of the transgression is probably the cause of the well-preserved remains of tree stumps and sediment ridges found in the Hanö Bay at a depth down to -20 m (Hansson et al. 2018). The transgression terminated when the water eroded the threshold at Darss Sill between Denmark and Germany, creating a drainage network of rivers through the Fehmarn Belt, the Great Belt and Mecklenburg Bay (Bennike et al. 2004; Björck et al. 2008)

This new low stand has been named the Initial Littorina Sea (Andrén et al. 2000) or the Early Littorina Sea (Berglund et al. 2005). Saline water indicators (for example as a shift to a more brackish diatom flora, the so called Mastogloia flora (Miettinen 2002)), have been dated to around 9800 cal BP in sediment studies done in coastal areas in Blekinge (Berglund et al. 2005) and in the Bornholm basin (Andrén et al. 2000). The brackish indicators points to a weak in-flow of saline waters through the Great Belt and the Fehmarn Belt.

It was not until about 8500 cal BP that the Öresund strait was opened, as a result of global sea-level rise, allowing a flow of saline water into the Baltic basin causing sea level rise and the Littorina Sea proper to develop (Andrén et al. 2011). The Littorina transgression reached its high-stand between 7500 and 6000 cal BP (Berglund et al. 2005; Kostecki et al. 2015).

1.3 Evidence of human activity in the Haväng area

Both Neolithic and Mesolithic settlements can be found in coastal areas around the Baltic Sea (Lübke 2002; Jussila & Kriiska 2004; Zvelebil 2006, 2008; Fischer 2007; Kriiska & Roio 2011; Rosentau et al. 2011; Boethius 2016). More specifically, these settlements are found close to river mouths or estuaries (Veski et al. 2005; Jussila et al. 2007; Kriiska & Roio

2011; Rosentau et al. 2013). Due to the complex nature of isostatic processes and global and local sea-level fluctuations, these early settlements are located at different elevations in different geographical locations.

Evidence of settlements from the Mesolithic times has been found on the sea floor outside of Haväng. Hansson et al. (2018) presented evidence for extensive foraging for fish indicated by findings of, for example, stationary fish traps. Layers of refusal have also been found in the well preserved sediment banks. Findings of a probable fish fermentation facility in Blekinge, about 60 km north east of Haväng, dated to the Mesolithic, suggests a population being able to sustain on preserved food and reside longer at one settlement and be less nomadic to hunt for food (Boethius 2016).

The Swedish National Heritage Board recognizes multiple archaeological monuments and sites in the area around Haväng. A Neolithic dolmen, Bronze age burial mounds and stone ships from the Iron age are located in this area. Further to the south is the town of Kivik with a large restored monumental cairn known as Bredarör, containing a stone cist with decorated surrounding stone slabs. The monument is dated to the Bronze age (Goldhahn 2008). The area in which the Öradekar site is situated is part of Swedish National Heritage Board object "Ravlunda 56:1". There have been a few archaeological studies in the area but a complete examination has not been performed. The Regional Museum in Kristianstad describes the Öradekar area and the Verkeån Rriver mouth as a nonsedentary tradepost and a harbour from the Vendel period in the early Iron Age (Helgesson 2002). From the lower part of the Verkeån River and the nearby Klammersbäck River, findings of gold brakteats and a gold figure, have been made.

The production of alum from the Cambrian shale at Andrarum, situated near the Verkeån River but about 12 km from the coast, was founded in 1637 and closed down in 1912 (Björkander 2008). The alum was transported by road to the mouth of the river where the goods was laden and shipped by boats (Persson & Sandell 2014). There are remains of two stone piers with remains of wooden piles, visible only when the water stand is low. This is according to a leaflet from the local museum association (Havängs Museiförening 2013) remains from a harbour, but the stone piers and wooden piles could also have had the function of preventing sand build up in the mouth of the river. Wooden piles have also been found upstream, about 100 m from the mouth of the river. The usage of these is unclear (Havängs Museiförening 2013). Small pieces of reddish waste material transported from this major industry are still found at the bottom of the Verkeån River.

The Örakarsfallen is a medieval fish trap construction located near the Öradekar site and upstream about 500 m from the coast (Persson & Sandell 2014). It was restored in 2010. Trout is the main species found in the river today. During fieldwork, in connection with the present project in February 2016, a transverse arrowhead (Björn Nilsson, personal communication) was found on top of a mole heap at the edge of the Ördekar site. This type of arrow was common during the late Mesolithic.

2 Methods

2.1 Field work

Field work was conducted at the Öradekar site (Fig. 3), named after the medieval fish trap construction in the Verkeån River. Field work was also done at the Havängsgården site, situated in the garden of a former local farm, Havängsgården, in Haväng (Fig. 3). The field work was done during one day in the summer of 2015, and additional field work was done in the autumn of 2015 and early spring 2016.

A sediment sequence (Örade 2) with a length of 330 cm, was extracted with a Russian peat corer from the Öradekar site for palaeoecological analyses and analyses of sediment properties (Fig. 4). Previous fieldwork made by a research group lead by Anton Hansson resulted in the extraction of the Örade 1 sediment sequence (490 cm long) at the coordinates N 55, 720564°; E 14,188650°, 1,5 m above sea level. The Örade 2 sediment sequence was extracted at coordinates N 55,720274°; E 14,188338° and 2 m above sea level, which is closer to the edge of the depression than Örade 1 (Fig. 4). Since the corer only provides 1 m sediment at a time, overlapping of the cores was done to ensure that the sequences were complete. At the Department of Geology at Lund University, the cores were cleaned, described, wrapped in plastic film and stored in a cold room.

At the Havängsgården premises, one additional sediment sequence was extracted for OSL-dating at the coordinates (N 55,723461°; E 14,193239°), at the site of a previous sequence, collected, described and analysed by the research group. This previous sequence showed a sediment stratigraphy with a layer of sand at 123-145 cm depth. Since the depth for the sand layer was known from previous coring, the core for the OSL dating was extracted and immediately placed in dark plastic bags and transported, still contained within the corer, to the dark room at the OSL-laboratory at the Department of Geology, Lund University.

2.2 Dating

^{14}C datings were performed on samples (mixed terrestrial plant remains) from the Öradekar sediment sequences. From the Örade 1 sequence, five ^{14}C datings at 476-477 cm, 445 cm, 380 cm, 300 cm and 50 cm depth below present ground surface were sampled. One sample at 277-278 cm from the Örade 2 sequence was also dated. From the Havängsgården sequence, six ^{14}C datings were made on samples taken at 349-350 cm, 230 cm, 145 cm, 119 cm, 114-115 cm and 75 cm depth. The ^{14}C dating was performed at the ^{14}C-laboratory at the Department of Geology, Lund University. The resulting ^{14}C dates were calibrated using the Ox-

Cal 4.2.4 software (Bronk Ramsey 2009) and the INTCAL13 atmospheric calibration dataset (Reimer et al. 2013). Optically stimulated luminescence (OSL) dating was performed on the quartz fraction from the sandy layer at 123-145 cm depth in the Havängsgården sequence. The OSL dating was performed at the Lund Luminescence laboratory at the Department of Geology, Lund University.

2.3 Grain size

In order to determine which processes were responsible for depositing the sandy layers in the Örade 1 and Havängsgården sequences, grain size analyses were made. The question to be answered was: Are the sandy layers deposited in a fluvial environment by the Verkeån River, or are they coastal beach deposits deposited at times of higher relative sea level?

Grain size analyses were performed on sand samples from the Örade 1 site, at the depth of 400-411 cm, and from the Havängsgården sequence at 123-145 cm and 352-392 cm depth. The samples were not washed in order to remove organic material, due to the very well-sorted, sand only, appearance of each sample. The samples were weighed and dried overnight at 105°C, weighed again and then dry sieved through sieve sizes ranging from 0,063 mm to 22,4 mm. Each fraction was then weighed and the percentage of each fraction was calculated in order to plot the results.

The sand for the OSL analysis was obtained from the separate core extracted only for this purpose as stated above. The grain size for the OSL analysis was performed through wet sieving of the samples from the Havängsgården sequence at 123-145 cm in order to remove organic material, with sieve sizes from 0.355 mm to 0.063 mm (Alexanderson 2016). The 0,125 mm sieve size was excluded which is a standard procedure when performing OSL analysis (Alexanderson, personal communication, 2018).

2.4 Loss on ignition

Loss on ignition (LOI) analysis (Dean 1974) was performed on the Örade 1 and Örade 2 sequences. The LOI data (from previous analysis by Anton Hansson) from the Havängsgården sequence were also used. The aim was to establish the organic content in the sediment sequences (Davies 1976; Tolonen et al. 1975). Samples were taken at 5 cm intervals throughout the sequence, but at some levels samples were taken at a closer distance (2-3 cm) in order to account for sediment boundaries. The samples were put in pre weighed crucibles, weighed again and dried at 105°C overnight. The samples were then weighed again to establish the dry weight. The crucibles were placed in a muffle oven for 4 hours at 550°C. After cooling in a desiccator, the samples were weighed again and the organic content was calculated. The results were presented visually using Grapher 6 software.

2.5 Magnetic susceptibility

This method was used to determine variations in magnetic properties caused by changes in the concentration, grain-size and composition of minerogenic material that could indicate transgressions and regressions. A higher magnetic susceptibility (MS) could indicate erosion caused by transgressions or regressions. The use of MS was also used to correlate the different sediment sequences in overlapping cores which was not obvious when visually describing the sediment sequences. Magnetic susceptibility was measured on the Havängsgården and the Örade 2 sequences. Previous measurements had been done on the Örade 1 core by Anton Hansson. The measurements were made at 5 mm intervals using a magnetic susceptibility surface scanner including a Bartington MS2 magnetic susceptibility meter with the sensitivity setting on 0,1 in the Palaeomagnetic Laboratory at the Department of Geology, Lund University. The results were plotted visually with the help of Grapher 6 computer software.

2.6 X-ray fluorescence

The main aim of the X-ray fluorescence (XRF) analysis in this study, was to find evidence of brackish or saline conditions at the sites, implying that the sea level not only reached, but also made clear brackish or saline footprints in the area.

11 samples from Örade 1 and 10 samples from Örade 2 were extracted with a distance of 50 cm between for XRF analysis. XRF analysis of the Havängsgården core had previously been done by Anton Hansson. The samples were freeze dried overnight and then homogenised in a jade mortar. The sediment samples were analysed by placing them one by one in a silicone cylinder covered with a thin plastic film inside the XRF instrument at the XRF laboratory at the Department of Geology, Lund University. The analysis was performed with the Cu-Zn-mining setting (with an exposure time of 300 sec) on the Niton XL3t GOLDD + X-ray fluorescence instrument. The element sequence Si-U was measured in all the sediment sequences. Selected elements were presented graphically using the Grapher 6 computer software.

2.7 Pollen

The pollen analyses were performed in order to reconstruct the vegetation. The exine of the pollen is very durable and survives very long time in organic sediments. In all were 10 samples (detritus gyttja) extracted for preparation, approximately 50 cm apart, starting at 480 cm depth in the Örade 1 sediment sequence. The preparation of samples for pollen analysis followed the procedure described by Berglund & Ralska-Jasiewiczowa (1986). Four tablets of Lycopodium spores were added to each sample to enable estimation of pollen concentrations (Stockmarr 1971). An Olympus BX41 microscope with a magnification of 400X was used for the analyses. Identification of the pollen was guided by the following pollen floras: Faegri &

Fig. 3. Overview of Haväng; Red ellipses show the study areas Öradekar and Havängsgården (closer to the shore). Satellite image via Google maps.

Iversen 1989, Beug 2004 and Moore et al. 1991. For additional guidance, the reference collection at the Department of Geology at Lund University was used. Approximately 400-500 pollen grains were counted in each sample, except for two samples where only around 200 pollen were counted because of few pollen found in each slide. The Tilia, version 2.0, computer software was used to calculate and visually display the result. The pollen percentage calculations were based on all pollen types, both terrestrial and aquatic because of the low number of aquatic pollen. Pollen zones were identified by visual inspection of the pollen diagram, taking into account changes in the dominant pollen taxa. For the description of the plant habitats the Nordic Flora (Mossberg et al. 1996) was used. In order to find evidence for a brackish or a saline influence, identifying dinoflagellates can be useful. These organisms can be found in the pollen samples as they are as durable as the pollen and survive the procedure for sample preparation. For identification of dinoflagellates Ning (2016) was used.

Fig. 4. Red dots indicate the Örade 1 and Örade 2 coring sites. Satellite image from Google Maps.

2.8 Macrofossils

The remains of, for example, plants, insects, and shells from gastropods aid the interpretation of the local environment at a certain time. They also reveal the hydrological conditions, for example if an area was waterlogged or characterized by dry conditions.

Macrofossil analysis was conducted on 14 samples on the Örade 1 sediment sequence. The distance between the samples was approximately 50 cm, but additional sediment samples were analysed in between if the sediments visually presented parts of shells or larger twigs. The samples were carefully washed with water in sieves with the sizes 500 µm, 250 µm and 100 µm and then placed in separate containers. The smallest sieve size was chosen to try to locate any foraminifera and if so, identify species and determine if brackish water species were present. The samples were then analysed with a WILD-Heerbrugg stereo microscope using a magnification of 150X. The macrofossils were identified using reference articles (Frenzel 2006; Birks 2007; Mauquoy & Van Geel 2007) and the macrofossil reference collection at the Department of Geology at Lund University. Fish scales found were identified (2016-04-21) by Adam Boethius, PhD student in Historical Osteology, Lund University. The Örade 2 core was not analysed because of time restrictions.

3 Results

3.1 Dating

From the Örade 1 sequence, the five ^{14}C datings at 476-477 cm, 445 cm, 380 cm, 300 cm and 50 cm depth yielded the following approximate calibrated ages: 10,800-11,100 cal BP, 10,200-10,300 cal BP, 8500-8600 cal BP, 8200-8300 cal BP and 6 300-6400 cal BP (Table 1). The sample from the Örade 2 sequence at 277-278 cm depth was calibrated to approximately 8200-8300 cal BP. From the Havängsgården core six ^{14}C dates were established, at 349-350 cm (8200-8300 cal BP), 230 cm (8030-8160 cal BP), 145 cm (4700-4900 cal BP), 119 cm (approximately 7000-7200 cal BP), 114-115 cm (approximately 7700-7800 cal BP) and 75 cm (530-630 cal BP).

The sandy layer in the Havängsgården sediment sequence contained two sub-layers which were discovered when preparing for the OSL-datings, one sub layer with coarser material and one with slightly finer. The results from the two samples showed an overall age between 3700 and 5500 years (Table 2). The dose from sample 15104 showed a higher dose-spread than the 15103 sample.

3.2 Lithology

The Örade 1 sequence is dominated by different gyttja layers with interbedded sandy layers (Table 3). Sandy gyttja is found in the deepest part of the sequence. Sand is also present at 401-422 cm. A thin sand layer appears at 392-393 cm depth, on top of a fine detritus gyttja. The upper layer consists of a highly humified fen peat, overlying a coarser fine detritusgyttja.

The Örade 2 sequence displays calcareous clay and silt in the bottom followed by coarser fine detritus gyttja on top (Table 4). Above that, finer detritus gyttja has been deposited and towards the present ground surface three layers of fen peat have been deposited. The first peat in the order, from bottom to top, includes pieces of wood and plant remains.

The Havängsgården sequence displays a variable lithology shifting between sand and algal fine detritus gyttja but also with an intermixed layer of gyttja and sand between two layers of gyttja (Table 5). A fen peat unit is found at the very top, only 18 cm thick.

Table 1. ^{14}C dates and calibrated age ranges from the three sequences.

Lab. no.	Sample (depth)	^{14}C age (BP)	Calibrated age (cal BP, 1σ)
LuS 11553	Örade 1, 50 cm	5520±50	6285-6395
LuS 11554	Örade 1, 300 cm	7410±55	8185-8315
LuS 12885	Örade 1, 380 cm	7780±45	8480-8605
LuS 12886	Örade 1, 445 cm	9060 ±60	10,180-10,260
LuS 11555	Örade 1, 476-477 cm	9615±60	10,795-11,135
LuS 11888	Örade 2, 277-278 cm	7460±50	8205-8345
LuS 12887	Havängsgården, 75 cm	560±40	530-630
LuS 11556	Havängsgården, 114-115 cm	6895±55	7680-7790
LuS 10975	Havängsgården, 119 cm	6180±50	7010-7165
LuS 10976	Havängsgården, 145 cm	4270±45	4720-4875
LuS 12888	Havängsgården, 230 cm	7275±50	8030-8160
LuS 10977	Havängsgården, 349-350 cm	7450±50	8205-8335

Table 2. Results from the OSL dating of the two sub-layers of the sand unit at 123-145 cm in the Havängsgården sequence. Data from Alexanderson (2016).

Lab. no.	**Depth (cm)**	**Age (years)**	**Dose (Gy)**
Lund 15103	123-130	5100± 400	11.3 ± 0.1
Lund 15104	130-145	4200± 500	9.3 ± 0.7

Table 3. Lithology of the Örade 1 sequence.

Depth (cm)	**Lithology**	**Remarks**
0-50	Highly humified fen peat	Plant remains
51-150	Coarser fine detritus gyttja	Gradual transition to upper layer. Shell fragments at 130-150 cm.
150	Silty gyttja	Fine band, 2-3 mm, with beige colour. A few shell fragments. Relatively sharp upper boundary.
150-391	Fine detritus gyttja	Wood fragment at 322 cm. Relatively sharp transition to upper layer.
392-393	Fine sand	Gradual transition to upper layer.
394-400	Fine detritus gyttja	Silty, sharp transition to upper layer.
401-411	Sand	Fine to medium grained sand, sharp transition to upper layer.
412-422	Sand	Fine to medium grained sand. Organic bands at 416-418 cm. Gradual transition to upper layer.
423-436	Sandy gyttja	Bands of medium grained sand. Gradual transition to upper layer.
437-455	Clayey gyttja	Compact, dark brown to black colour, gradual transition to upper layer.
456-481	Silty clayey gyttja	Dark brown colour. Bands of fine grained sand. Relatively sharp transition to upper layer.
482-487	Fine sand	Light grey brown colour. Coarser grain size at the bottom of the layer. Sharp transition to upper layer.
488-490	Sandy gyttja	Dark brown colour. Fine grained sand. Gradual transition to upper layer.

Table 4. Lithology of the Örade 2 sequence.

Depth (cm)	Lithology	Remarks
0-11	Fen peat	
12-25	Highly humified fen peat	Mineral particles, sand, diffuse transition to upper layer.
26-75	Fen peat	Wood pieces, plant remains, gradual transition to upper layer.
76-220	Fine detritus gyttja	Layers of fine detritus gyttja with plant remains. Gradual transition to upper layer.
221-284	Coarser fine detritus gyttja	Wood pieces, plant remains. Relatively sharp boundary to upper layer.
285-330	Calcareous clay and silt	Coarser calcareous material in the bottom and calcareous clay interbedded with sand above. Some shell fragments. Colour variation from pale beige to reddish brown. Relatively sharp transition to upper layer.

Table 5. Lithology of the Havängsgården sequence.

Depth (cm)	Lithology	Remarks
0-18	Fen peat	Remains of Carex/grass
19-122	Algal fine detritus gyttja	Silty. Thin roots probably from plants forming the overlying fen peat. Gradual transition to upper boundary.
123-145,5	Sand	Gradual transition to upper boundary.
146-194	Algal fine detritus gyttja	Low minerogenic content. Plant remains. Sharp upper boundary.
195-218	Gyttja/sand	Mixed together. Relatively sharp upper boundary.
219-352	Algal fine detritus gyttja	290 cm: wood (*Pinus?*) Some fine sand content. Plant remains, 267 cm: wood (*Alnus?*).
353-392	Sand	

3.3 Grain size

The results from the grain-size analyses from the Örade 1 and the Havängsgården sequences show that the sediments at the sampled levels are very well sorted (Fig. 5-8). The Havängsgården sand layer at 123-145 cm depth was visually regarded to be one consistent layer, thus the dry sieving was performed on the entire sand layer (123-145

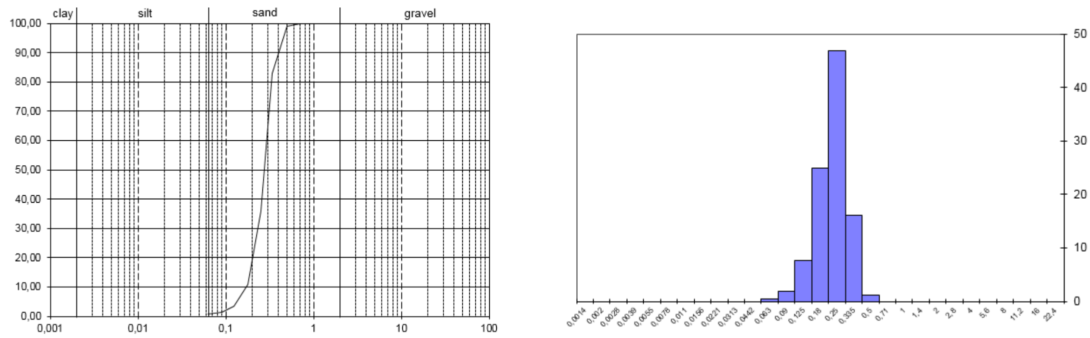

Fig. 5. Grain-size distribution of the sample from 400-411 cm in the Örade 1 sequence. Very well sorted sediments. Y-scale= percentage, x-scale=grain size, mm.

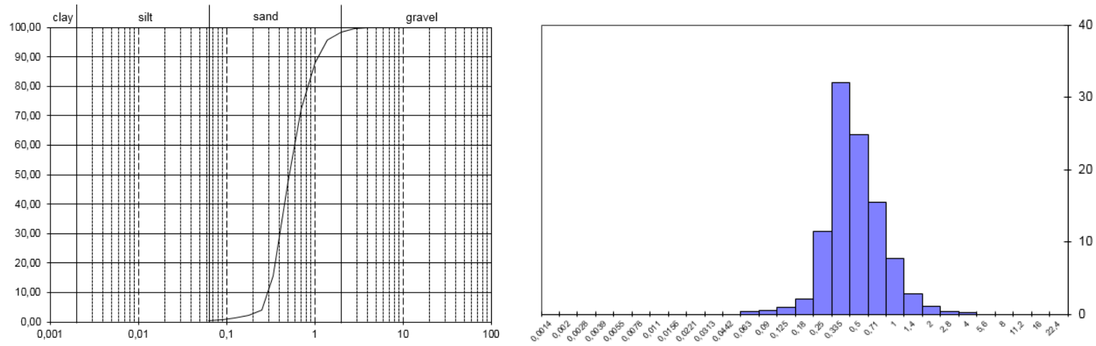

Fig. 6. Grain-size distribution of the sample from 353-392 cm in the Havängsgården sequence. Very well sorted sediments. Y-scale= percentage, x-scale=grain size, mm.

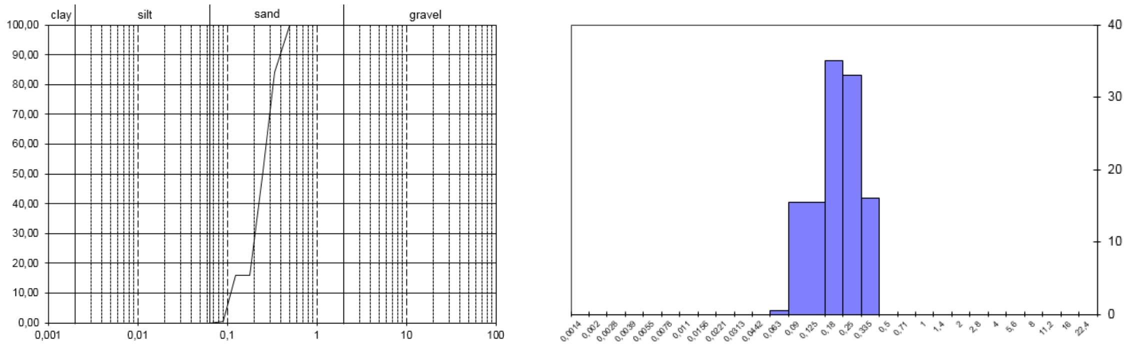

Fig. 7. Grain-size distribution of the sub-sample nr 15103 (123-130 cm) in the Havängsgården sequence. Very well sorted sediments. Y-scale= percentage, x-scale=grain size, mm. Values from the OSL dating report by the Lund Luminescence Dating Laboratory. In the OSL preparation 0,125 mm is excluded (Alexanderson 2016), an extrapolation was done towards the finer fraction.

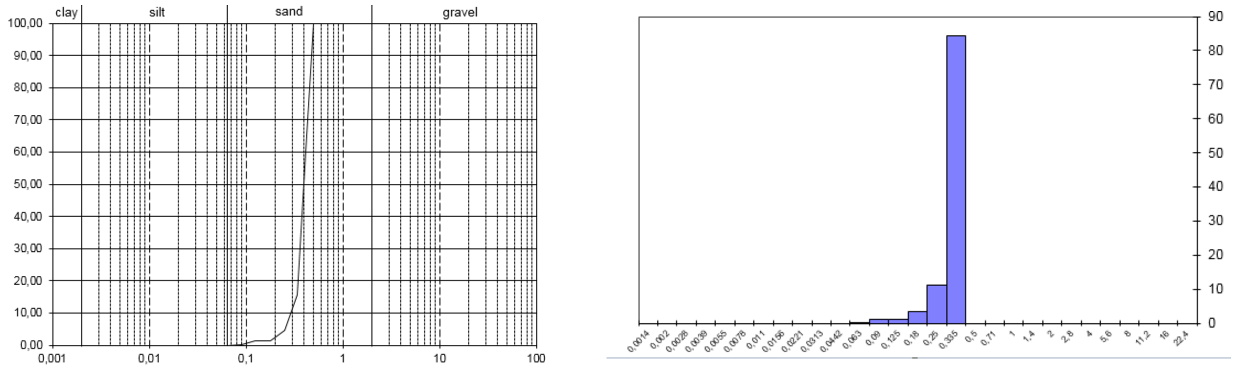

Fig. 8. Grain-size distribution of the sub-sample nr. 15104 (130-145cm) in the Havängsgården sequence. Very well sorted sediments. Y-scale= percentage, x-scale=grain size, mm. Values from the OSL dating report by the Lund Luminescence Dating laboratory. In the OSL preparation 0,125 mm is excluded (Alexanderson 2016), an extrapolation was done towards the finer fraction.

cm). However, when the OSL dating analysis was performed on sand from the same location and depth, but from a different core, two sub-layers were identified, one with a slightly finer fraction, at 123-130 cm and one slightly coarser and better sorted at 130-145cm. Consequently, the result of the grain size analysis from the OSL preparation was used in this thesis and the dry-sieved result disregarded.

The grain size distribution for the sand units 123-130 cm and 130-145 cm in the Havängsgården sequence displays dominantly medium grained sand and smaller amounts of finer grained sand. The 15104 sample shows better sorting compared with the 15103 sample.

3.4 Magnetic susceptibility

The results from the Örade 1 analysis show peaks at 440 cm and above 50 cm. The Örade 2 sequence shows higher values in the bottom of the core, below 270 cm and also the top 30 cm. (Fig. 9). This correlates with the calcareous facies at the bottom and the peat at the top, although the peat starts at a lower level

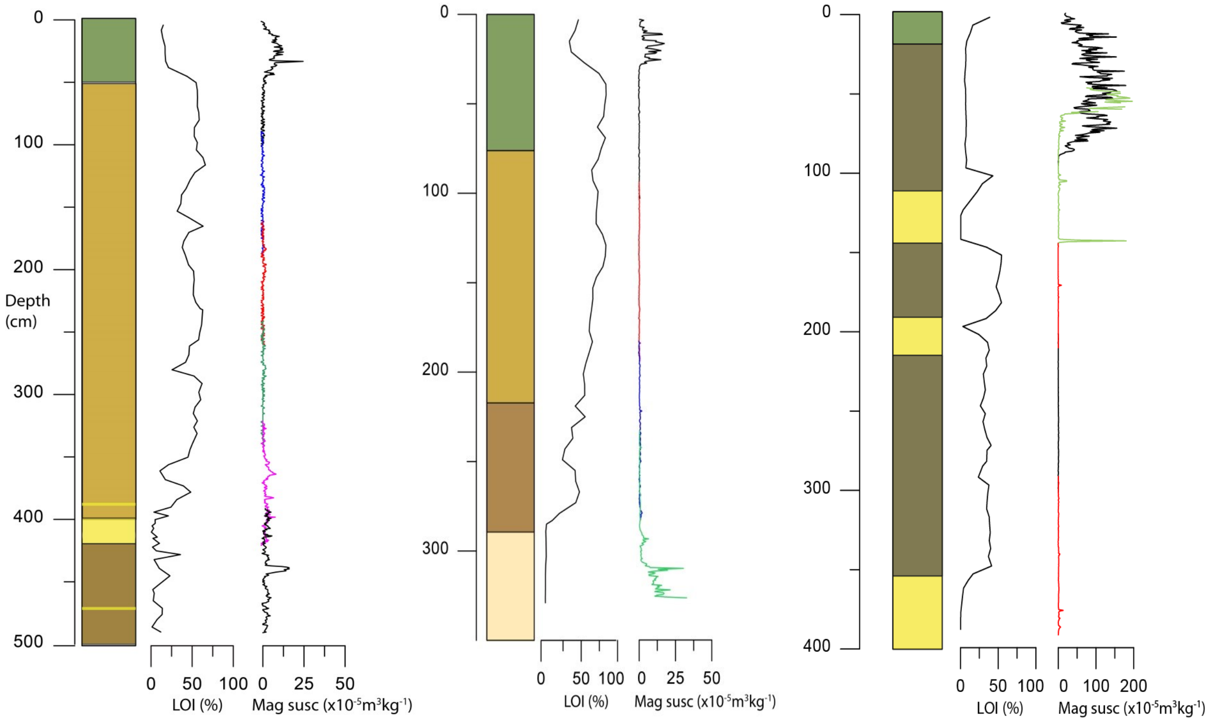

Fig. 9. From left: Lithology (simplified), LOI and magnetic susceptibility of Örade 1, Örade 2 and Havängsgården. Overlapping cores shown in different colours (Mag susc).

in Örade 2. The Havängsgården sequence yielded a highly diverse set of values. At the top there are differences in values at the same depth between overlapping cores. Despite re-measuring with a different core between 47 cm and 147 cm, there were very high values. This was probably caused by an insufficient contact with the core surface. The core had been used for other analytical purposes, thus leaving the cold room several times and being exposed to air. This was taken into consideration when cleaning and applying the measuring device, so that it was fit in the best possible way. In the graphic presentation the values were cut (green line in the Havängsgården plot) at 200 to exclude the highest measurement of 444 (Fig. 9).

3.5 X-ray fluorescence

The following elements were below detection limit in the analysed sequences.

Örade 1: Mn, Mg, Ni, Cl, Se, Co, Sb, W, Au, Bi.
Örade 2: Mn, Mg, Ni, Se, Co, W, Au, Bi.
Havängsgården: Mn, Ni, Cl, Co, W, Au, Bi

At 50 and 100 cm depth in the Örade 2 sequence, chloride (Cl) was detected. All other levels are below detection limit. In the Örade 1 and the Havängsgården sequences, Cl is below detection limit throughout. A selection of elements is presented in Fig 10-12. In the Örade 1 sequence there is a covariation between the elements Al and Si. Ca and Sr are relatively independent of the previously mentioned elements but show a closer relationship between each other. At 150 cm Ca and Sr peak. Fe peaks at 250 cm. The highest values of Ti is found at the very top and the bottom of the sediment sequence. Si follows the same pattern. P is highest at the very bottom of the sediment sequence.

The Örade 2 sequence shows covariation between Si and Zr, between Al, K and Rb and between Mo, Fe and S. At 298 cm, Si, Ti, K and

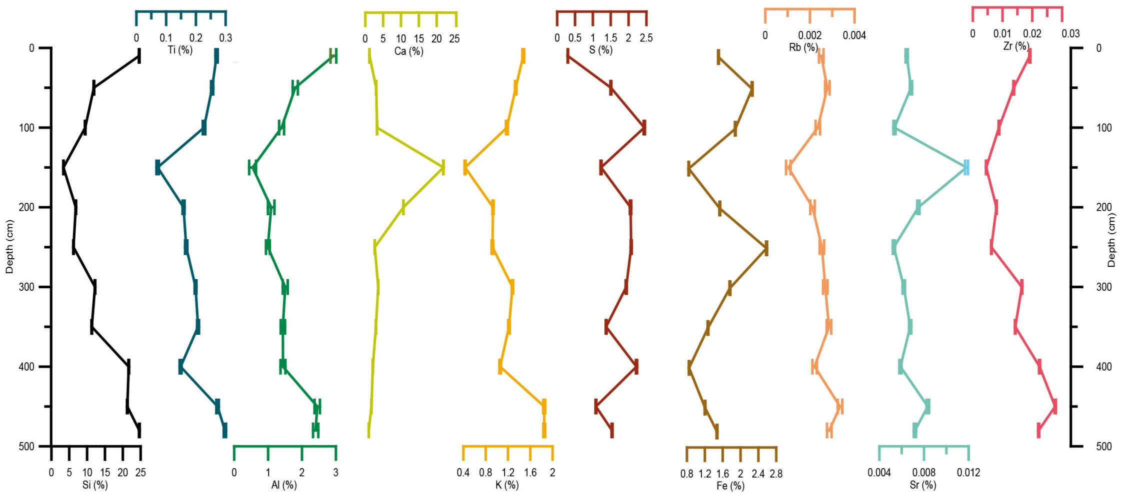

Fig. 10. Örade 1, results from the XRF-analyses for a selection of elements.

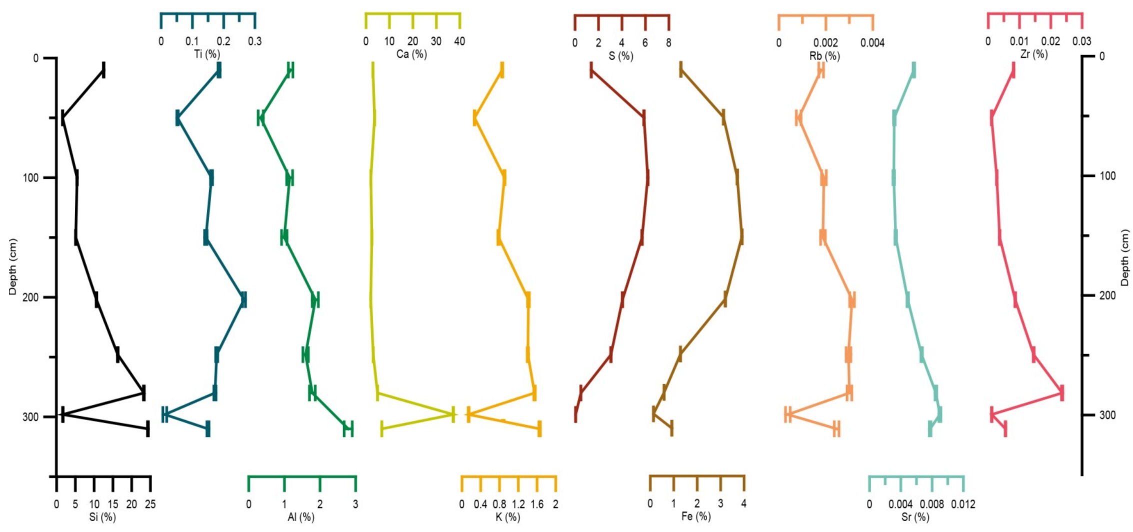

Fig. 11. Örade 2, results from the XRF-analyses for a selection of elements.

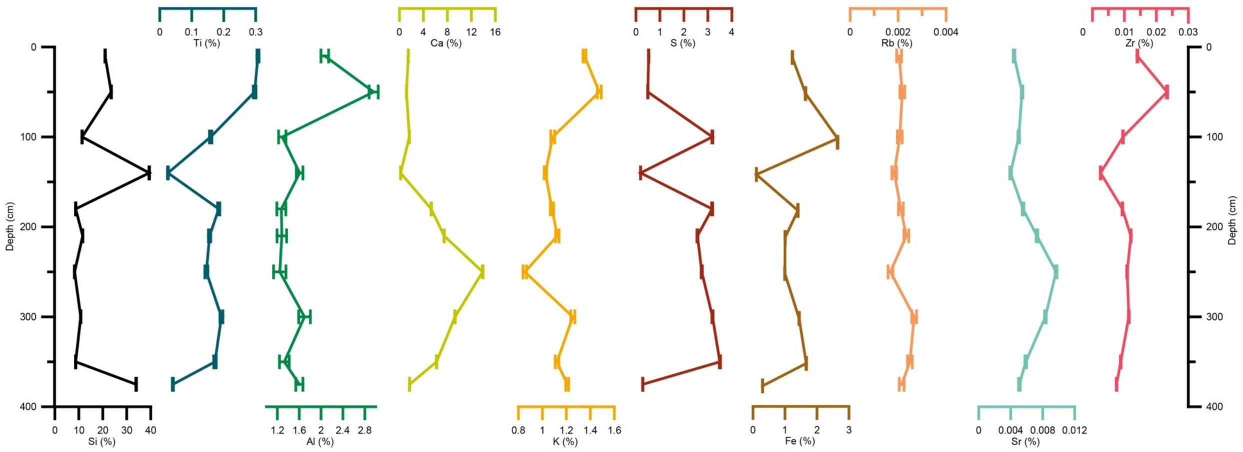

Fig. 12. Havängsgården, results from the XRF-analyses for a selection of elements.

Rb all show very low values but a distinct peak of Ca. Ca and Sr do not show closer connection with another element measured. The Havängsgården sequence displays some covariance between Ca and Sr but higher covariance exists between Ti and Zr and with K and Al.

3.6 Pollen

46 different pollen taxa were found in the Örade 1 sequence, although species level was only identified in some cases. The pollen diagram was divided into 6 pollen zones (Fig. 13).

In the sample from the lowest part of the core at 480 cm, predominantly *Pinus* pollen are found (79% of the total pollen sum). *Salix* is present (5%) and a few pollen of *Betula* together with grass (Poaceae) (10%), a few Brassicaceae and sea buckthorn (*Hippophaë rhamnoides*). A sharp decline in *Pinus* (to 22%) is seen and *Alnus* becomes dominant (32% of the pollen sum) between 480 cm and 400 cm depth. Also *Corylus* (12%), *Tilia* (6%) and *Betula* (3%) are present. In addition, Poaceae (14%) and sedges (Cyperaceae) (4%), and a few pollen grains of *Ranunculus* and meadow sweet (*Filipendula*), were found. Single pollen grains of *Viburnum*, *Galium* and the aquatic plant water-milfoil (*Myriophyllum alterniflorum*) were also recorded at 400 cm depth.

At 350 cm depth, there has been a change towards an increase of *Pinus*, now constituting 50% of all the pollen found, and a decline in *Alnus,* now 12%. *Corylus* (8%) *and Tilia* (8%) are present. *Quercus* and *Ulmus* are present but only with 4 pollen grains each.

At 300 cm, *Pinus* dominates by 70% and *Alnus* is only present by 4%. *Tilia* is still found in substantial numbers (10%). A few *Betula* grains are found together with herbs like *Filipendula,* Rosaceae and single horsetail (*Equisetum*)*,* and nettle (*Urtica*) grains. A significant increase in *Alnus* (35%) and *Betula* (17%) is seen at 250 cm, and *Pinus* (22%) is still abundant. *Ulmus* (6%), *Corylus* (6%) and Poaceae (4%) is present along with two grains of the aquatic plant whorled water-milfoil *Myriophyllum verticillatum* and a few other pollen of herbs like *Artemisia* and Asteraceae *(anthemis* type).

At 200 cm there are *Myriophyllum verticillatum* (0,8%) and a few *Myriophyllum spicatum* (spiked water-milfoil) grains found together with *Ranunculus* and bulrush (*Typha*). Pollen of trees like *Pinus* (22%) and deciduous species like *Alnus* (31%), *Ulmus* (5%) and *Tilia* (9%) are present. *Betula* constitutes 10% of the pollen sum. Poaceae is present (1%). One pollen of heather (*Calluna*) and *Solanum nigrum* (European black nightshade) and a few *Myrica*, *Viburnum,* and *Filipendula* are recorded.

An increase in pollen from deciduous trees at 150 cm depth is seen, especially *Alnus* (44% present), and *Corylus* (15%). *Tilia* remains at about 10 % of the pollen sum and *Ulmus* at 6%. *Pinus* constitutes 15% of the pollen sum and *Betula* 4%. Poaceae is found in higher numbers (4%) than the sample at 200 cm. Pollen of herbs from the family Apiaceae together with ivy (*Hedera helix*) is found. *Ranunculus* and *Urtica* are represented as well, but in low numbers.

At 100 cm, *Pinus* is found at 12% together with *Alnus* (30%) *Tilia* (12%), *Corylus* (10%) and *Betula* (8%), with *Quercus* and *Ulmus* at 7% each. Cyperaceae (4%) was found in higher numbers than Poaceae (1%) at this level. *Urtica* and Apiaceae pollen are more common than at previous levels but still only a few of each were found. Brassicaceae, Asteraceae Tubuliflorae, *Juniperus, Hedera helix* and Cyperaceae occur together with one single grain of *Rumex*. One hop (*Humulus*) pollen was identified.

Pinus (30%) and *Alnus* (20%) dominate the pollen sample at 50 cm. *Tilia* (13%) and *Corylus* is also present (14%) with *Quercus* and *Betula* (3% each) and *Ulmus* at 7%. Poaceae constitutes 10% of the pollen sum at this level. Herbs like *Filipendula* and Ranunculaceae occur but in very low numbers. Goosefoot (Chenopodiaceae), *Galium,* Ranunculaceae and *Juniperus* are all present but only one grain each was found.

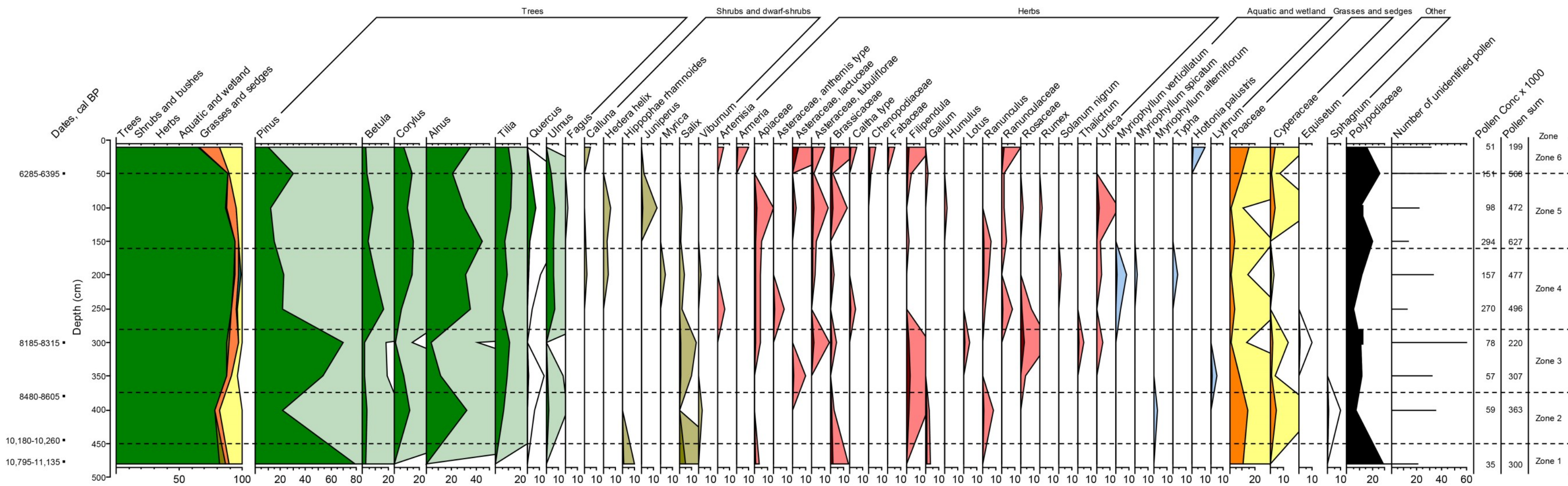

Fig. 13. Pollen diagram showing the percentage of each pollen taxon, total pollen concentration, pollen sum and zoning for the Örade 1 sediment sequence.

10 cm below the present day ground surface, *Pinus* was found in much lower numbers (10%) than at the previous depth. *Alnus* is abundant with 35% followed by *Tilia* (10%), *Corylus* (7%) and *Betula* (2%). Grasses and sedges are present with Poaceae (16%) and Cyperaceae (3%). Pollen of a variety of herbs were found like Asteraceae Lactuceae, Brassicaceae, water violet (*Hottonia palustris*), thrift (*Armeria*) and Chenopodiaceae, and one Fabaceae was also found. Apart from pollen grains, dinoflagellates were also found. At the depths of 50 cm (not identified to species), at 250 cm (probable dinoflagellate), and at 480 cm, one dinoflagellate cyst was identified (Fig. 14).

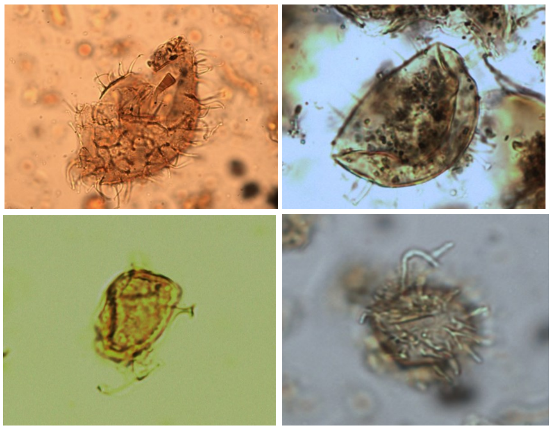

Fig. 14. Top left, unknown zoo-plankton remains at 350 cm. Top right, dinoflagellate cyst (Operculodinium centrocarpum) at 480 cm. Bottom left, probable dinoflagellate cyst at 250 cm. Bottom right, dinoflagellate cyst, probable Operculodinium at 50 cm. Photo: Anette Nilsson Brunlid.

3.7 Macrofossils

The 14 samples from the Örade 1 sequence contained remains of both plants and sand grains (predominantly quartz) virtually throughout. Fish scales were found at 416-418 cm. Two of the four fish scales found were identified as perch (*Perca fluviatilis*) but the other two were too fragmented to allow identification (Fig. 15).

The overall occurrence of fruits and seeds was low throughout the sequence, but seeds and fruits of *Carex,* Asteraceae, *Circium*, and *Betula* were found (Table 6). Large amounts of small-sized plant material were found throughout the samples but predominantly in the sample 95-97 cm. Leaves and stems of brown mosses (non-Sphagnum mosses) were present in the lowermost, as well as the uppermost part of the sequence. One *Pinus* needle was found at 248-249 cm.

Twigs and wood pieces were found at 150 cm, 320 cm and in all of the samples from 400 cm to 478 cm. A twig, identified as probable *Alnus* was found at 440-441 cm (Hans Lindersson, Head of the Dendrochronology lab at Lund University, personal communication, 2015-05). Four opercula of the gastropod faucet snail or common Bithynia (*Bithynia tentaculata*) were found at 150 cm depth, and one operculum at 189-191 cm. Characeae oospores were found at 189-191 cm and 400-405 cm depth. Remains of Acari (Oribatida) mites were found in small numbers at various depths, the deepest at 418 cm (Table 6). Head capsule fragments of Chironomidae larvae were found in all samples above 387 cm (Table 6). Black round grains identified as fungal spores (sclerotia) of *Cenococcum geophilum* were found at 418 and 440 cm depth (Frenzel, 2006).

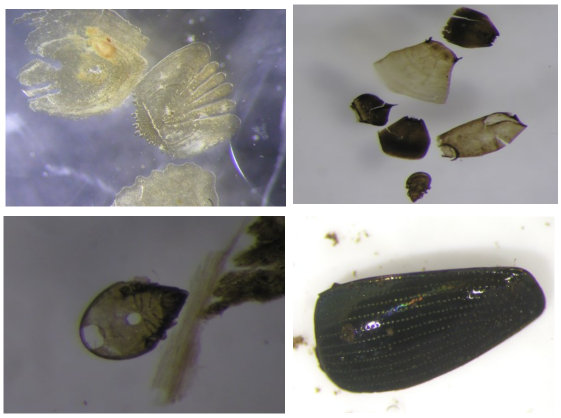

Fig. 15. Top left; fish scales from 416-418 cm in the Örade 1 sequence. Scale at right (center) is identified as Perca fluviatilis. Top right: unidentified insect remains and one Acari mite (bottom of the photo) found at 320-321 cm in the Örade 1 sequence. Bottom left; Acari mite at 320 cm in the Örade 1 sequence. Bottom right; unidentified Coleoptera fragment from 113 cm in the Havängsgården sediment sequence. Photo: Anette Nilsson Brunlid.

Table 6. Results of the macrofossil analysis of the Örade 1 sequence.

Depth (cm)	**Sieving size (µm)**	**Macrofossils**	**Remarks**
53-54	500	1 *Equisetum* root, 1 brown moss stem, unidentified plant fragments, 5 quartz grains.	
	250	4 parts of Chironomidae; head capsules mouth parts. >50 quartz grains. Unidentified plant fragments.	
	100	High amount of plant fragments. Lower amount of mineral grains including quartz and mica. 1 Chironomidae part. 1 fern sporangium.	
95-97	500	1 *Equisetum* root, 1 *Equisetum* stem part. 1 *Carex* seed. Few quartz grains. 3 twigs (0,4-1,5 cm thick).	
	250	100 quartz grains, 10 Chironomidae parts. Plant fragments.	
	100	High amount of plant fragments, few quartz and mica flakes.	
113		Coleoptera fragment visible on the surface.	
150-152	500	4 *Bithynia tentaculata* opercula. 1 *Carex* seed. 2 wood pieces, 0,5 cm x 0,03 cm. 1 Coleoptera part. Few Chironomidae head capsules. Plant fragments.	
	250	Not analysed.	
	100	Not analysed.	
189-191	500	1 probable *Cirsium* seed. 1 *Betula* seed. Few other unidentified plant material.	
	250	1 *Bithynia tentaculata* operculum. 100 Characeae oospores. <10 Chironomidae head capsules. 1 Acari (oribatide) mite. 10 quartz grains.	
	100	<50 Characeae oospores. 1 Acari (oribatide) mite. <5 Chironomidae parts. 100 quartz grains, few mica. Plant fragments.	
248-249	500	1 wood piece, 1,5 x 0,03 cm. 1 Brassicaceae seed. 1 *Carex* seed. 1 *Pinus* needle scale. 1 unidentified seed.	
	250	<5 Chironomidae head capsules. 1 Poaceae stem. <5 quartz grains. Plant fragments.	
	100	>10 Chironomidae head capsules. 1 Acari (oribatide) mite. <10 fern sprorangia. <50 quartz grains.	
295-297	500	2 twigs, 0,5-1 cm x 0,04 cm. 1 *Betula* seed. 2 probable *Filipendula* seeds. Plant fragments.	
	250	>100 plant material. 5 quartz grains.	
	100	Plant fragments. Few quartz grains.	
320-321	500	<5 wood pieces, 1,5 x 0,5 cm. 1 *Betula* seed. 1 *Carex* seed. >10 root fragments. 1 stem fragment. 1 bark fragment.	
	250	<5 Chironomidae body parts. <5 Acari (oribatide) mites. Plant material.	
	100	<10 *Cenococcum geophilum* spores. <100 quartz and other mineral grains. Plant fragments.	

Depth (cm)	Sieving size (µm)	Macrofossils	Remarks
395-400	500	NOT ANALYSED	
	250	6 unidentified seeds/fruits. 1 probable *Urtica* seed. <5 Characeae oospores. 1 brown moss stem. <5 wood fragments. >100 sand grains, mostly quartz with a few calcareous particles. Plant fragments.	
	100	High amount of sand. Mostly quartz but also a few mica flakes. Plant fragments. 1 Chironomidae part.	
416-417	500	>10 wood fragments and twigs, 2 x 0,5 cm. 6 seeds, 4 unknown and 1 probable Asteraceae and 1 probable *Cirsium*. 1 unidentified leaf. 1 Brown moss stem. <10 quartz grains.	4 Fish scales, 2 *Perca fluviatilis,* 2 unknown.
	250	<100 brown moss leaves. 1 unidentified seed. Wood and plant fragments. Few sand grains, mostly quartz.	
	100	Sand grains, mostly quartz, few mica flakes and some calcareous grains. <10 probable *Cenococcum geophilum* spores.	
418-420	500	>100 plant and wood material. 1 unidentified bark piece. *Pinus* seed. 1 probable *Ranunculus* seed. <50 Brown moss stems. Few quartz grains.	Wood pieces have a dark brown to black colour.
	250	Mostly sand, quartz and few mica flakes. >50 brown moss leaves. Plant fragments. Few unidentified bark fragments.	
	100	Sand, mostly quartz. 1 Acari (oribatide) mite. >10 *Cenococcum geophilum* spores.	
423-425	500	<5 wood pieces, 3x3cm, 1,5x1cm, 1x1cm. <5 brown moss stems. <5 quartz grains.	
	250	1 brown moss leaf. >100 quartz grains. Plant fragments.	
	100	>100 sand grains, mostly quartz. Plant fragments.	
440-441	500	1 *Alnus* twig. >10 unidentified wood pieces. <10 quartz grains.	Wood pieces have a black colour.
	250	>100 plant remains. <10 stems, roots. >100 quartz grains.	
	100	>100 sand grains, mostly quartz, some mica flakes. >100 *Cenococcum geophilum* spores.	
478-479	500	2 wood fragments 1 x 0,5 cm. >10 plant remains. < 5 quartz grains. 1 mica flakes.	
	250	>100 sand grains, mostly quartz. <100 plant remains.	
	100	Mineral grains, quartz, mica flakes and others.	

4 Discussion

4.1 The use of X-ray fluorescence data for palaeoenvironmental reconstruction

Sediment deposited in lacustrine or marine environments vary in terms of chemical and physical composition along with local and regional biological characteristics (Davies et al. 2015). Davies et al. (2015) discuss with the background of earlier papers by e.g. Boyle (2001) and Engström & Wright (1984) the importance of combining geochemical methods with other proxies to obtain more reliable results.

Iron (Fe) is derived mainly from terrigenous sources, originally from the erosion of rocks. It can dissolve easily and bond to other elements, for example forming iron sulphid and iron phosphates. Rothwell (1999) suggests high amount of Fe together with, Ti, Si, K and Al is an indication of coastal erosion but could also be indicators of aeolian processes.

The use of concentrations of certain elements and their ratios as palaeosalinity indicators is debated. Chlorine (Cl) has been used as a marine indicator by Tjallingii et al. (2007). The elements and ratios of strontium (Sr) and barium (Ba) are according to Chen et al. (1997) indicators of marine transgressions because of the higher values of these elements in seawater when compared to freshwater. Strontium was rejected by López-Buendía et al. (1999) as an indicator for palaeosalinity. This is because of strontium being an element in aragonite and calcite, the forms of calcium carbonates that mollusk shells are built off. They, however, concluded from their study of an island bog and a coastal marsh that instead bromine, sodium, germanium, uranium and iodine were the main geochemical indicators of salinity. Since only uranium was measured in this analysis, this approach is not possible in this thesis.

It is difficult to draw definite conclusions of a supposed marine influence at the sites, based on the present XRF data. When studying the literature about the application of XRF to Quaternary sediments, it is clear that data from various studies can have the same elemental composition but may be interpreted differently, and is depending on environmental settings like climate and temperature. Additional proxies (for example diatoms) must be used to confirm or decline a potential saline or brackish influence of the sites, since the findings in this study does not show any such influences.

4.2 The character of the palaeoecological data and the inferred Holocene flora and fauna.

Although the pollen record from the Örade 1 sequence is of relatively low resolution, with approximately 50 cm distance between the samples, it is possible to identify trends and changes throughout the sediment sequence. The sampled site (Öreda 1) was a relatively small lake implying a local pollen signal (Seppä 2007). But airborne pollen transport and fluvial transported pollen from the Verkeån River probably provided a more regional distribution in the pollen record. The overall pollen preservation in the samples was not good, possibly due to post-depositional processes. Many pollen grains were corroded and/or folded and consequently hard to identify. Because of this, thick-walled pollen may have an overrepresentation of identified pollen in the results. The highest number of pollen found belonged to trees, dominated by *Pinus* and *Alnus* throughout the Örade 1 sediment sequence. Bushes such as *Salix*, *Juniperus,* and *Hippophaë rhamnoides* grew in different biotopes in the area at different times. A large diversity of herbs, from aquatic and wetland species to drier meadow and coastal beach plants were growing in the surroundings at different times. Deciduous trees like *Tilia, Ulmus* and a minor population of *Quercus* grew in the river valley, being dependent on the more nutrient rich soils surrounding the Verkeån River. *Corylus* grew in the undergrowth. Broad-leaved trees surround the modern day Verkeån River as well. In the moist surroundings of the former Öradekar lake and close to the Verkeån River, *Alnus* was thriving and small populations of *Betula* occurred. Alder swamps are common along the Baltic Sea coastline. They develop in waterlogged shallow depressions dependent on the groundwater level, which in turn is affected by sea level change (Gaillard & Lemdahl, 1994). On the sandier and drier soils *Pinus* dominated. *Artemisia,* Chenopodiaceae and *Armeria* can be found in the sandy beach environment.

Birks (2003) discussed the problem with discrepancies between pollen and plant macrofossil assemblages when trying to reconstruct the vegetation. Long-distance transported pollen can mix with locally derived pollen and create an overrepresentation. In this study the *Pinus* pollen with its large air sacks most likely represents *Pinus* populations that were not in close vicinity of the Örade area. Birks (2003) suggests validation with plant macrofossils in climate reconstructions. In the data presented here, the number of pollen assemblages and macrofossil finds, are too few to allow a detailed reconstruction of climate and vegetation. It is, however, interesting to note, for example, the abundance of *Pinus* in the pollen record, but only one needle in the macrofossil samples. *Carex* seeds were found at different levels during the macrofossil analysis, but no *Carex* in the pollen samples. Comparison of pollen and macrofossil data is, however, hampered by the relatively low sample resolution due to time restrictions and the fact that the data come from slightly deviating depths. Still macroossils have been included in the discussion of the different pollen zones.

The chitin headcapsules from the Chironomidae, non-biting midgets, of the order Diptera are preserved well in lake and bog deposits. The multiple larval stages of Chironomidae require an aquatic environment (Solhøj 2001). Remains of mites (Acari) in lake sediments often belong to the suborder called Oribatida of the Actinotrichida class. The mites have a wide range of habitats, from aquatic to tree dwelling species. Since they do not have wings they are often found *in situ* or in close proximity of their habitat (Solhøj 2001). Since the depth where the mites were found coincide with almost all levels of Chironomidae, this points to an aquatic environment.

Oospores from Characeae (stoneworts), macrophyte reproductive vessels, are common in clear and mineral rich lacustrine waters (Karlsson 2002). Also fond of lacustrine waters is *Bithynia tentaculata,* a freshwater mollusc with a preferred habitat in stagnant shallow, littoral waters (Szymanek 2013).

Cenococcum geophilum is an ectomycorrhizal fungus. That means that it acts in symbiosis with tree roots by producing a mantle to cover the roots, with both an inward growth of hypha (fungal tissue) and an outward growth of hypha to connect with the soil. It can then affect the nutrient and water uptake of the tree (Smith & Read 1997). It is one of the dominant species in forests in the Fennoscandian area (Jany et al. 2002; Dahlberg et al. 1997; Kåren et al. 1997). The finding of the fungus in the macrofossil record is in line with the results from the pollen analyses and confirms that trees were present in close vicinity of the site.

Dinoflagellates are small planktonic unicellular organisms, living in fresh, brackish or marine waters, some of them producing cysts that sink to the bottom and rests in the sediments. Sildever et al. (2015) showed that both abundance and species diversity of dinoflagellate cysts are lower at lower salinity. However, the very few dinoflagellates found when analysing the pollen samples at 50 cm (*Operculodinium spp)* and 480 cm (*Operculodinium centrocarpum*) do not prove to be enough for any major conclusions, although the *Operculodinium* is a brackish species. It cannot be ruled out that the dinoflagellates travelled by wind instead of water to the site.

4.3 The sedimentological and hydrological development

To interpret the different successions of the sediments in the Örade 1, 2 and Havängsgården sequences, it is important to consider the different sea level high and low stands. From Hansson et al. (2018), a sea level curve for the Haväng area was presented proposing the Yoldia Sea low stand at 24 m b.s.l., after the drainage of the Baltic ice lake at approximately 11,700 cal BP. The Ancylus transgression peaked in the area at 5 m b.s.l. at around 10,300 cal BP, and was followed by a regression down to 10 m b.s.l. The initial Littorina Sea began around 9800 cal BP and the Littorina transgression peaked at 4 m a.s.l. (Nilsson 1961) between 7500-6000 cal BP (Berglund et al. 2005; Kostecki et al. 2015).

4.3.1 The Öradekar Site

The sediment sequence of the Öradekar site was likely deposited in a former dead ice hollow, formed as a large ice residue melted and left a depression in the soft sediments predominantly composed of glaciofluvial sand. The silty gyttja at the bottom of Örade 1 indicates a lake, a calm environment not connected to the river. The gyttja is followed by a 5 cm fine sand layer on top, indicating a deposition from an overflow from the Verkeån River or an aeolian deposition. The oldest calibrated ^{14}C date comes from 476 cm in the Örade 1 sequence (10,795-11,135 cal BP), before or near the onset of the Ancylus transgression. This transgression is not likely to have influenced the Öradekar lake level due to the Ancylus peak at 5 m b.s.l. (Hansson et al. 2018) which is below the base of Örade 1 and 2 sediment sequences.

The sandy gyttja layer interbedded with sandy sublayers, beginning at 436 cm depth in Örade 1, transitions into sand with organic bands at 416-418 cm. This points to probable seasonal overflow from the river into the lake depositing sand above gyttja multiple times (436-423 cm). The river eventually eroded parts of the lake threshold and made a semi-permanent connection to the lake, depositing sand, decreasing the water level and eroding parts of the gyttja leaving sand with organic bands (416-418 cm). In the organic bands, scales from perch were found, further indicating that the lake was in fact connected to the river. The connection would also explain the presence of numerous wood pieces, twigs and bark fragments and in some of the samples, brown moss stems that indicate erosion for example at 416-417 and 423-425 cm. Veski et al. (2005) interpret sand with laminated band of organic material, in an area surrounding the Pärnu River in Estonia, as a transgression sequence. This is according to the datings at 445 cm (10,180-10,260 cal BP) unlikely to have occurred at the Öradekar site because the sea level at the time was a few meters below present day sea level.

The sand in the Örade 1 sequence, disappears at 400 cm and fine detritus gyttja is deposited. This proposes a transformation from a high velocity depositional environment, the site being in connection and part of the river, to more stable, calmer and deeper waters, a lake. At this time the Verkeån River probably found a new path and left stagnant deep water behind. The pollen from aquatic plants together with the macrofossils of aquatic species point to a lacustrine environment with no saline or brackish influences.

The fine detritus gyttja is interrupted by a 1 cm fine sand layer at 392-393 cm. Veski et al. (2005) recognize a similar sand layer in between detritus gyttja in a coastal lake, as a storm surge. In their study, the overlaying peat was dated to 8400-8200 cal BP, contemporaneous with the cooling event at 8200 cal BP (Alley et al. 1997). The thin sandy layer in Örade 1, points to a storm deposit or a flood, however not likely in connection to the 8200 cal BP event. A sample extracted at 380 cm shows an age of 8480-8605 cal BP, and at 300 cm an age of 8183-8313 cal BP is indicated. This is 12 cm and 92 cm above the sandy layer.

Above the sandy layer, the fine detritus gyttja continues. Aquatic plants again indicate a fresh water lake. The peaks in Ca and Sr at 150 cm depth in Örade 1 are likely derived from mollusks as strontium is an element in aragonite. At this level *Bithynia tentaculata* a fresh water gastropod, was found in the macrofossil analysis. In the sample for the XRF, shell fragments were present.

The relative sea level of the Littorina maximum at 4 m a.s.l. (Hansson et al. 2018) reached the level of the Öradekar sites, but based on the lacustrine indicators mentioned above, a barrier built up during the Littorina transgression could have dammed the river outlet and created a barrier, behind which, the lake or lagoon, was protected from brackish influences. This is in line with the lagoonal formation during the Littorina Sea transgression proposed by Hansson et al. (2018).

A transition to a coarser (less decomposed) detritus gyttja occurs at 150 cm, followed by peat at 50 cm. This implies a lowering of the water level in the lake and since the onset of the peat formation is dated to 6283-6395 cal BP, this suggests a lowering of the groundwater table in response to the lowering of the Littorina Sea which favored overgrowth.

The sequence in Örade 2, which is closer to the basin shore, does not have any sandy layers, except for the calcareous silty sediment with sandy layers in the very bottom of the sediment sequence (284-330 cm). These calcareous sediments consist of a coarser layer, at the bottom, of possible cretaceous origin with fossil shells. These older sediments could have been transported by ice from the areas north of Haväng, in the Kristianstad area where Cretaceous bedrock is found. There are no calcareous sediments in the Örade 1 sequence, suggesting a local accumulation of sediments at the Örade 2 site. Tufa is formed by the precipitation of calcium carbonates from fresh water high in CO_2 and from water with dissolved calcium carbonates (Viles & Pentecost 2011). The clayey calcareous layers interbedded with coarser layers of calcareous sand resemble tufa as described by (amongst others) Gedda et al. (1999), but the interbedded sandy layers imply a more fluvial deposition than described by Gedda et al. (1999). There is also no apparent organic material, like plant remains in the sediment which would be expected. However a shell fragment of an unidentified Holocene gastropod was found in the coarser calcareous sediment. This suggests an underwater development of the deposit. The time of deposition of tufa in the county of Scania is proposed by Gedda et al. (1999), as having a starting point around the Younger Dryas-Preborial shift, approximately 11,500 cal BP, continuing to about late Boreal, 8500-7800 cal BP. Formation of tufa is favoured by low lake levels thus depending on precipitation and temperature (Gedda et al. 1999). The only dating from the Örade 2, at 277-278 cm, is 8205-8345 cal BP. This is during the initial Littorina Sea. The alleged tufa is formed before this timeframe when the lake level could have been very low, which speaks in favor of the tufa-hypothesis. However the results from the XRF show peak in Ca at 298 cm but considerable lower values at 280 and 310 cm. Si has the highest value at these depths together with Ba. Si is most likely derived from the sand fraction as well as Ba.

The coarser fine detritus gyttja at 284-220 cm transitions into fine detritus gyttja at 220-74 cm. This indicates deeper water. Since there is only one ^{14}C-dating (8205-8345 cal BP at 277-278 cm) it can be assumed that the formation of fen peat from 74 cm to the surface happened close in time with the fen peat formation in Örade 1, at around 6300 cal BP. At 50 and 100 cm depth in the Örade 2 sequence, chloride (Cl) was detected. All other levels are below detection limit.

4.3.2 The Havängsgården sediment sequence

The sediment sample from the algal fine detritus gyttja at 349-350 cm in the Havängsgården core is dated to 8205-8335 cal BP. This equals the time of the ongoing Littorina Sea transgression. The sand deposited just below, in the very bottom of the sediment sequence, was most likely deposited shortly before this time. The sand, moderately to well sorted with some gravel, indicates a higher velocity depositional environment. If the transgression reached the Havängsgården site at this time (before 8200-8300 cal BP) it could indicate beach deposits, but the transition to gyttja at 352 cm more likely suggests fluvial deposition. For example the river might have been forced to change path, perhaps as a consequence of damming by a sediment ridge build up due to the rising sea level. The change in the depositional regime to a calmer and deeper setting, indicated by the gyttja starting at 352 cm, suggests a lagoonal or lake setting. The dating at 230 cm is about 100 years younger than the dating at 349-350 cm (8205-8335 cal BP) but there is a considerable amount of sediment deposited (119 cm) during this time. This gives a sediment accumulation of approximately 1 cm per year. This is consistent with the proposed sediment accumulation in Hansson et al. (2018) at the initial Littorina stage at 9100-8600 cal BP. The ongoing transgression most likely disturbed the calm highly productive environment, as indicated by the gyttja/sand mixing at 195-218 cm. In contrast to the laminations in the Örade 1 sequence, the sediments indicate a higher energy environment, which eroded parts of the previously accumulated gyttja, mixing it with beach sand and redepositing it in the deeper parts of the lake.

The image of the geomorphology of the Haväng area (Fig. 16) shows the modern Verkeån River path. The area of the Havängsgården site (smaller ellipse) gives room for possible channel migrations as proposed above but also a lagoonal/lake development during the Littorina transgression. This lagoon could have acted as a blockage of saline water reaching the

Öradekare site (larger ellipse), creating a threshold by barrier build-up of sediments in the narrow river valley. Dilution of the brackish water could also have occurred when the fresh water from Verkeån River mixed with the brackish. The overlying algal fine detritus gyttja at 194-145 cm is dated (at the very top, (145 cm)) to 4730-4875 cal BP. This was a time when the Littorina Sea would have moved passed the site again due to the isostatic uplift lowering the sea level. The sharper transition from the mixed gyttja/sand layer, to the upper gyttja layer suggests a quick transformation to calmer and deeper waters.

The sandy layer at 123-145 cm depth at the Havängsgården study site visually appeared to be made up of only one layer. However when the OSL-dating was prepared, two different sub-layers were identified. The deepest of the two layers had a slightly courser grain size and was more well sorted than the other. This indicates deposition in a fluvial environment with a steady flow regime. The upper layer was deposited in a calmer but fluctuating flow regime due to the finer but less sorted appearance. The river probably was on the verge of changing path and the gradual transition to the gyttja layer above the sandy layers indicates stagnant water due to a final cut off from the river. The water level remained shallow regulated by groundwater, precipitation and occasional overflow from the river. Eventually overgrowth occurred and fen peat was formed.

4.3.3 The matter of the geochronological inconsistency in the Havängsgården sequence

The stratigraphical inconsistencies in the sequence from Havängsgården where seemingly older material has been deposited on top of younger sediments, yields questions about the cause for this sedimentological succession. If the datings are correct, the datings at 114-115 cm (7680-7790 cal BP), and 119 cm (7010-7165 cal BP) are considerably older than the sandy layer at 123-145 cm and the ^{14}C sample at 145 cm (4720-4875 cal BP). It is possible that the sample at 145 cm was contaminated by younger material, perhaps during the core retrieval, but the results from OSL-dating of the sandy layers (4000-5000 years old), point towards the ^{14}C sample at 145 cm being accurate. The two datings, from the mixed macrofossil material, at 114-115 cm and 119 cm, are calibrated between 7160-7790 BP. The ^{14}C sample at 114-115 cm depth was taken to rule out a possible contamination resulting in an incorrect dating of the sample at 119 cm. An additional dating at 75 cm, proved to be very young, only 600 years old. This young age could imply contamination by younger material when sampling.

If the datings are correct, this means that there has been a redeposition of older sediments on top of younger. According to Berglund et al. (2005) and Kostecki et al. (2015), the Littorina transgression had its peak between 7500 and 6000 cal BP. The ^{14}C-datings from 114-115 cm and 119 cm are roughly in this time span (7160-7790 cal BP). At this presumed high sea-level stand at the site, the sediment with the macrofossils were deposited on a higher ground level, probably on a (fluvial) terrace, upstream, created by the high water stand. When the sea level decreased, the sediments were left at the higher ground level until, for example undercutting the river banks by channel migration, caused erosion and slumping, which made the deposits fall into the river. The sediments were then transported to the Havängs gården site and deposited above the sand (dated to 4000-5000 cal BP).

The sand (at 123-145 cm) itself was probably deposited by fluvial processes during a possible channel migration into a previously stagnant water body (on top of already deposited gyttja sediments, dated to 4730-4875 cal BP). The lower boundary of the sand, towards the gyttja is sharp, indicating that erosion occurred. The sandy sublayer at 123-130 cm appears to be older than the sublayer beneath (130-145 cm). But when taking into account the uncertainties of the age span, and the variation of the dose spread of the two samples, resulting in the more reliable 123-130 cm sample (less dose spread), it cannot be ruled out that the two fractions of sand have been deposited in the same time frame.

In the Örade 1 and the Havängsgården sequences, Cl is below detection limit throughout. It is questionable that the Cl found in Örade 2, is an indicator of saline influences, as there is no indication of Cl in the Örade 1 or Havängsgården sequence, which is closer to the present shore. It can, however, not be ruled out that Cl is present somewhere else in the sequences not covered by the samples analysed in this study.

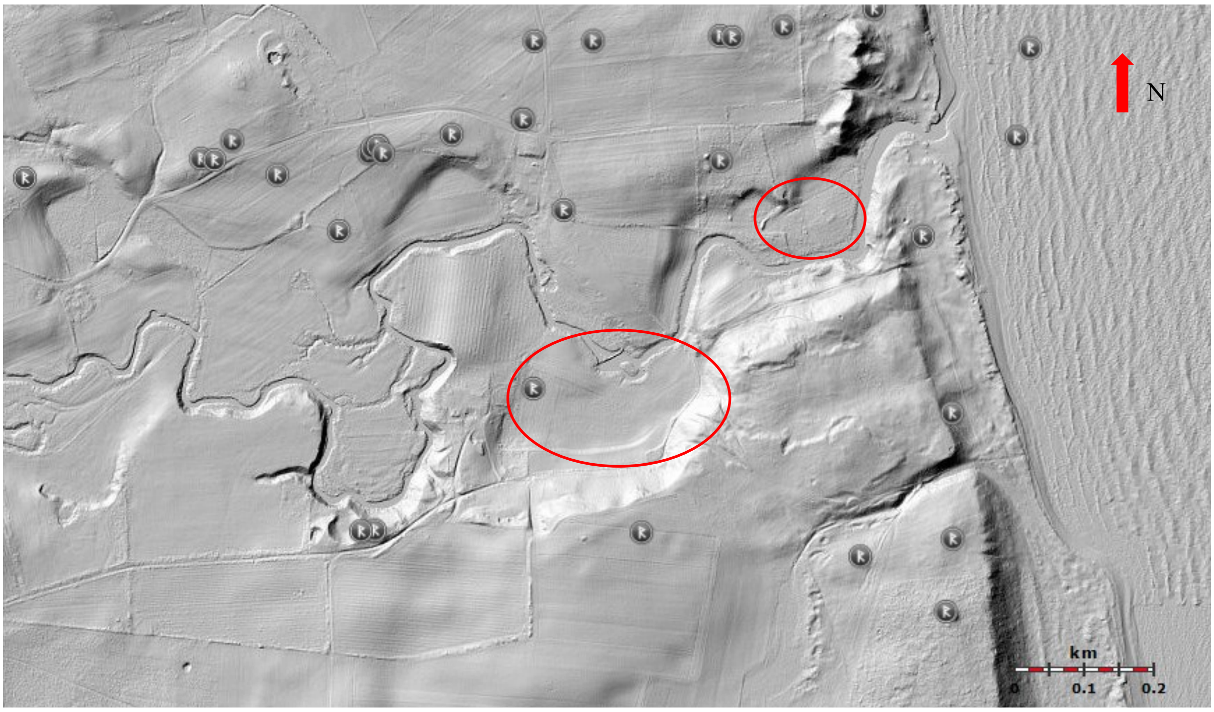

Fig. 16. Terrain shadowing image (LiDAR) of the Haväng area. Hanö Bay at the far right. Red ellipses show the Öradekar site (larger ellipse) and the Havängsgården area (smaller ellipse). The meandering course of the Verkeån-River is visible. R-symbols mark ancient cultural heritage sites. Modified image from Lantmäteriet, coordinates SWEREF 99 E, N 449788, 6174850 Scale 1:7559. From the National Heritage board of Sweden.

4.4 Reconstruction of the vegetation and aquatic habitat

4.4.1 Pollen zone 1

The area was dominated by pine forests and ground vegetation typical for the early Holocene. Open grounds allowed *Hippophaë rhamnoides* and Poaceae to thrive. A few *Betula* and *Salix* stands surrounded the lake. Dating in this zone at 476-477 cm and 445 cm showed between 11,150 and 10,100 cal BP. The Ancylus transgression began and peaked at approximately 10,800 and 10,300 cal BP respectively. The transgression drowned the former landscape outside Haväng, with its extensive forests predominantly of pine. The large amount of *Pinus* pollen clearly reflect the pine forest before the transgression sequence inundated the trees, because of the older dating, 10,795 to 11,135 cal BP, at 476-477 cm. This is the closest dating to the pollen sample taken at 480 cm. The *Pinus* pollen have large air sacks allowing them to travel by wind long distances, creating a more regional imprint in the pollen records. At 480 cm, one dinoflagellate cyst was identified as *Operculodinium centrocarpum*, a low saline species which is common today along the Baltic coast. It is not likely that this species was deposited by the sea, as in a transgression sequence, because of the low sea level at this time. The cyst could instead have been transported, for example, by wind into the lake.

4.4.2 Pollen zone 2

The drastic transformation of the landscape outside Haväng, due to the rapid transgression of the Ancylus lake, is visible in this zone. A clear decline in pine trees is seen compared to zone 1. This indicates that the Ancylus transgression affected the pollen signal by reducing the pine trees outside of Haväng. *Tilia* appears for the first time at 400 cm, together with *Corylus, Alnus, Ulmus* and *Quercus. Corylus* grew in the shade in the undergrowth of the trees. Taken into account the supposed hiatus at 401 cm, the middle of the zone could not be older than 8800 cal BP because this is the age when *Tilia* first appeared in the pollen records at Haväng (Hansson et al. 2018). The cause of this hiatus could be a connection with the Verkeån River, which deposited sand and partly eroded the underlying gyttja. The fish scales, belonging to perch, *Perca fluviatilis,* found at 416-418 cm, has two forms, one inhabits the brackish coastal waters, and one form migrates in fluvial (non–brackish) systems that enter the Baltic Sea (Tibblin et al. 2012). The fish scales supports the hypothesis of a connection to the river at the time of deposition. However, it was not possible to identify which of the perch species that the scales belong to, or how old they are. The fish scales could have been transported into the lake with floods or by reworking and deposition of older sediments containing these scales. The low number of fish scales does not enable any interpretation of population or a further definition of the ecosystem in which the fish swam. At 395-400 cm (in the fine detritus gyttja) the macrofossils consist of freshwater species like oospores from the family Characeae. Also found was one operculum from *Bithynia tentaculata*, and one Chironomidae head capsule fragment together with one Acari mite.

Filipendula, *Ranunculus* and Cyperaceae grew in the moist meadows. In the water grew *Myriophyllum alterniflorum.* Poaceae covered the hills and the drier areas. *Salix* has almost disappeared, probably out-competed by *Alnus* in the wet areas. The plant macrofossils found were brown moss stems and leafs, a *Pinus* seed, single (probable) *Ranunculus,* thistle (*Circium)* and Asteraceae seeds. A few (probable) *Urtica* seeds and single *Juncus* (rush) and *Filipendula* seeds. All macrofossils mentioned above are inhabitants of moist or wet biotopes. A probable *Alnus* twig was also found among several unidentified wood and twig pieces.

4.4.3 Pollen zone 3

Pine forests thrive on the sandy soils and peaks in this zone. A decline of alder occurs in this zone suggesting a change to drier climate. *Salix* is growing in small populations in the moist areas, together with *Urtica* and *Filipendula,* in close vicinity of the lake. *Tilia* is dominating the deciduous trees but *Corylus, Quercus* and *Ulmus* seem to have disappeared at 300 cm depth. The age at 300 cm was 8135 to 8315 cal BP, in time with the 8200 cal BP event, a short cooling episode lasting a couple of hundred years. Digerfeldt (1977) reported decreased numbers of broad-leaved trees at this time from Lake Flarken. However, Lake Flarken is situated in south central Sweden approximately 300 km northwest from Haväng. On the ground, moist meadow plants closest to the lake, *Filipendula* and *Thalictrum* grew and in the lake *Lythrum* could be found. On the more dry soils a diversity of herbs grew, like Rosaceae and Asteraceae together with *Lotus* and Brassicaceae. From the macrofossil analysis at depths within this zone, seeds of *Carex, Filipendula* and *Betula* were found. Fragment of Chironomidae, head capsules and an Acari mite were found in this zone with preferred habitats in fresh water lakes.

4.4.4 Pollen zone 4

The climate appears to have become more humid based on the increase of *Alnus*. *Pinus* holds a steady population after a decline compared to the previous zone. The small *Betula* populations seen in previous zones increase in the bottom of the zone, but decrease again towards zone 5. The deciduous forests close to the river is still dominated by *Tilia* but an increasing population of *Ulmus* and *Corylus* are evident towards the upper part of the zone. *Quercus* is present in a small population but likely suppressed by the denser forest. At the edge of the forest *Viburnum,* Ranunculaceae and *Hedera helix* was present. *Hedera helix* is an indicator for a mild climate. In this zone aquatic plants like *Myriophyllum, (M. verticillatum, M. spicatum* and *M. alterniflorum*) and near shore, *Typha*, was found. On the wetter areas around the lake grew *Myrica* bushes, and herbs like *Ranunculus* and *Caltha* were a part of the vegetation. Closer to the approaching Littorina sea shore, plants like *Artemisia* grew and on the sandy hills a vegetation of herbs like Apiaceae and Asteraceae flourished. *Urtica* and *Solanum nigrum*, plants related to human land use, were found in this zone. The macrofossils found in this zone were single Brassicaceae*, Circium* and *Carex* seeds. One *Pinus* needle*,* a *Betula* seed and a stem from Poaceae were also found. Oospores from Characeae at 181-191 cm, Chironomidae head capsules and one Acari mite were found in this zone, together with one operculum from *Bithynia tentaculata*.

4.4.5 Pollen zone 5

A steady population of trees was found in this zone, with no apparent large decline or rise in any species. However, *Alnus* decreases somewhat towards the upper zone (zone 6) perhaps as a result of increasing lake level drowning the trees closest to the river and lake. *Pinus* inhabits the drier grounds but seems to increase toward the upper zone (zone 6). The deciduous trees *Tilia, Corylus* and *Ulmus* still occupy the river surroundings but an increase in *Quercus* can be seen in comparison with the previous zone. One single pollen of *Fagus* was found in this zone. On the edge of the forest *Hedera helix,* Ranunculaceae and Apiaceae grew together with *Juniperus*. *Juniperus* could possibly also be found on the surrounding hills. Dry meadow herbs like Asteraceae*,* Brassicaceae and *Rumex* grew on open patches. Possible human presence could be indicated by the presence of *Urtica* and *Humulus*. The Littorina Sea likely peaked in this zone. There is no dating in this zone but at the transition between zone 5 and zone 6, (at 50 cm) the calibrated age was 6285-6395 BP. Seeds of *Carex* were found in few numbers in the macrofossil assemblage within this zone, but no other seed. *Equisetum* roots and stems and brown moss stems were also present. Opercula from *Bithynia tentaculata* were found in this zone at 150-152 cm, with parts of Chironomidae head capsules, all indicators of a fresh water environment.

4.4.6 Pollen zone 6

Alnus, *Pinus, Corylus* and *Tilia* increased in the lower part of the zone (50 cm) compared to the previous zone, but toward the upper part of the zone (10 cm) all trees decline and *Quercus* and *Ulmus* disappear alltogether. The dating at 50 cm was 6285-6395 cal BP. The gyttja from previous zones is replaced by a courser detritus gyttja and above that peat. This implies a lake level lowering caused by the retreating Littorina Sea which lead to an overgrowth. The decrease in trees suggests possible human impact, involving clearing land for animal grazing and cultivation.

On the sandy grounds closer to the shoreline of the Littorina Sea, *Artemisia, Armeria* and Chenopodiaceae grew. A diversity of meadow plants like Asteraceae Lactuceae and A. Tubuliflorae*, Galium* and Fabaceae thrived in the grassy meadows. The more moist areas were inhabited by *Filipendula* and *Caltha. Hottonia palustris*, was living in small open water patches on the more overgrown lake. No identifiable macrofossils of plants were found at this level.

4.5 Comparison to pollen analyses in previous studies

Gaillard & Lemdahl (1994) presented pollen data from sediment sequences from corings under water, ranging from Preboreal to Boreal time zones (11,500-8900 cal BP). These showed a similar dominance of *Pinus* in the early Holocene, as in the result from this study and the few *Betula* pollen are also in line with the results from Gaillard & Lemdahl (1994), suggesting it was not common close to the sites. Hansson et al. (2018) presented a pollen analysis from a sediment sequence from cores taken under water, ranging from 8600-9100 cal BP. The time span in Hansson et al. (2018) is roughly equivalent to pollen zone 2 in this study, showing similarities with the amount of *Pinus* (20%) and *Alnus* (c. 35%) but there are a few percent more of *Corylus, Betula* and *Ulmus,* found by Hansson et al. (2018). In common are also *Filipendula,* Ranunculaceae and Apiaceae*,* which show that similar habitats were present at both the Hansson et al. (2018) site and the Örade 1 site.

Other pollen diagrams from Scania, for example Lake Krageholmssjön (Gaillard 1984), show *Pinus* and *Betula* dominating the early Holocene, followed by *Corylus. Ulmus* followed by *Alnus* expanded at around 10,000-9500 cal BP and soon after *Tilia* is present in the pollen records. The succession cannot be compared in detail with the Örade 1 site, because the low resolution revealed *Corylus, Alnus, Ulmus, Tilia* and *Quercus* appearing for the first time in the same sample at 400 cm. The previous sample at 480 cm showed no pollen of deciduous trees. However the arrival of deciduous trees at Haväng happened between about 10,000 and 8500 cal BP, well in time with the same species in the pollen data from Krageholmssjön. A single grain of *Fagus* found in the pollen record for the Öreda 1 site, is in line with the late appearance (< 6000 cal BP) in the Krageholmssjön record.

5 Conclusion

The dramatic changes in relative sea level in the southern Baltic Sea from the onset of the Holocene to approximately 6000 cal BP left imprints in the sediment sequences retrieved from the Haväng area close to the modern day shore of Hanö Bay in SE Scania. During the Baltic Ice Lake (about 15,000-11,700 cal BP) the Haväng area was submerged in deep water, but became an inland area when the second drainage of the Baltic Ice Lake took place. The study sites were lakes that from time to time stood in connection to the Verkeån River. The vegetation at the beginning of the Holocene was dominated by *Pinus* trees with elements of *Betula*, bushes of *Salix* and grasses and plants such as Poaceae and *Hippophaë rhamnoides.* The Ancylus Lake transgression caused a decline in *Pinus* shown in the pollen records at Öradekar site by drowning the established forests outside the modern coastline. The transgression did not affect the two study sites hydrologically because the Ancylus maximum was below modern sea level. There are indications that the Öradekar site had very low water level and was in connection with the Verkeån River around this time.

During the Littorina transgression, the relative sea level was higher than the elevation of the two sites. However, the freshwater signature at the sites was preserved, proposing that a sediment ridge formed at the Verkeån River mouth, in the narrow river valley, created a calm lagoonal environment by damming the river. The lagoon probably maintained its protective threshold by sediment accumulation in pace with the rising sea level. This is in line with the proposed lagoonal development inferred by Gaillard & Lemdahl (1994) and Hansson et al. (2018). Pine trees dominated the vegetation on the more dry and sandy areas. Open deciduous forests with predominantly *Alnus* occurred on the moist shores of the lake and river*,* and *Tilia, Quercus, Ulmus,* and *Corylus* thrived in the river valley. *Hedera helix* climbed on trees at the edge of the forest during a warmer period from about 8000-6000 cal BP. On the moist grounds a variety of herbs like *Filipendula, Thalictrum, Caltha* and *Urtica* grew, and on the higher, dryer grassy meadows, Apiaceae*, Lotus, Galium* and Asteraceae thrived. A decline in trees is seen after 6000 cal BP suggesting human land use.

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