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This innovative journal is dedicated to the presentation, discussion and interpretation of the archaeological record of southern Scandinavia in its international, regional and local context. Providing a platform for publication and debate for professionals from the museum as well as the university sectors this journal is open for empirical, methodological and theoretical contributions covering all time periods and all kinds of archaeology with relevance for the Scandinavian, Baltic, and North Atlantic regions. In addition, the journal may publish articles of wider theoretical, discursive or global reach.

The *Danish Journal of Archaeology* includes original research articles, news and discoveries, and discussion pieces with the intention of fostering open debate about the archaeological record in its broadest sense and the position of archaeology as a discipline in the modern world.

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Cover: Trackway A20 being excavated in 2017 seen from the north (Photo: East Jutland Museum, article from Jesper Olsen et al.).

Contents

Editorial

Rune Iversen, Xenia Pauli Jensen, Thomas Grane, Helene Agerskov Rose, Sarah Croix and Lasse Vilien Sørensen

Danish Journal of Archaeology welcomes all archaeological contributions of relevance to the Scandinavian, Baltic and North Atlantic regions. Such a broad scope naturally results in very diverse topics, but we observe some underlying trends in this year's volume, which we believe also reflect current trends within archaeological research on a global scale. Organic materials are woefully underrepresented in the archaeological record, but several contributions investigate exceptional finds of wood, birch tar, animal hides and bone using multidisciplinary methodologies. These range from more traditional archaeological methods to both established and cutting-edge scientific methods, such as ZooMS, ATR-FTIR and radiocarbon wiggle matching. This successfully demonstrates that even the smallest sample has immense potential if we analyse it using the right methods. It also coincides with another trend, involving increasing interdisciplinarity and growing numbers of collaborations from several countries contributing to individual research projects.

The Scandinavian research landscape is vast and complicated, and the relevant information does not always end up with the relevant people, so that research projects miss out on important potential insights. The Danish Journal of Archaeology has decided to facilitate the sharing of knowledge by launching a new *Current Research* platform, where researchers are invited to share short notifications about their current projects with a wider, professional audience. It will be possible to make submissions from January 2025 via the homepage and we hope you will all support the initiative, and help create a project gallery with an updated overview of ongoing research.

The current volume of Danish Journal of Archaeology involves a diverse array of topics, ranging from contributions from international and interdisciplinary science-orientated research to considerations on current excavation practices, which are highly relevant in relation to the new Danish museum reform and ongoing discussions about the possible privatisation of Danish excavation practice. We will briefly introduce you to this volume's exciting papers here in chronological order.

The first of four research articles concerns the hafting of Neolithic leisters using birch tar. Between 2012 and 2022, extensive excavations took place in the Syltholm Fjord area in the southernmost part of the Danish island of Lolland, prior to the construction of the Fehmarn Belt tunnel connecting Lolland with the German island of Fehmarn. These very fruitful excavations keep adding new, valuable details and insights to our understanding of the local and regional developments at the Mesolithic-Neolithic transition and later. In this volume, we are happy to publish two fascinating studies that came out of the excavations and which both result from the extraordinarily good preservation of organic material at many of the sites. Pieces of birch tar are among the organic residues that have been recorded in the excavations in southern Lolland. Chewed tar has already revealed genomic details of one of Syltholm's now famous Early Neolithic inhabitants, nicknamed 'Lola', although as demonstrated by Tabea Joanna Koch and colleagues, birch tar played a previously unknown but important role in composite fishing tools. In their article on Neolithic leister hafting at Syltholm, the interdisciplinary and international team of authors successfully identify the performance of birch tar in aquatic environments, noting its adhesive and waterproofing properties.

The fruitful results of joint interdisciplinary efforts are also evident in the research article written by Jesper Olsen and colleagues, in which they present the in situ preserved Middle Neolithic trackway from Kastbjerg Å in eastern Jutland, Denmark. This significant wooden feature came to light together with a series of other well-preserved prehistoric and early historic trackways revealed during excavation campaigns undertaken by Museum East Jutland in 2015-2017. Thanks to high-precision dating they were able to date the trackway to 2911±5 BC using the wiggle match method, making it the oldest solid-built Neolithic trackway in Denmark. The interesting results provide new insights into the area's transport and communication routes facilitating the movement of wagons or carts and/or livestock.

Apart from in the exceptional conditions recorded at the sites mentioned above, organic materials are rarely preserved among archaeological remains. Danish wetland deposits, however, include a rich material of fur skin capes from the Early Iron Age, which were analysed by René Larsen et al. with the aim of identifying tanning substances and evaluating the condition of the material. The ATR-FTIR and GC-MS analyses, combined with visual examination using both light microscopy and the naked eye, showed the different processing of the capes, including stretching, tanning and other methods.

When did Viking Age Aarhus become a town of supra-regional importance? Did this happen early in the 8th and 9th century, or did it not occur until later in the 10th century, or not until the Middle Ages? With Moesgaard Museum announcing its intention to build a Viking Museum in the centre of the city to promote the importance of Aarhus as a Viking Age town, as a node in the network of Southern Scandinavia in the Early Viking Age, this research article by Jette Linaa contributes to current public discourse. As only a small part of Viking Age Aarhus has been excavated and little space is available for further excavations in the future, Linaa has looked at old excavations, examining some 16,000 finds to get answers. Using a method which measures the density of finds per m^3, Aarhus is compared to important contemporary sites, such as Haithabu, Ribe and Kaupang as well as local, rural sites. Based on the density as well of the nature of finds, the evidence leads to the conclusion that Aarhus was more like local, emerging townships, such as Odense and Aalborg, rather than a key player in a larger network of emporia, despite its location between Haithabu in northern Germany and Kaupang in Norway. The results thus undermine the arguments for building a new Viking museum in the centre of Aarhus.

In a debate article, Simon Kjær Nielsen and Johan Sandvang Larsen advocate adopting a responsive approach in field archaeology. The method of constantly evaluating is already practised, but the authors argue that the documentation of the prioritisation should also be systematically registered, in order to make the excavation process as transparent as possible.

In the first of two brief pieces, Daniel Groß and his international and interdisciplinary team of co-authors update us on the status of domestic animals from the Fehmarn Project. In their article 'Denmark's not-so-oldest sheep' the authors present new important and updated identifications of the so far oldest presumed ovicaprids using ZooMS analyses. These updated analyses enable the research group to demonstrate the important point that there are significant risks of misidentification using bone morphology alone when attempting to identify sheep and goat husbandry.

Another method of analysing archaeological objects is experimental archaeology, as presented by Henriette Lyngstrøm and her colleagues. This involves T-shaped wooden spades found in wetlands in Mid-Jutland – a find type associated with both surprisingly high-quality timber and careful and thorough manufacture. The experiments both shed light on the production of the spades and their efficiency. The authors conclude that the T-shaped spades were specialised tools, made from carefully selected oak, but are relatively easy to produce and well-suited for digging peat.

We hope you will enjoy this volume!
The editorial team

Hafting of a Neolithic leister: Identification of adhesives from Lolland (Denmark)

Tabea J. Koch[1,2,4], Daniel Groß[3], Bjørnar Tved Måge[3] and Aimée Little[2]

[1] Université Côte d'Azur, CEPAM, CNRS, Nice, France.
[2] YEAR Centre, PalaeoHub, Department of Archaeology, University of York, York, United Kingdom
[3] Museum Lolland-Falster, Frisegade 40, 4800 Nykøbing F., Denmark
[4] Corresponding author (tabeakoch@palaeome.org) ORCID: 0000-0001-9907-2554

ABSTRACT

Birch tar has been identified as the predominant adhesive used for hafting purposes in the European Mesolithic and Neolithic. Its role in the manufacture of composite tools and weapons comprising wooden, bone and flint components attests its importance during these periods. The discovery of birch tar lumps, some bearing tooth imprints, suggests a broader range of functions beyond its adhesive properties. In this study, we present an analysis of five residues from two sites (Syltholm II and Strandholm I) that have been excavated through the Femern project, with the aim to shed light on the adhesives used in relation to their functions. Through chemical analyses, we show that birch tar constitutes the main component of two lumps and one chewed piece. We also found that birch tar served to haft a bone point within leister prongs, providing new information on its previously unknown role in composite fishing tool technology. These findings have significant implications for our understanding of the functional role and performance of birch tar in aquatic environments.

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Introduction

Adhesives have been produced and used as early as the European Middle Palaeolithic (Grünberg et al., 1999; Mazza et al., 2006; Niekus et al., 2019; Schmidt et al., 2023). Birch tar (also referred to as birch bark tar or birch pitch), is the predominant adhesive identified in the archaeological record throughout prehistory. In more recent periods, adhesive types and their functionality diversified (Nardella et al., 2019; Rageot et al., 2021). Various discoveries of birch tar lumps (Binder et al., 1990; Regert et al., 2000; Vahur et al., 2011), some bearing tooth imprints (Aveling and Heron, 1999; Fuchs and Wahl, 2013; Jensen et al., 2019; Kashuba et al., 2019), attest the importance of this material across diverse Meso- and Neolithic contexts. During these periods, birch tar played an important role as a hafting adhesive for the manufacture of composite tools such as daggers (Bjørnevad et al., 2019; Manninen et al., 2021; Osipowicz et al., 2020), arrows (Larsson et al., 2016), or hafted bone points (Kabaciński et al., 2023; Mirabaud et al., 2015, p. 1007). To our knowledge, no previous studies have been conducted to investigate the role of adhesives in the composite technology of fishing equipment, and only few studies suggest that hydrophobic properties could be of advantage in such conditions (Kabaciński et al., 2023). To address this gap, we conducted chemical analyses to identify the residue on a hafted leister point recovered during the Femern project on Lolland (Denmark) (Stafseth and Groß, 2023). In addition, we included four other artefacts in our study: three nondescript pieces of residue and one chewed piece. The purpose being to chemically characterise and cross-compare similar appearing black substances.

All samples were recovered during the Femern project and come from waterlogged sediments in site complexes 4 and 5 in the former Syltholm fjord (Figure 1), dated to the Late Mesolithic and/or Neolithic. As the finds come from lacustrine environments that underwent changing depositional processes (erosions, accumulations, etc.) they cannot be easily contextually dated. Due to the potential intermixture of sediments, only direct dating can provide correct age determinations for the single finds. The chewed piece is one of the most prominent finds from the Femern project and a previous study revealed that it contains human aDNA material from a female

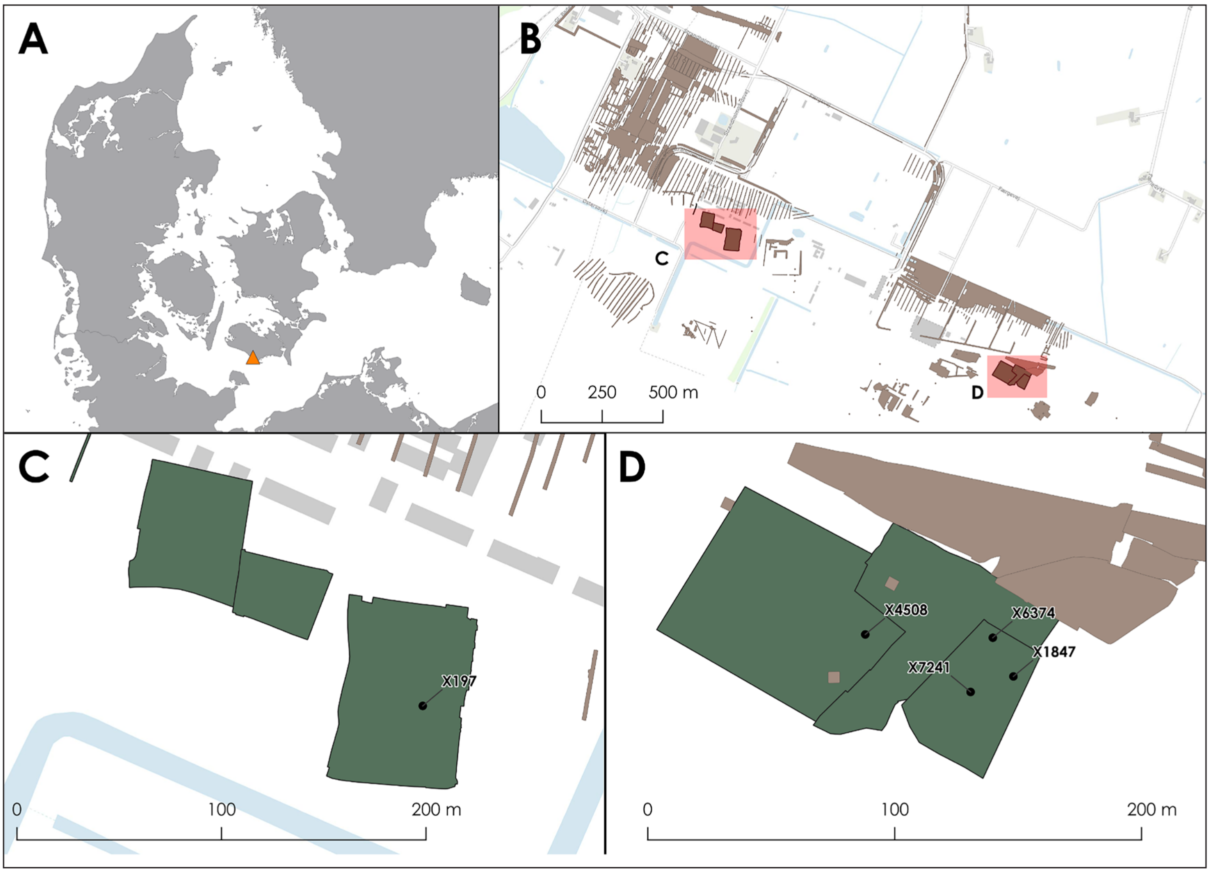

Figure 1. A) Location of the excavations from the Femern project. B) All excavation trenches from the project (brown) and sampled sites (green). C) Excavation trenches of the site Strandholm I (MLF00909) and find locations of the sampled artefacts. D) Excavation trenches of the site Syltholm II (MLF00906) and find locations of the sampled artefacts.

individual, dating to 3930-3710 cal. BC, from the site Syltholm II (MLF00906-II) (Jensen et al., 2019). Our findings of additional artefacts therefore help strengthen our understanding of the adhesives used at this site.

Materials & methods

Archaeological samples

We sampled residues from five different archaeological artefacts. These include a black substance adherent to the bone point found in situ with wooden leister prongs (MLF00909-II X197), three non-descript pieces/lumps (MLF00906-I X4508, MLF00906-II X6374 and MLF00906-II X7241) and one chewed piece (MLF00906-II X1847) (Figure 2). Two of these artefacts have been directly dated to the Late Neolithic (2020-1780 cal. BC for MLF00909-II X197; Måge et al., 2023, supp. mat.) and Early Neolithic (3930-3710 cal. BC for MLF00906-II X1847; Jensen et al., 2019).

Chemical characterisation

The samples were prepared using protocols adapted to the analysis of adhesive materials (for details on the extraction protocol, see Rageot et al., 2021, 2019). In brief, sample powders were solvent extracted using dichloromethane and derivatised with N,Obis(trimethylsilyl)trifluoroacetamide (BSTFA) and pyridine. We used two internal standards (Tetratriacontane and Hexadecane). The extracted and derivatised samples were analysed using a Shimadzu GC 2010 PLUS gas chromatograph equipped with an Agilent J&W HP-5MS GC Column (30 m length x 0.32 mm diameter x 0.25 µm film thickness). Mass spectra were recorded using a Shimadzu QP2010 ultra mass spectrometer and spectral acquisition spanned the range of m/z 50-950. A blank solvent sample was run to assess in-

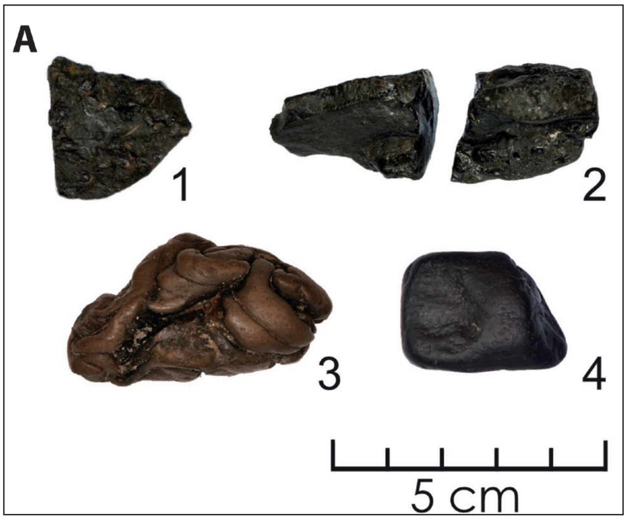

Figure 2. A) Sampled birch tar fragments from the site Syltholm II (MLF00906-II): 1 X6374; 2 X7242; 3 X1847. 4 is a piece of charcoal from Syltholm II (MLF00906-I) X4508, that was initially misidentified as potentially being birch tar. B) A hafted leister point in situ from the site Strandholm I (MLF00909-II): X197. Remains of the birch tar are visible on the proximal part of the bone point (red arrow) (copyright: Museum Lolland-Falster; after Stafseth and Groß 2023, Fig. 1).

laboratory contamination. Compound identification was done using the NIST library and previously published data (Aveling and Heron, 1998; Rageot, 2015; Reunanen et al., 1993).

Results

Four of the archaeological samples contained characteristic compounds indicative of birch tar (Table 1; Figure 3). These include specific biomarkers that can be associated with the molecular composition of birch bark (Aveling and Heron, 1998; Hayek et al., 1990, 1989), natural degradation markers, and molecular markers linked to birch tar production (Rageot et al., 2019; Reunanen et al., 1993). Betulinic acid and allobetulin were present in the leister and chewed tar, but absent in the two lumps that were identified as birch tar. Multiple combinations of diacids and unsaturated fatty acid were also detected. One of the nondescript lumps (MLF00906-I X4508) did not contain any triterpenoid compounds and only showed the presence of two unsaturated fatty acids. These were also detected in the control sample and can hence be regarded as contamination. A list of all compounds detected can be seen in Table 1.

Discussion

Our analysis presents the first chemical identification of birch tar as a hafting agent for prehistoric leisters and active fishing tools in general (see Stafseth and Groß, 2023) in Denmark, and possibly even Europe. While another specimen from the Ertebølle site Næbbet, settlement 24 (Skaarup and Grøn, 2004), shows a similar quality of preservation, no analysis of hafting agents has been conducted to confirm its composition. The identification of birch tar lumps, one bearing genetic material, further underscores both the favourable preservation conditions and the importance of this material in this region. In the context of fishing equipment, it remains unclear whether birch tar had a particular advantage over other adhesives for use in water contexts. Current research has assessed the performance of birch tar as a hafting adhesive (Koch and Schmidt, 2023; Kozowyk et al., 2017; Schmidt et al., 2022, 2021). However, no studies have addressed how these mechanical properties change under water. Still, birch tar has been suggested to yield waterproofing abilities, as shown in the context of coating organic or ceramic containers (Regert et al., 2003; Reunanen et al., 1993), which might also present an advantage for its use as a hafting adhesive in an aquatic environment. Kabaciński et al. (2023) suggest that birch tar on a composite point from Krzyż might have been used both for its

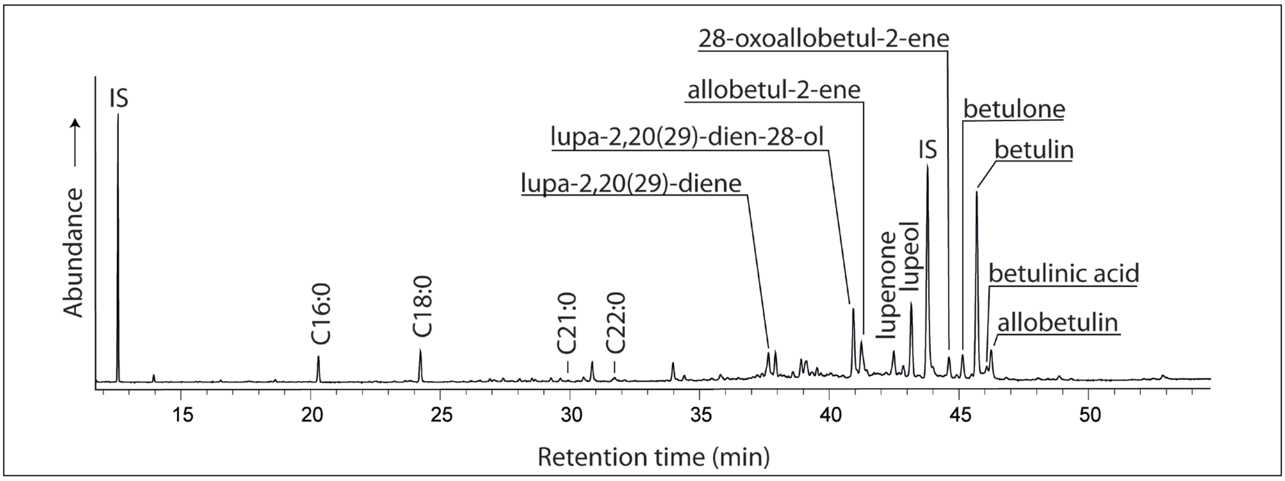

Figure 3. Chromatogram obtained through GC-MS analysis of the residue adherent to the leister bone point (MLF00909-II X197) indicating the presence of unsaturated fatty acids (CX:Y, X = number of carbon atoms, Y = number of saturations) and triterpenoid compounds characteristic for birch tar, IS = Internal Standard.

	MLF00906-II X1847	MLF00906-II X6374	MLF00909-II X197	MLF00906-II X7241	MLF00906-I X4508
Azelaic acid				✓	
Hexadecanoic acid	✓	✓	✓	✓	✓
Heptadecanoic acid		✓		✓	
Octadecanoic acid	✓	✓	✓	✓	✓
Heneicosanoic acid	✓	✓	✓	✓	
Docosanoic acid		✓	✓	✓	
Lupa-2,20(29)-diene	✓	✓	✓	✓	
Lupa-2,20(29)-dien-29-ol	✓	✓	✓	✓	
Allobetul-2-ene	✓	✓	✓	✓	
Lupenone	✓	✓	✓	✓	
Lupeol	✓	✓	✓	✓	
28-oxoallobetul-2-ene	✓	✓	✓	✓	
Betulone	✓	✓	✓	✓	
Betulin	✓	✓	✓	✓	
Betulinic acid	✓		✓		
Allobetulin	✓		✓		

Table 1. List of compounds identified in the archaeological samples from Lolland-Falster. MLF00909-II X197 = leister adhesive, MLF00906-I X4508, MLF00906-II X6374 and MLF00906-II X7241 = nondescript lumps, MLF00906-II X1847 = chewed piece.

adhesive and waterproofing properties, which might also be the case for the leister. Numerous components of other leisters, individual prongs or bone points, have been recovered at the Femern project (Chaudesaigues-Clausen, 2023; Stafseth and Groß, 2023), but whether birch tar was also used to assemble these remains hypothetical for now. To strengthen our understanding of these cultural and technological aspects, it is important for future studies to explore specific categories of artefacts and their association with adhesives (e.g. fishing equipment) on a larger, comparative scale. Through analytical approaches aiming at the identification of organic, but also inorganic materials, we can assess the range of adhesive substances used throughout prehistory, but also reveal unprecedented insights into, for instance, prehistoric technologies (e.g. Kabaciński et al., 2023) or personalities (Jensen et al., 2019). This will enable us to better understand potential differences in the chaîne opératoire, functional purpose, regional preferences and potentially also the social role of birch tar and other adhesive products in different archaeological and historical societies (Little et al., 2022).

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Declaration of interest statement

The authors declare no conflict of interest.

Credit statement

T.J.K is responsible for conceptualisation, investigation, visualisation and writing. A.L. is responsible for supervision, project administration, writing, funding acquisition. D.G. is responsible for writing, visualisation, data curation and resources. B.T.M. is responsible for resources.

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Middle Neolithic trackway A20 at Kastbjerg Å

High-precision dating and archaeological context

Jesper Olsen[1,3], Bo Madsen[2], Marie Kanstrup[1], Carsten Korthauer[2] and Lutz Klassen[2]

[1] Aarhus AMS Centre (AARAMS), Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, 8000 Aarhus C, Denmark
[2] East Jutland Museum, Stemannsgade 2, 8900 Randers C, Denmark
[3] Corresponding Author (jesper.olsen@phys.au.dk)

ABSTRACT

In 2015-2017, East Jutland Museum excavated a series of well-preserved prehistoric and early historic trackways at Kastbjerg Å in the Kastbjerg Å river valley (eastern Jutland, Denmark). In this article, we will present the earliest of the in situ preserved structures, the Middle Neolithic trackway A20, and the high-precision dating of this structure. Dendrochronological dating of wood sequences provides very precise ages for archaeological timbers from buildings or structures, such as bridges or ships. This is not possible, however, when the dendrochronological samples lack sapwood, if the wood sequence has too few rings to provide definite placement on the dendrochronological master curve, if the wood sequence falls outside the range of the master curves or if the species of wood is not suitable for dendrochronological analysis. Here, we date a wood sequence of an alder tree from trackway A20 using the radiocarbon wiggle-match method to 2911 ±5 BC. The function of the trackway and the significance of the Neolithic river crossing at the Kastbjerg Å site are discussed in the light of European parallels and the regional cultural context.

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Introduction

In 2015, East Jutland Museum monitored a river valley rehabilitation project in the Kastbjerg Å valley in Enslev parish, north of Randers in East Jutland, Denmark (Figure 1). This former glacial tunnel valley is characterised by numerous springs from which considerable amounts of water flow: no fewer than 21 springs are located within the project area. The nature rehabilitation project involved re-meandering and regulation of the river. It was expected that the chalky soils and high groundwater levels would provide favourable conditions for the survival of organic archaeological material. The re-establishment of a large curve of the river, Curve 2, on the south side, along the old parish boundary, resulted in the groundwater levels dropping by more than 2 m and drainage of the peat. At least 14 different trackways dating to the Neolithic, Iron Age and medieval period were observed during the course of construction work and subsequently excavated between 2015 and 2017 (DKC site number 140403-26; Madsen 2018; Madsen in press). This article discusses the earliest of the (partially) in situ preserved constructions, A20, and the associated high-precision radiocarbon dating.

There are five in situ preserved Neolithic trackways at Kastbjerg Å: A2, A20, A23, A24 and A25 – see Figure 2. Individual radiocarbon dates place these five structures within the timespan *c.*3000 and 2500 BC, i.e. the period between the later Middle Neolithic Funnel Beaker Culture and the late Single Grave Culture. An even earlier date (*c.*3280 BC) was obtained from an isolated, probably redeposited piece of Y-shaped timber, which most likely represents the remains of an earlier structure located upstream, which was destroyed by water erosion or later human activity (Madsen in press).

Due to the shape of the radiocarbon calibration curve for the period in question, individual calibrated dates correspond to time intervals of 2-300 years for each of the different structures. This chronological resolution is unsatisfactory for providing precise contextualisation and properly evaluating the importance of these significant remains of communication infrastructure. In this article, we therefore use an approach that allows the

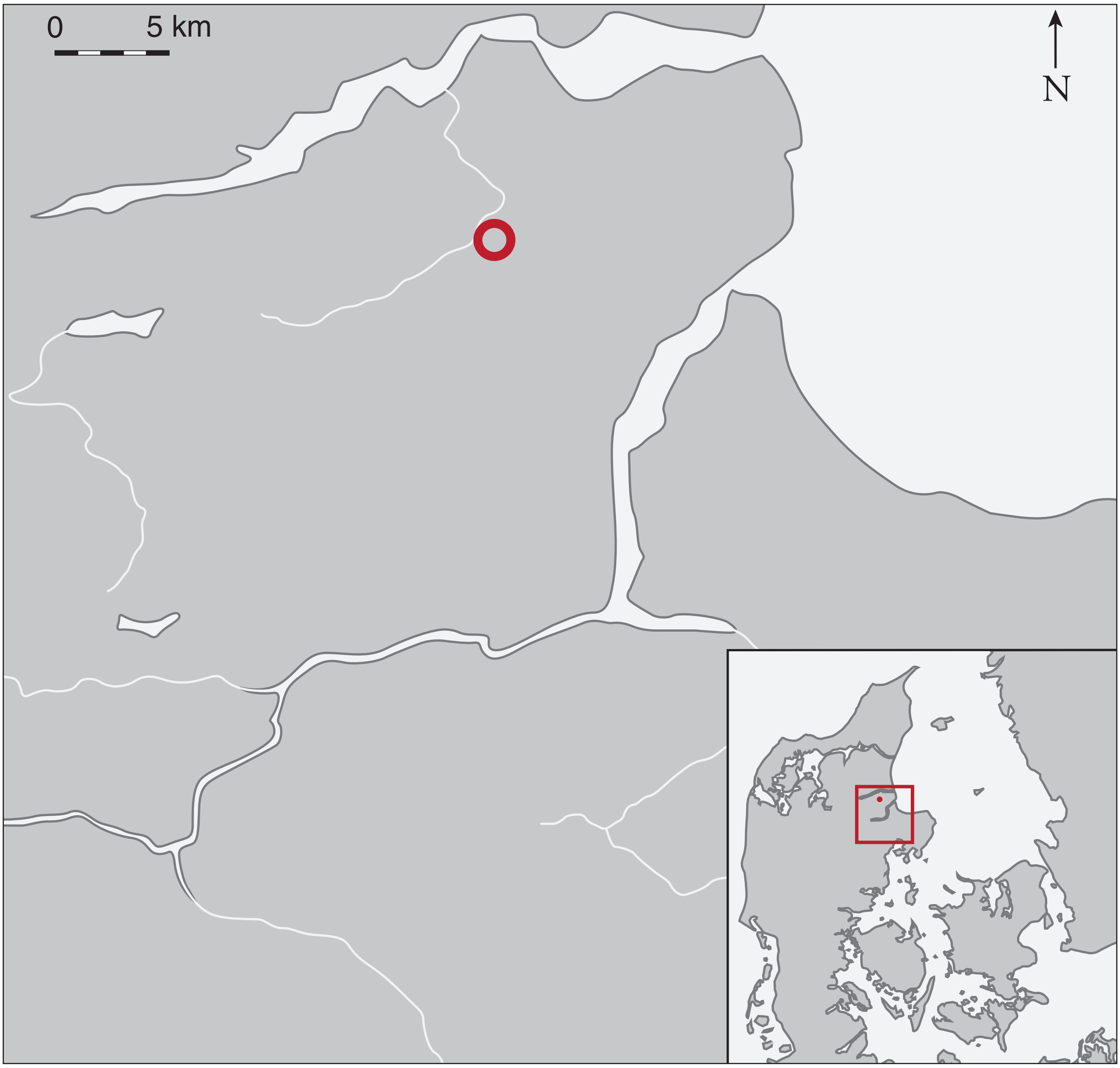

Figure 1. The location of the site at the Kastbjerg Å river, south of Mariager Fjord in north-eastern Jutland, Denmark (Illustration: Ea Rasmussen).

dating of the oldest trackway preserved in situ, A20, to be narrowed down to a period of a few years. Dendrochronological dating using the ring widths of wood sequences provides very precise (typically ≤1 year) ages for archaeological timbers from buildings and structures, such as bridges or ships (e.g. Bill and Daly 2012; Christensen 2006; Dominguez-Delmas et al. 2019). This is not the case though when the sapwood is missing from dendrochronological samples, as this hinders accurate dating of the outermost ring. There are some limitations to the dendrochronological method, however. Most importantly, it can only be used on oak or pine wood, as the most comprehensive master curves used for dendrochronological dating are based on these two species. The method also requires a sufficient number of rings to be present in the archaeological timber sample. When there are too few rings the statistical fit with a dendrochronological master curve becomes inaccurate or even impossible. In other cases, the timber may be too old, and thus falls outside the age range of the dendrochronological master curve. Although in such circumstances the dendrochronological method may not enable the dating of archaeological timbers, the radiocarbon wiggle-match method can produce an accurate and especially precise result (e.g. Bronk Ramsey, van der Plicht and

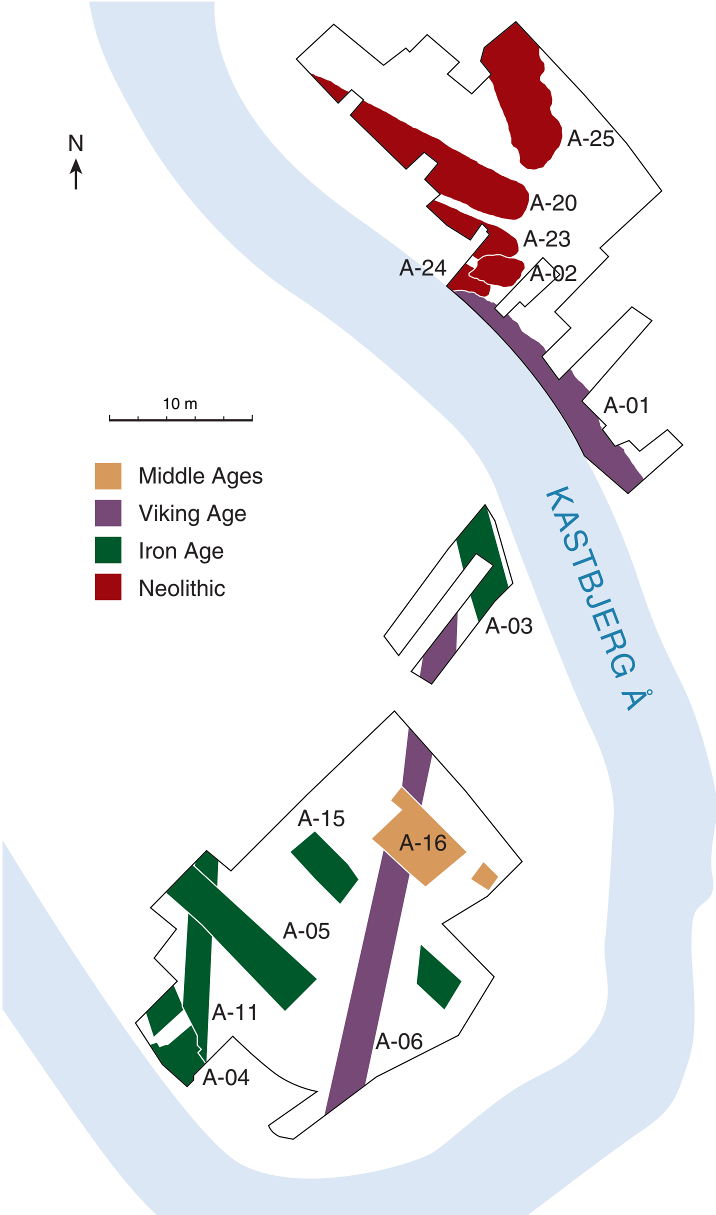

Figure 2. Summary plan showing the distribution of roads and causeways at Kastbjerg Å. Light brown: Viking Age/ Early Middle Ages; Purple: Viking Age; Green: Iron Age; and Red: Neolithic (Illustration: Thomas Guntzelnick Poulsen/Ea Rasmussen).

Weninger 2001; Christensen et al. 2021; Friedrich et al. 2006; Hogg et al. 2019). Radiocarbon dating of several samples (preferably more than five) from the sequence of a piece of wood, where the gap in years between each sample is known, may result in very precise age estimates for the piece of wood. This is because the wiggle-match method corresponds to resampling a smaller section of the international radiocarbon calibration curve. The shape or structure of the resampled section of the calibration curve can be fitted onto the actual calibration curve, which is called a wiggle-match.

Materials

The Neolithic trackways at the Kastbjerg Å site were all found in the northern part of the excavation area (Figure 2) and excavated in 2017. Structure A20 was the deepest and stratigraphically earliest, and was partly preserved in situ. It was found in the deepest peat horizons, almost 2.7 m beneath the surface and 6 m above sea level, and was only partially uncovered, leaving its wooden components in situ. Signs of water erosion were observed above and underneath the structure, in the form of a subsoil-like sediment of clay and silt.

Figure 3. Trackway A20 being excavated in 2017 seen from the north (Photo: East Jutland Museum).

The preserved parts of the construction consist of roundwood measuring up to 0.4 m in diameter and placed like longitudinal sleepers in a structure spanning up to four courses. The timbers may originally have been more regularly placed. They were up to 3.5 m long (Figure 3). In several cases, these selected straight trunks show signs of having been trimmed and two examples have angled recesses for other

Figure 4. Assembled timber elements of trackway A20 viewed from the west (Photo: East Jutland Museum).

timber at the ends, providing evidence of some kind of basic joinery (Figure 4). This may be due to the former use of these timbers in a construction, possibly a house. Several upright wooden posts had been rammed down between the longitudinal timbers.

The space between the large, longitudinal trunks in A20, held in place by the vertically rammed down posts, must have contained an internal filling. Due to the non-invasive sondage character of the excavation, only the upper part of the basal construction, the longitudinal trunks, was uncovered. No in situ remains of filling material were observed in the limited area that was opened up (Figure 3). This may have consisted of local, compressed, fibrous peat (turfa spagni) mixed with straw, clay and silt, which later washed away. At a higher level, near the north-western end, a number of less substantial tree trunks were observed close by and downstream of A20. These may have been dislodged from A20 by the flowing waters and are perhaps remains of an upper construction consisting of transverse roundwood and branches. This is the most likely design of the worn structure A20, as the numerous Neolithic trackways known from especially North-West Germany and the Netherlands (see more detailed discussion below) were all constructed according to the same design principles: longitudinally placed roundwood sleepers held in place by vertically rammed down posts and covered with transverse roundwood (which in some, but by no means all cases, was also held in place with vertical posts). This specific type of wooden road was called *Pfahlweg* by Hayen (1957), who developed a comprehensive typology and terminology for the numerous wooden trackways dating from the Neolithic to modern times, which had been discovered in bogs in North-West Germany. Feature A20 was at least 4 m wide, but its full width was not uncovered to the south-west.

Around 14 m of its length were recorded, but the feature was not delimited to the north-west. At the southern end where the trackway ends, the terrain rises, indicating that a bank was previously present. Accompanying artefacts, which were found embedded in the construction, consist of a few lengths of young tree trunks, which were presumably chopped with a flint axe as well as a digging stick, made from a split, bark-covered piece of roundwood with a makeshift, hourglass-shaped

Figure 5. Digging stick or simple double spade found at A20 being excavated (Photo: East Jutland Museum).

handle part (Figure 5). Most of the wooden material used to construct trackway A20 consists of alder. This includes a trunk from which sample D49 was taken for wiggle-match dating. The trunk may have been used as timber in a building before it was laid down to form part of trackway A20. Bark or branches were not present, but it showed no further signs of having been worked or trimmed, with the exception of the end, where it had been hewn into a V shape, perhaps to fit together with other beams in a construction.

Methods

The wooden sample D49 has been microscopically identified as *Alnus sp*., a species of alder. It is not possible to distinguish between different species of alder using wood anatomy (Schweingruber 1978, 74). However, the species is most probably *Alnus glutinosa*, black alder. This species corresponds well with the wetland habitat at Kastbjerg Å and is otherwise well known from the Danish Neolithic period. The sample comprises a preserved sequence of 41 annual growth rings. The surface is somewhat worn, bark is completely absent, and there are minimal traces of one more outer growth ring, which have decayed. Importantly, however, the sample represents a full cross section of an alder trunk, with no more than at most a few of the outer rings missing.

Sampling of the ring sequence for wiggle-matching was undertaken by cutting a *c*.6 cm-thick slice from the alder trunk. This was stored in a deep freezer at -24 °C. Still frozen, the surface of the slice was cleanly cut using a razorblade, to reveal the wooden structure. Individual growth rings could then be identified using a binocular microscope. Every fourth ring was marked with a needle, which meant that 11 rings could be used for radiocarbon dating. A sample was taken from each of these rings by cutting into the ring boundaries with a razorblade, so that a sufficient amount of material could be extracted from the growth ring without 'contamination' from the adjacent rings (Figure 6).

Alnus glutinosa is a diffuse-porous wood, i.e. it lacks the large pores in the early wood that are characteristic of ring porous wood like oak. Therefore, the boundaries between the growth rings in alder wood can be somewhat unclear. In three cases in D49, this means that there is some uncertainty whether the gap in the three rings between two samples is accurate:

- Between D49-0 (ring 0) and D49-1 (ring 4), there are 2 or 3 rings (a very small, faintly defined ring is counted as full growth ring).
- Between D49-1 (ring 4) and D49-2 (ring 8), there are 3 to 4 rings (a very faintly defined ring boundary is disregarded).
- Between D49-8 (ring 32) and D49-9 (ring 36), there are 3 to 4 rings (also in this case, a very faint ring boundary is disregarded).

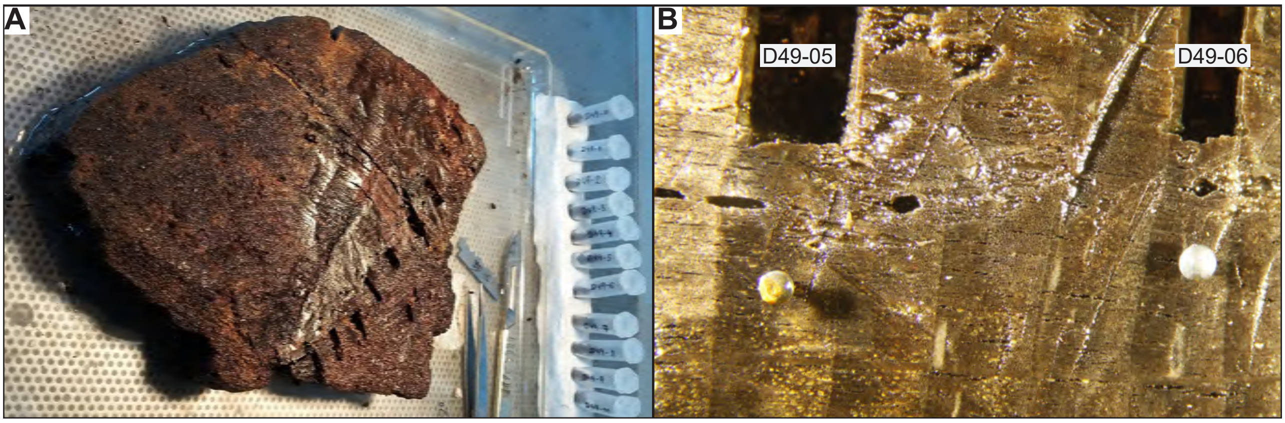

Figure 6. A. The slice of alder wood D49, after the series of samples for wiggle-matching had been taken. B. Microscopic picture of part of the sequence of tree rings, showing the gap of three annual growth rings between samples D49-05 and D49-06, and at the top of the picture the voids where the samples have been cut from the growth ring (Illustration: Carsten Korthauer).

For radiocarbon analysis, the wood samples were pretreated with acid-base-acid (ABA) at AARAMS (e.g. Brock et al. 2010). First, the samples were treated with 1M HCl at 80 °C for one hour to remove carbonates, then with 1M NaOH at 80°C for at least three hours to remove humic acids (checking the colouring every hour and adding new 1M NaOH to very dark coloured samples). Subsequently, the samples were treated overnight with 1M HCl at room temperature to remove CO_2 absorbed during the base treatment stage. The pretreated samples were converted to CO_2 by combustion in sealed evacuated quartz tubes with 200 mg CuO wires. The CO_2 was reduced to graphite by the H_2 reduction method using an iron catalyst and $MgClO_4$ to remove the water (Santos et al. 2007; Vogel et al. 1984). The samples were ^{14}C dated using the HVE 1MV tandetron accelerator AMS system at the Aarhus AMS Centre, Department of Physics and Astronomy, Aarhus University (Olsen et al. 2016). ^{14}C dates are given as uncalibrated ^{14}C ages BP normalised to 25‰ according to international conventions using the online $^{13}C/^{12}C$ ratios (Stuiver and Polach 1977). The radiocarbon ages are calibrated with OxCal v.4.4 (Bronk Ramsey, van der Plicht, and Weninger 2001) using the international calibration curve IntCal20 and are given as calibrated ages (Reimer et al. 2020). The piece of wood D49 is calibrated using the wiggle-match method by a sequence and using the function 'intervals' to provide information about the gap in years between the ^{14}C dated samples (Bronk Ramsey, van der Plicht and Weninger 2001). The gap between each ^{14}C-dated sample is 3 ±1 years, with the error taking into account the possibility of missing rings or other uncertainties in the ring count. The OxCal time resolution is set to 0.2 years.

Results and Discussion

The outermost ring of the wiggle-matched piece of wood D49 dates to 2910-2902 BC (68.2% confidence interval). The resulting probability distribution resembles a normal probability distribution and the result can therefore be given as 2911 ±5 BC (Table 1, 7). The overall model agreement of the wiggle-match is 108.8%. However, the agreement index of the outermost ring AAR31158 is 57.9% and thus slightly lower than the lower limit of 60%. Although the agreement index of AAR-31158 is low, the overall wiggle-match of the sequence of the piece of wood D49 is regarded as valid.

To test the robustness of the wiggle-match, two alternative models are constructed: one where the sample AAR31158 is removed and another where an outlier model is applied to the wiggle-match. Removing AAR31158 results in agreement indices that are all above 60%. The outermost ring dates to 2994-2981 BC (20.7%) or 2923-2906 BC (47.6%). The latter calibrated age interval agrees with the wiggle-match result including all samples, whereas the interval 2994-2981 BC (20.7%) would date the road slightly earlier. The outlier

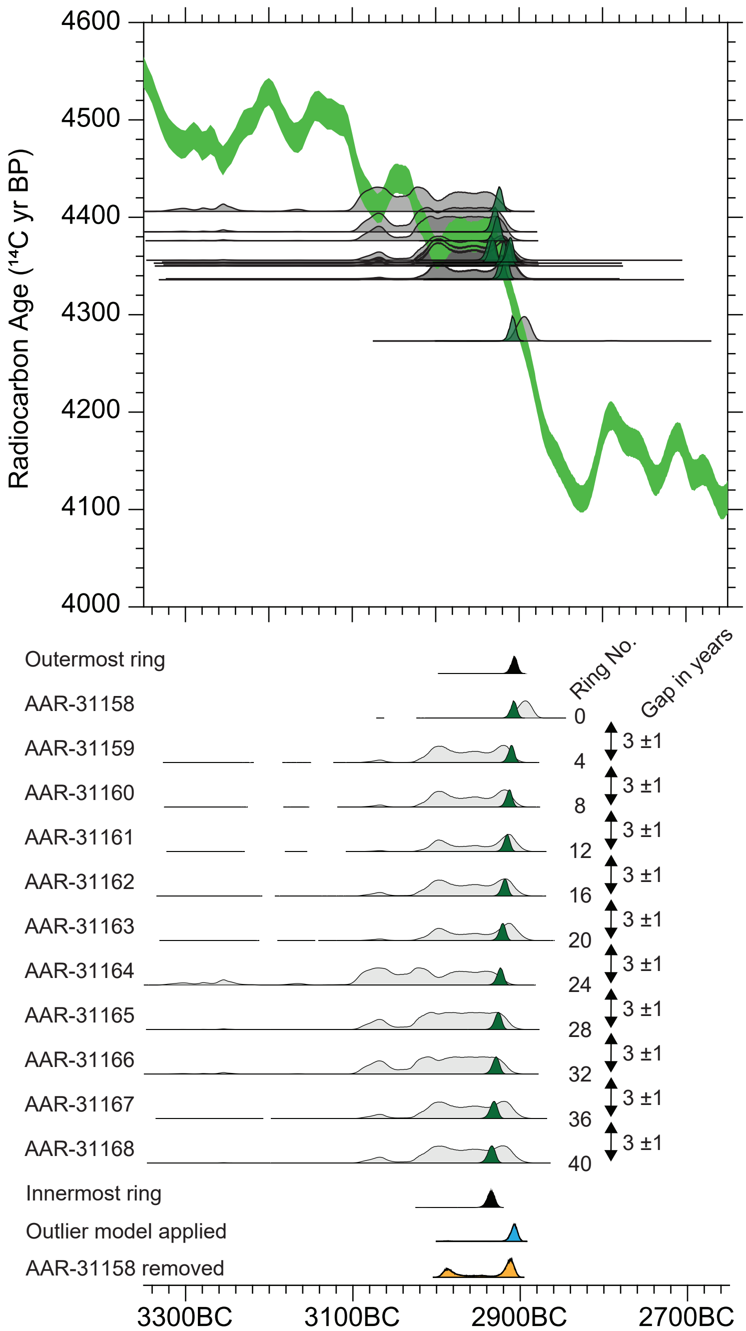

Figure 7. Upper part: The Intcal20 calibration curve plotted together with the calibrated probability distribution (grey) of the 11 ^{14}C-dated samples from the piece of wood D49. The wiggle-matched probability distributions of D49 (green) are also shown. Lower part: Wiggle-matched probability distributions of the ^{14}C-dated samples from the piece of wood D49 (green), together with the calibrated probability distributions (unmodelled in grey) (Illustration: Jesper Olsen).

model suggests that there is a 12% chance that AAR31158 is an outlier and gives the outer ring a date of 2909 ±16 BC. The result of the outlier model thus agrees with the model using all samples. However, the outlier indicates that the calibrated age uncertainty is higher than in the case of the model including all samples. Overall, the alternative models support the model including all samples, and if anything, there is a chance that the road structure is slightly earlier in date. We therefore propose that the probable date of the road structure is 2911 BC (or slightly later, if the sample is from a re-used timber, see above).

River crossings constructed of brushwood and branches are known in Denmark from the earliest Neolithic, around 3900 BC, onwards (find from Baarse, southern Zealand, crossing the Risby River (Jørgensen 1977, 147), but see Rostholm (1978, 202-203) for doubts regarding the function of this construction). Trackway A20 from Kastbjerg Å is, however, up until now the earliest example from Denmark of a road structure involving massive roundwood. Similar Neolithic structures are known in quite large numbers from *c.*4700 BC onwards, from the relatively nearby bogs in north-western Germany (Bauerochse and Metzler 2001; Both and Fansa 2011; Burmeister 2002; Metzler 1997) and neighbouring parts of the Netherlands (Casparie 1987; van der Sanden 2002, 104-110). Other important and comparable (although geographically more distant) structures have been excavated at several locations in the British Isles, with a remarkable concentration in the Somerset Levels in south-western England (Bell 2020; Coles 1984) and other, more isolated examples from locations such as the Thames Estuary (Bates and Stafford 2013; Hart 2010), the Isle of Wight (Tomalin et al. 2012) and in Ireland (Raftery 1990); for a complete survey see Bell (2020, Supplementary Appendix 6.1). The numerous wooden trackways which are known from the north alpine forelands (Heumüller 2002) differ from the Kastbjerg Å examples and their parallels listed above in that they were discovered in settlement contexts rather than isolated in bogs. But due to their often precise dendrochronological dating and constructional observations they are still of value to the interpretation of the Kastbjerg Å trackways.

The numerous parallels from the European Neolithic with structure A20 at Kastbjerg, as outlined above, can be broadly divided into two categories based on their width: very narrow trackways that are only a few decimetres wide which can only have functioned as pedestrian walkways for one person at a time, and much broader and more massive constructions that were as much as over 5 m wide. The first group is only represented by a few examples, the best known of which is probably the Sweet Track from the Somerset Levels in England, dating to the early fourth millennium BC (Coles and Coles 1986). The Sweet Track differs from the general *Pfahlweg* category due to its very elaborate construction, but proper *Pfahlwege* of comparable dimensions and date are known from North-West Germany (trackway XXXV (Pr): Bauerochse, Leuschner and Metzler 2012, 149). The second group comprises dozens of trackways from all of the European regions mentioned above. The earliest known example, which also is the oldest known preserved wooden road in the world, is trackway XXXI (Pr) from North-West Germany. As mentioned above, it is dated to around 4700 BC (Both and Fansa 2011, 147-149). Trackways of the same construction, including those from Kastbjerg Å, were constructed throughout the whole of the subsequent parts of the Neolithic and into the Bronze Age (see e.g. Both and Fansa 2011 and Casparie 1987 regarding North-West Germany and the Netherlands).

These trackways may have had several different functions: for the movement of large groups of people possibly carrying heavy goods, as roads for moving livestock to distant grazing areas across rivers and bogs, and as roads for the transportation of cattle-drawn vehicles. It is not possible to determine the function of individual trackways based solely upon their construction. The latter remained unchanged through the entire period in question – trackways predating the introduction of carts/wagons are similar to those constructed after this occurred (Burmeister 2004, 130-131; Heumüller 2002, 136-137). Finds recovered in or at the trackways, such as parts of wagons/carts or cattle hooves, can provide clues. But such finds are often absent (as at Kastbjerg Å) and finds of hooves may indicate both use as a transport route for carts or wagons and also the movement of herds of cattle. Because of this, as well as its poor state of preservation, it is not possible to decide what purpose the Kastbjerg Å trackways served, but it is worth considering different lines of circumstantial evidence for both possibilities.

The interpretation of structure A20 as a possible transport route for carts or wagons is entirely plausible, as the earliest direct evidence of wheeled transport in Denmark, in form of a wooden disc wheel from Pilkmose near Give in Central Jutland, has been dendrochronologically dated to 2935 BC (Christensen 2007, 231). From a chronological point of view, the use of cattle-drawn vehicles may even have started several hundred years earlier, as indicated by tracks recorded at Flintbek (Zich 1993), even though these probably indicate that sledges were in fact used, which may not have been suitable for use on wooden trackways. It should also be noted that in both the north alpine region (Heumüller 2002, 136; Maier and Schlichterle 1992; Schlichterle 2002, 10) and North-West Germany (Burmeister 2004, 329-330), the earliest finds of parts of carts/wagons combined with trackways occur around 3000 BC. This is probably no coincidence, but demonstrates that there was a chronological horizon for the introduction the use of carts/wagons on wooden trackways across a broad geographical region. Trackway A20 at the Kastbjerg Å site may have been part of this development. Moreover, wheel tracks have been observed running in a parallel direction to alignments of the so-called stone heap graves in north-western Jutland, which date to the period 3100-2800 BC. These graves involve burials of pairs of draught cattle with a cart, often arranged in lines following the direction of contemporary roads (Johannsen and Laursen 2010, 39-44).

The stone heap graves are of particular interest in relation to trackway A20 from Kastbjerg Å. The main distribution area of this grave type in north-western Jutland is associated with a regional group of the later Middle Neolithic Funnel Beaker Culture, which was probably characterised by a mobile or semi-mobile lifestyle with considerable economic focus upon cattle herding (Johannsen et al. 2016). The easternmost stone heap graves have been found at Galgevang (Fabricius and Becker 1996, 257 no. 23) and Øster Tørslev (Stidsing 1989), just 2-5 km south-east of the Kastbjerg Å site, indicating that the Kastbjerg Å trackway may have played a part in wheeled transport between the area and north-western Jutland (Figure 8A and 8B). The Kastbjerg Å site is located in a border zone between the aforementioned pastoral Funnel Beaker group to the west/north-west and Pitted Ware farmer-hunter-fishermen groups located to the north, east and south-east on the shores of Mariager Fjord and Randers Fjord, as well as on the Djursland peninsula (Figure 8A). Several important Pitted Ware sites are known from the Randers Fjord area at Øster Tørslev, 8 km south-east of the Kastbjerg Å site (Aagaard I and II, Becker 1951, 174-176; Højvang, unpubl., j.no. KHM 1053) and even closer to the aforementioned stone heap graves (Figure 8B). The river crossing at Kastbjerg Å may thus have of been of importance in contact and communication between two quite different Neolithic groups. This is also indicated by a straight-walled beaker with a pronounced foot found at the important Pitted Ware site of Kainsbakke, *c.*50 km to the south-east in Djursland (Wincentz 2020, 64 Fig. 30.4; Figure 8C, top). The vessel is decorated with a rhombic pattern, in which the rhombuses are alternately undecorated and filled with short, oblique lines. This specific vessel, for which there is a possible parallel at the nearby Pitted Ware settlement of Kirial Bro (Wincentz 2020, 123 Fig. 69.32-34), has previously probably been somewhat misidentified as reflecting Swedish Boat Axe Culture influences (Wincentz 2020, 66, 72). The Kainsbakke vessel closely resembles a vessel from Ørum, east of Vejle (Davidsen 1978, 114 Fig. 57g), and especially finds from several stone heap graves in North-West Jutland (Ristoft III and particularly Herrup XXI: Fabricius and Becker 1996, 265 Pl. 6, 266 Pl. 7 and 271 Pl. 12; Figure 8C). It thus provides evidence of contact and communication between north-western Jutland and Djursland. The Kainsbakke vessel, which according to analyses of its fabric is a local product of the Pitted Ware group inhabiting the Kainsbakke site (Blank, Brorsson and Fridén 2020), is dated to around 2900 BC (Philippsen, Iversen and Klassen 2020, 263-271) and is thus contemporary with trackway A20 at Kastbjerg Å. The river crossing may therefore have played a role in long-distance transport and communication, not only between the Randers Fjord area and north-western Jutland, but also between regions of Jutland that were even further apart (Figure 8A). As Kainsbakke is located on what was a large island at the time in question, the main importance of the Kastbjerg Å trackway may have been the connection between North-West Jutland and the Pitted Ware communities in the Randers Fjord area, from where transport could have continued by boat (Randers Fjord and Kolindsund, near which Kainsbakke is located, were interconnected at the time in question).

The relationship between pastoral or semi-pastoral groups in North-West Jutland and farmer-hunter-fishermen groups of the Pitted Ware culture further east in Jutland is also of interest regarding the second possible function of trackway A20 at Kastbjerg Å – as a means of moving herds of cattle. Strontium isotope analyses of a large group of cattle from the central Pitted Ware site Kainsbakke indicate that two different groups of these animals were present. The first group, which most likely stayed within the same restricted area/the same grazing zone until the cattle were slaughtered, has strontium isotope ratios that probably indicate a local origin. A second group of cattle had been moved around during their lifetimes and were probably reared in a mobile way (Klassen et al. 2020, 428). Measurements of the strontium isotope ratios for these animals

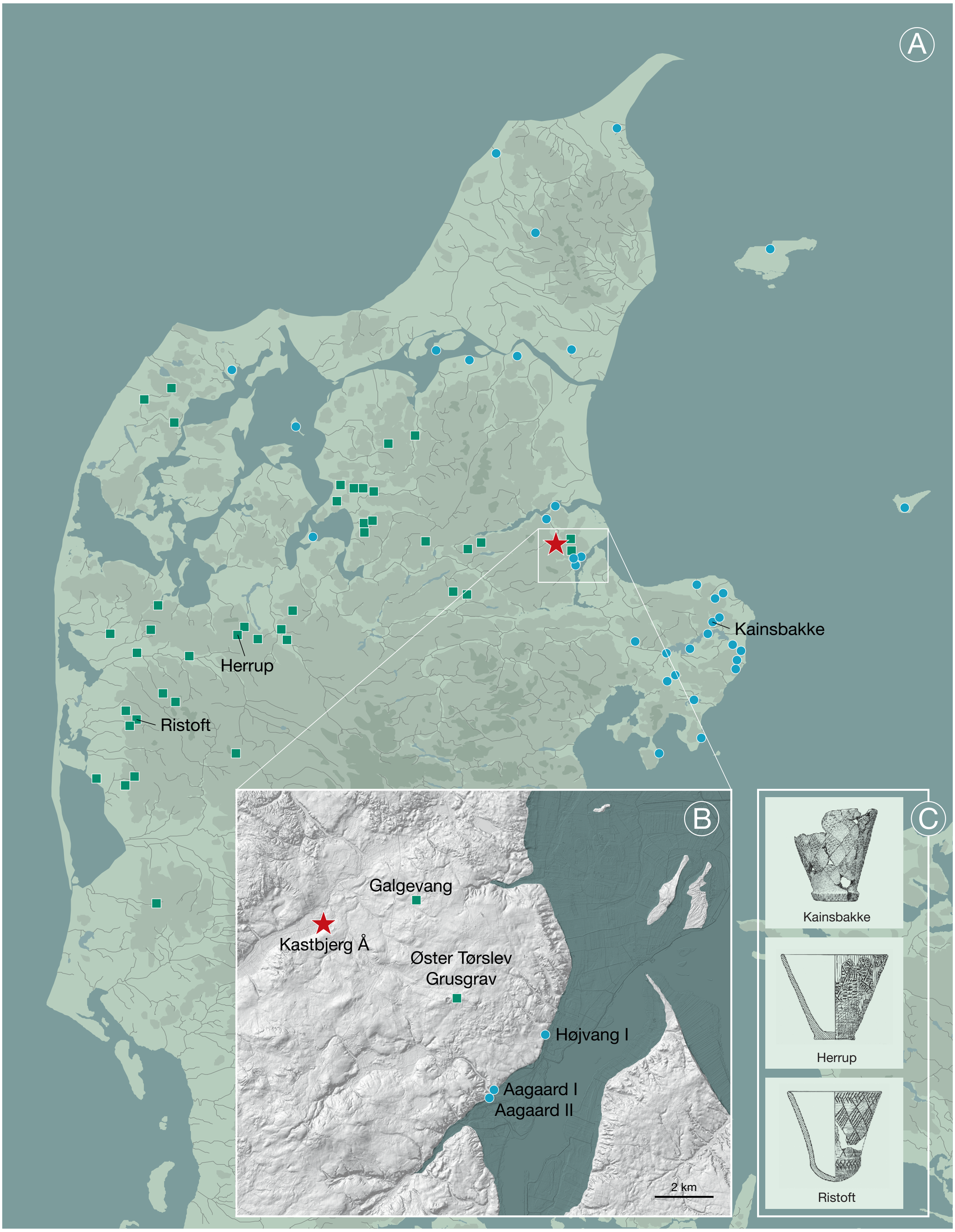

Figure 8. A. Distribution of stone heap graves (green rectangles, after Johannsen and Laursen 2010), important sites of the Pitted Ware culture (blue dots, after Becker 1951, Iversen 2010 and Rasmussen et al. 2020) and the location of the Kastbjerg Å site (red star). B. The location of the Kastbjerg Å site (red star), the Aagaard I, Aagaard II and Højvang I sites of the Pitted Ware Culture (blue dots) and the stone heap graves at Galgevang and Øster Tørslev Grusgrav (green rectangles). Coastline reconstructed for the period in question (*c*.3000 BC). C. Typologically related vessels from Kainsbakke (from Wincentz 2020), Herrup and Ristoft (from Fabricius/Becker 1996) (Illustration: Lutz Klassen/Ea Rasmussen).

involved values exceeding the local baseline and thus indicated a non-local origin. The stone heap grave area of north-western Jutland may well be where these cattle came from, although this cannot be demonstrated for certain (Klassen et al. 2020, 437). This possibility is further supported by the relationship between Kainsbakke/Kirial Bro and North-West Jutland, as is suggested by the ceramic vessels discussed above. From a general perspective as well, this scenario is entirely plausible, as the movement of cattle over considerable distances as part of complex Neolithic economies has been demonstrated in the case of Funnel Beaker groups in central western Sweden (Sjögren and Price 2013; Sjögren et al. 2021). The fact that Kainsbakke and Kirial Bro were located on an island, which was separated from the mainland by a sound (Kolindsund/Randers Fjord) that was a few hundred metres wide, does not contradict this assumption. The appearance of domesticated cattle, pigs and sheep/goats on the island of Bornholm, at the time of neolithisation around 4000 BC, clearly demonstrates that the transportation of livestock, even over considerable stretches of open sea (Bornholm is around 37 km from the nearest mainland), could be undertaken by Neolithic farmers in South Scandinavia.

The available evidence does not allow us to reach a definite conclusion about the function of trackway A20 at Kastbjerg Å. Apart from a simple use as pedestrian walkway, which judging by its dimensions was not its main purpose, both a use as a transportation route for carts or wagons and as infrastructure for moving herds of cattle are possible and not mutually exclusive functions. The fact that at least 14 different trackways were constructed at the site during a period spanning *c.*4,500 years, from the Middle Neolithic through the Iron Age, Viking Age and into medieval times, indicates that the river crossing was of at least regional importance. During the Neolithic, no less than five of these constructions indicate that it was of continual importance. This significance may even have extended back several hundred years earlier than trackway A20, which is discussed here, as is indicated by the aforementioned possible remains of a sixth, even earlier construction dating as far back as the early Middle Neolithic, around 3300 BC. Large numbers of burial mounds and megalithic graves located to the north of the Kastbjerg Å site (Bekmose 1977, 53 Fig. 5; Madsen in press) indicate that the area was focused on from at least this point in time onwards. At the time of trackway A20, around 2900 BC, the site could even have been of superregional importance, as part of a connecting link between Neolithic groups in different parts of Jutland.

Conclusion

Construction work in wetlands at sites such as Kastbjerg Å is comparatively rare today. Nevertheless, the scientific potential of archaeological investigations that are prompted by such work can be highly significant. In this case, they have led to the discovery of the oldest solidly built Neolithic trackway in Denmark. Here, the application of state-of-the-art analyses enabled trackway A20 from Kastbjerg Å to be precisely dated to 2911 ±5 BC. In the future, our findings can be better contextualised by utilising other high-resolution results from evidence of contemporaneous transport and communication. In the meantime, our results contribute to our growing understanding of an important period of the Neolithic, which is characterised by the co-existence of different groups that followed very different social, economic and ritual strategies.

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Iron Age Fur Skin Tanning – a Sustainable Practice?

René Larsen[1], Anne Lisbeth Schmidt[2, 5], Martin N. Mortensen[3], Yvonne Shashoua[3], Dorte Vestergaard Poulsen Sommer[1], Jane Richter[4]

[1] Fonden Bevaring Sjælland, Videncenter for Bevaring af Kulturarven, Vasebækvej 30D, 4600 Køge, Denmark
[2] National Museum of Denmark, Conservation and Restoration, I.C. Modewegsvej 1, Brede, 2800 Kgs. Lyngby, Denmark
[3] National Museum of Denmark, Environmental Archaeology and Materials Science, I.C. Modewegsvej 1, Brede, 2800 Kgs. Lyngby, Denmark
[4] Royal Danish Academy, Conservation, Esplanaden 34, 1263 Copenhagen K, Denmark
[5] Corresponding Author (anne.lisbeth.schmidt@natmus.dk)

ABSTRACT

Tanning is among the most polluting industries in the world. Industrial-produced hides and skins are fully or pre-tanned with highly polluting chromium salts. The purpose of the study was to gain new knowledge about Iron Age tanning methods to clarify whether sustainable tanning methods can be developed based on this. Fur skin capes, uncovered in Jutland bogs, from Baunsø Mose (20-220 AD), Borremose I (365-116 BC), Huldremose I (1-174 AD) and Vindum Mose (386-203 BC) were analysed by Attenuated Total Reflection-Fourier Transform Infrared Spectroscopy (ATR-FTIR), Gas Chromatography-Mass Spectrometry (GC-MS) and morphological assessment of the skin fibres to identify tanning substances and material condition. Analyses were supplemented with source studies of previous visual assessment of the capes and measured shrinkage temperature of leather and skins excavated from bogs. Our results show that only the samples from Baunsø Mose, Borremose I and Huldremose I contain vegetable tannins. Furthermore, Baunsø Mose contains cow fat and Borremose I, Huldremose I and Vindum sheep fat. All contain indications of the presence of aluminum and iron compounds. The samples are decomposed to varying extents. Remnants from conservation were detected on Huldremose I, Baunsø Mose and Vindum Mose.

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Introduction

From ancient times until the 19th century, the tanning of hides and skins for leather and furs was mainly based on vegetable tanning substances extracted from local deciduous and coniferous trees, i.e., bark, wood, fruits, leaves, etc. Tanning methods involving smoke and fatty substances and tawing with alum were also used to preserve hides and skins (Reed 1972, 86-117). From 1830 to 1850, new fast methods transformed the European tanning industry, using overseas vegetable tannins, chemicals and modern techniques. However, the resulting leather had a shorter lifetime. At the beginning of the 20th century, tanning with chromium salts once again revolutionized the tanning industry in general (Aabye 1955, 97-98). Combined with the use of biocides, synthetic dyes, aluminum salts, etc., the tanning industry today poses a severe environmental burden for many countries especially in the Third World by exploiting the natural mineral resources and polluting the delicate environment. Worldwide, the disposal of toxic used waste products forms a significant challenge to societies and governments (e.g., described by Dixit et al. 2015; Sivaram and Barik 2019; Syed et al. 2010).

The current project aims to gain information from ancient but well-preserved fur capes from Jutland bogs, dated to the Danish Early Iron Age (500 BC-400 AD). The purpose is to investigate the original tanning methods that were possibly sustainable in utilizing local resources and producing minimum toxic waste. The project addresses the following UN Sustainable Development Goals: sustainable management of water (6), sustainable industrialization (9), responsible production (12), sustainable use of the oceans (14) and strengthening sustainable development (17) (United Nations). We intend to influence today's tanning industry towards sustainable production. By analysing

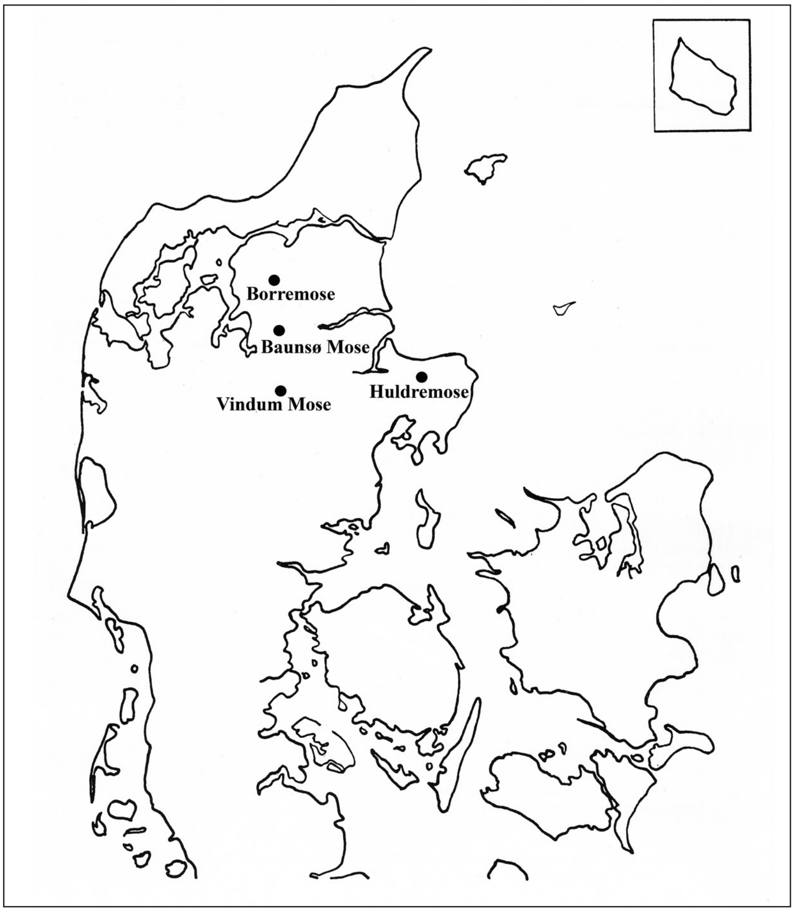

Figure 1. The four sites in Jutland, where the studied skin capes, dating from the Danish Early Iron Age (500 BC-400 AD), were recovered. After Hald 1980, p. 14.

samples from cohesive fur garments and fur fragments around 2000 years old from the collections of the National Museum of Denmark, we expect to identify for the first time, which tanning methods and tanning agents were used using Attenuated Total Reflection-Fourier Transform Infrared spectroscopy (ATR-FTIR), Gas Chromatography-Mass Spectrometry (GC-MS) and morphological analyses of the skin fibres. The aim was to establish whether and, if so, which vegetable tannins are present. Can fatty and mineral substances perhaps used for tanning be identified? In addition, we aimed to estimate the extent of tanning and to assess the state of preservation in relation to long term stability and conservation strategies.

Materials

In Denmark, in the 19th and 20th centuries until 1953, numerous finds of well-preserved human bodies, some of them with garments and accessories of textile, de-haired skin or fur, were uncovered in bogs in connection to cutting peat for fuel. Most bog finds date from the Danish Early Iron Age. The finds were often excavated on the Jutland peninsula (Mannering et al. 2010, 262). The bog finds are described in numerous publications (e.g., Asingh and Lynnerup 2007, 290-301; Broholm and Hald 1940, 146; Ebbesen 2009; Fischer 2000, 105-125; Glob 1966, 52-83; Hald 1980; Jensen 2003, 176-185, 323-327; Munksgaard 1974, 126-128, 138-139; van der Sanden 1996; Thorvildsen 1952).

The National Museum of Denmark stores numerous skin and fur items from the bogs. In this study, we took one small sample of dermal skin from each of four garments for the above-mentioned analyses. Three samples were from fur capes: Baunsø Mose (D11103b), sample size ~4,5 x 7 mm, Borremose I (C26450), sample size ~2,5 x 4,4 mm, and Huldremose I (C3471), sample size ~3,6 x 8,7 mm. The fourth sample was a fur fragment from a cape or a wrapping skin from Vindum Mose (C5030), sample size ~6,8 x 15 mm.

All fur objects were found associated with bog bodies. See Figure 1 for the geographical location of the bog finds. The items are shown in Figure 2. The three capes (D11103b, C26450, C3471) had previously been identified for animal species by means of Mass Spectrometry of Peptide Sequence (MS-PS)

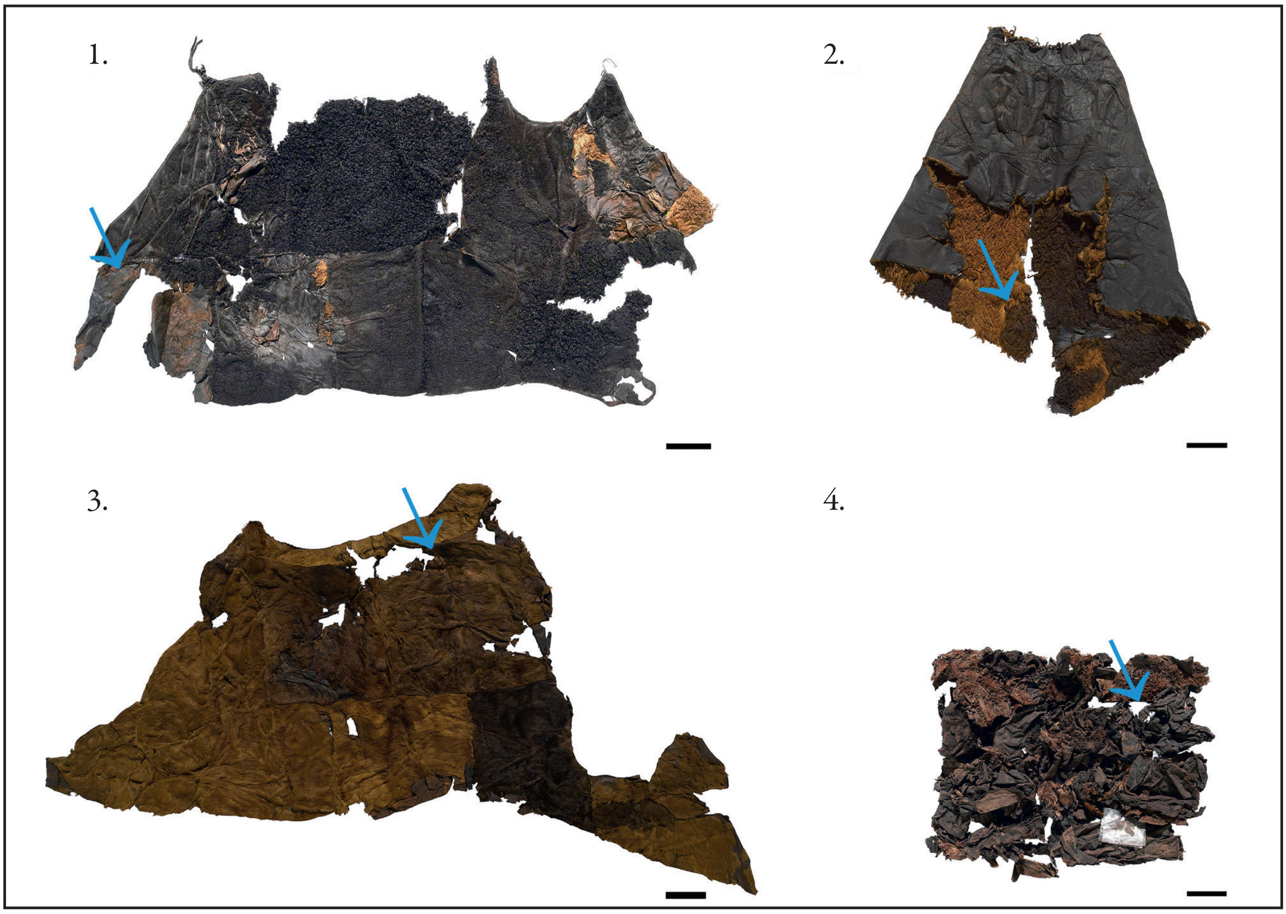

Figure 2. The four studied skin capes and fragments from the Danish Early Iron Age (500 BC-400 AD): 1) Baunsø Mose, 2) Borremose I, 3) Huldremose I and 4) Vindum Mose. The arrows indicate where the samples were taken. Bars = 10 cm (Photos: the National Museum of Denmark, Roberto Fortuna).

(Brandt et al. 2014), while the fragment (C5030) was identified through hair microscopy in transmitted light (internal notes at the National Museum of Denmark, publication in progress). Table 1 provides a survey of the analysed items. The skin samples have been buried in peat for approximately two millennia, which may have affected their properties and composition.

Analytical Methods

All analyses were performed starting with the non-destructive ATR-FTIR analysis, after which approx. 0.2 mg of fibres were used for the fibre morphological analysis and the remaining part of the sample for the GC-MS analysis.

Condition Assessment

Depending on colour, physical condition, etc., visual examination by naked eye and light microscopy may give some coarse information on the state of condition, material type and animal origin.

Method

The condition assessment of the archaeological fur skin was carried out as a visual examination and careful handling by hand by trained conservators. The flexibility of the skin, the cohesiveness of the fur layer to the skin and the tendency to shed hair or grain surface were assessed. Additionally, the possible presence of insect debris and fungal growth was noted.

Provenance Inventory no.	Object	Unearthed	14C dating	Species	Object dimensions (cm)
Huldremose I, Nimtofte, Djurs Nørre, Randers C3471	Asymmetrical inner fur cape	1879	350-41 BC[1]	Sheep[2]	Height 80 width 150
Borremose I, Aars, Aars, Aalborg C26450	Symmetrical fur cape	1946	365-116 BC[1]	Sheep[2]	Height 90 width 158
Baunsø Mose, Roum, Rinds, Viborg D11103b	Symmetrical fur cape	1927	20-220 AD[1]	Cattle[2]	Height 89 width 194
Vindum Mose Vindum, Middelsom, Viborg C5030	Fur fragments	1883	386-203 BC[1]	Sheep[3]	Not measurable

[1] ^{14}C dating (Mannering et al. 2010)
[2] Species identification (Brandt et al. 2014)
[3] Species identification (internal notes at the National Museum of Denmark)

Table 1. Survey of analysed items.

Analysis of Shrinkage Temperature Data

The use of the shrinkage temperature (Ts) as a criterion for whether skins are tanned or not tanned by burial in bogs has been subject to discussions (Thomson 2007; Ogilvie 2019, 74). To clarify this, we have analysed Ts data from previous measurements of the capes from Baunsø and Borremose I and the literature. Table 2 provides an overview.

Method

The method, used as a measure of the quality and hydrothermal stability of leather and skin, has proven also to be a fine measure of the degree of deterioration of these materials (Larsen et al. 1993, 151-155; Larsen 2000, 90-97. Upon degradation, the Ts and the shrinkage activity decreases. Untanned mammal skin has a shrinkage temperature of around 65 °C, new dehaired skin and parchment 55-60°C, new vegetable tanned leather 70-90°C and heavily degraded material may have a Ts below room temperature (Larsen et al. 1993, 151-152).

The shrinkage is a process taking place over several temperature intervals of increasing and decreasing activity. The start of the main interval, where the largest number of fibres shrink, is defined as the Ts. The measurement is performed by soaking the skin or leather fibres and heat them in the water, normally at a rate of 2°C/minute. However, the measurements of Borremose I and Huldremose I were performed using a Mettler Hot-Stage with a temperature rate of 3°C/minute (modified after Young 1990). The other samples were measured using a Mettler Hot Stage with a temperature rate of 2°C/minute according to Larsen et al. (1993, 151-152).

Fibre Morphological Analysis

Fibre morphological studies are widely used to identify the extent of degradation of skin and leather and have been used in several studies of historical parchment (Badea et al. 2012; Bell et al. 2018; Kern et al. 2018; Larsen et al. 2012; Mühlen Axelsson et al. 2012; Mühlen Axelsson et al. 2014; Mühlen Axelsson et al. 2017; Sommer et al. 2017) and more recently also in studies of vegetable tanned and non-vegetable tanned archaeological skins (Warming et al. 2020). The method is based on the observation of the morphology of separated corium

Item	Inventory number and object type	Ts (+/- 2 °C) and year of measurement	Vegetable Tannins
Borremose I	C26450, Cape	42,8 °C / 1995 (internal notes)	Yes
Huldremose I	C3471, Cape	48,2 °C / 2007 (internal notes)	Yes
Vindum Mose	C5030, Cape	31,0 °C / 2013 (Sommer et al., 2013)	No
Vester Torsted	Cape	42,5°C / 2013 (Sommer et al., 2013)	?
Baunegaard 1	Weapon shield	31,5 °C / 2019 (Warming et al., 2020)	No
Baunegaard 2	"	40,1 °C / 2019 (Warming et al., 2020)	No
Birka rim	"	36,9 °C / 2019 (Warming et al., 2020)	Yes
Birka facing	"	32,9 °C / 2019 (Warming et al., 2020)	Yes
Borremose 1*	"	- 2019 (Warming et al., 2020)	Yes
Borremose 2	"	47,2 °C / 2019 (Warming et al., 2020)	Yes
Borremose 3	"	51,1 °C / 2019 (Warming et al., 2020)	Yes
Borremose 4	"	50,8 °C / 2019 (Warming et al., 2020)	Yes
Tira 3	"	55,0 °C / 2019 (Warming et al., 2020)	No
Tira 5	"	55,3 °C / 2019 (Warming et al., 2020)	No
Tira 6	"	40,8 °C / 2019 (Warming et al., 2020)	No
Grauballe Man 1	Bog body	51,6 °C / 2005 (Larsen and Poulsen, 2007, 84)	Yes
Grauballe Man 2	Bog Body	56,8 °C / 2005 (Larsen and Poulsen, 2007, 84)	Yes

* Ts was not measurable due to severe degradation of the fibres.

Table 2. Shrinkage temperatures previously measured on tanned and untanned skins.

fibres in fully hydrated condition in excess water at ambient temperature. By uptake of the water, the fibres may transform into a range of morphological types in the form due to, e.g., swelling, shrinking, fragmentation and dissolution into a gelatinous substance, depending on the state of their condition.

Method

A 0.2 mg corium sample was taken out by careful scratching with the tip of a scalpel. The sample was placed on an object glass and covered completely with water and left to soak till the fibres were completely saturated with water (no fibres float on the water surface). Then the fibres were separated carefully using two preparation needles and covered with a cover glass. The fibres were assessed on 10-15 representative microscopical images recorded in transmitted light at x100 to x400 magnification.

The state of degradation is determined by judgement of the degree of the coherence of the fibre network, the degree of fragmentation and the type and extent of morphologies present that can be attributed to deterioration. Based on this, the samples can be roughly classified within the following five damage categories and assigned a score of between 1 and 5, with a condition between two of the categories assigned the value 0.5:

1. None or insignificant damage: Fibre network coherent, fibres intact and few fragments.
2. Slight damage: Less coherent fibre network with some fibres or part of fibres shrunken and more fragments.
3. Damage: fibre network poorly coherent and more fragmented with few intact fibres and/or part of fibres. Majority of fibres and fragments are shrunken, partly gelatinised and containing, to a minor part, frayed and/or uncoiled forms, flat, pearls on a string flat, and butterflies.
4. Severe damage: Minority of fibres intact and very little remaining of fibre network. Most fibres and fragments are shrunken and gelatinised to vari-

ous degrees as well as in the form of the morphologies mentioned in 3 and may appear as individual free and/or in bundles "glued" together.

5. Complete damage: Fibre network is completely fragmented, disconnected and/or in smaller bundles, normally in a high to completely gelatinised condition. In some cases, the fragmentation is complete with a lower degree of gelatinisation due to crosslinking caused by oxidative reactions.

ATR-FTIR Analysis

FTIR spectroscopy has been widely used to study the chemical structure and degradation of proteins and skins showing that changes in chemical structure may be attributed both to applied surface treatments and the surrounding environment (e.g., Haris and Chapman 1995; Jackson and Mantsch 1995; Kong and Yu 2007; Usoltsev et al. 2019).

The method was used in studies of the deterioration of parchment, vegetable tanned leather and other collagen-based materials (Badea et al. 2008; Boyatzis et al. 2016; Carsote et al. 2012; Derrick 1991; Odlyha et al. 2009; Plavan et al. 2010; Rowe et al. 2018; Sommer et al. 2017; Vandrucci et al. 2020; Vyskocilová et al. 2019; Warming et al. 2020) and to identify lipids in the form of fats and oils (Che Man and Mirghan 2001; Guillen et al. 2003; Nina Naquiah et al. 2017; Portaccio et al. 2023; Rohman and Che Man 2010; Safar et al. 1994; Tatulian 2019; Van de Voort and Sedman 2000).

Furthermore, the method has also been used to identify vegetable tannins in cultural heritage leather and skin materials (Carsote et al. 2012; Falcao and Araujo 2014; 2018; Ricci et al. 2015; Warming et al. 2020) as well as aluminum and iron compounds (ChemicalBook spectra base; Farahmandjou et al. 2020; Veneranda et al. 2018; Wiley spectra base).

Method

The samples were analysed on a Perkin-Elmer Frontier FTIR spectrometer fitted with a Universal ATR accessory with a diamond internal reflection element and adjustable pressure. Pressure was adjusted manually to maximise energy absorbance and minimize noise. All samples were analysed using 20 scans in the spectral range 4000-650 cm^{-1} with a resolution of 4 cm^{-1}. Five spectra were run for each sample and an average produced.

Analysis of the Spectra

FTIR spectra of skin and especially tanned skin are characterized by intensely overlapping bands that confuse interpretation. These can be resolved by calculating the second derivative of the spectrum (Baldassarre et al. 2015; Cameron and Moffatt 1987; Dong et al. 1995; Susi and Byler 1988; Usoltsev et al. 2019). One of the main advantages of the analysis of the second derivative is that it can be performed objectively without an arbitrary choice of deconvolution parameters (Usoltsev et al. 2019). Moreover, the maxima of overlapping bands are shifted compared with the true maxima, the effect of which can also be corrected by using the second derivative. The calculation of the second order derivative and other data processing such as baseline correction, peak search, normalization etc. were performed using OPUS/IR, FTIR Spectroscopy Software Package version 8 from Bruker.

The calculation of the second derivative was performed to identify key markers for collagen (Vindum Mose), vegetable tannins (Baunsø Mose, Borremose I and Huldremose I), animal fats, aluminum compounds and iron compounds (all four samples).

To evaluate the condition of the collagen, the position and intensity of the following bands of were recorded. The major amide I band (AI), found between 1680 and 1610 cm^{-1}, is mainly associated with the C=O stretching vibration related to the protein backbone and is sensitive to protein conformations (Vadrucci et al. 2020). The major amide II band (AII) found between 1540 and 1500 cm^{-1} associated with the N-H bending vibration and from the C-N stretching vibration, depending on the conformation adopted by the peptide (Jackson and Mantsch 1995; Tatulian 2019). The relative intensities and shifts of these two bands provide information on the protein denaturation. Thus, the intensity of the AI band decreases significantly relative to the AII band due to hydrolysis of the collagen while changes in the original positions of the AI and AII main FTIR peaks ($\Delta\nu$) indicates gelatinization (Derrick 1991; Odlyha et al. 2009; Plavan et al. 2010; Vadrucci et al. 2020;

Vyskocilová et al. 2019). Oxidation of the amino acid residues and the polypeptide chain results in the formation of carbonyl compounds absorbing in the 1700-1750 cm^{-1} region. Thus, increase of the band at about 1720 cm^{-1}, is related to oxidation of side chain groups, and the relative extent can be calculated as the proportion of the band intensities, AI/1720 (Vadrucci et al. 2020).

GC-MS Analysis

Various analytical procedures are widely applied in museum contexts and involve GC-MS. These often aim at characterizing organic chemical constituents in museum objects from paintings to ethnographica (e.g., Mills and White 1999). In the present study, the method using the following protocol was applied.

Method

Three extractions were carried out on each sample. The first one was with dichloromethane (DCM) to isolate nonpolar substances. The second extraction used a mixture of water and acetone to isolate more polar components. In the third extraction, methanol with sulfuric acid was used to methylate by transesterification and to extract. The extracts were derivatised and analysed by GC-MS

Samples from Baunsø Mose, Borremose I, Huldremose I and Vindum Mose were placed in a 2 mL GC vial which was then filled with dichloromethane (DCM) and placed in an ultrasonic bath for ca. 4 hours and then left to settle overnight. The clear solvent was isolated in a new GC vial and evaporated to dryness under a gentle stream of nitrogen. The extraction was repeated with a mixture of acetone and water (50/50) in an ultrasonic bath for 4 hours and left overnight after which the solvent was isolated and evaporated under a stream of nitrogen gas.

The two condensates were silylated by adding 10 µl internal standard (0,62 mg/ml deuteropalmitate CAS 39756-30-4 d31 in MTBE (methyl tert-butyl ether)) and 70 µl anhydrous pyridine. The contents of the vials were mixed thoroughly until everything was dissolved. 70 µl N, O-Bis(trimethylsilyl)trifluoro-acetamide with trimethylchlorosilane (BSTFA+TMCS) was added, mixed and left with a tight lid on a heating block at 70°C for 60 minutes. After cooling the liquid was evaporated to dryness under a gentle stream of nitrogen. The condensate was re-dissolved in 0,5 ml n-hexane using ultrasonic bath and whirl mixer and centrifugated for 5 minutes at 5000 rpm to clear the solvent, which was then isolated in a new GC vial and analysed on GC-MS.

The skin sample that has been extracted twice was dried under a stream of nitrogen. Then 10 µl intern standard (0.56 mg/ml deuteropalmitic acid) and 0.5 ml methanol were added. After whirly mixing for a minute, 25 µl 96% sulfuric acid was added. The vial was left on a heating block at 70°C for 2 hours. The solution was extracted with 3x500 µl hexane and then isolated in a new GC vial after the two phases have settled. The hexane was evaporated under a stream of nitrogen and the condensate re-dissolved in an appropriate aliquot of hexane and analysed on GC-MS.

The GC-MS instrument was a Bruker SCION 456GC-TQMS equipped with a Restek Rtx-5 capillary column (30 m, 0.25 mm ID, 0.25 µm) programmed for a 1 ml min^{-1} helium flow. 1 µl sample was applied on the PTV (Programmed Temperature Vaporization) injector, which was held at 64°C for 0.50 min, raised to 315°C at 200°C min^{-1} and held at that temperature for 40 min. The split ratio was 10 the first 0.5 min and then switched to 5. The GC oven temperature was held at 64°C for 0.5 min, then raised to 190°C at 10 °C min^{-1} and then to 315°C at 4°C min^{-1} and held at that temperature for 15 min. The EI (electron ionisation) source temperature in the mass spectrometer was 250°C and the ionisation potential was -70 eV. The mass spectrometer was operated in the full scan mode from m/z 45 to m/z 800. Peaks were identified using the NIST 2.0 MS database.

Results and Discussion

Condition Assessment

The visual inspection indicated that the Baunsø Mose, Borremose I and Huldremose I capes were in good condition: cohesive and not fragmented, and without pest or fungi infestations. The Baunsø Mose and Borremose I capes had no evident traces of daily wear, while the Huldremose I cape contained 24 patches of furred sheep skin, sewn with coarse stitching to the original worn garment. Regarding

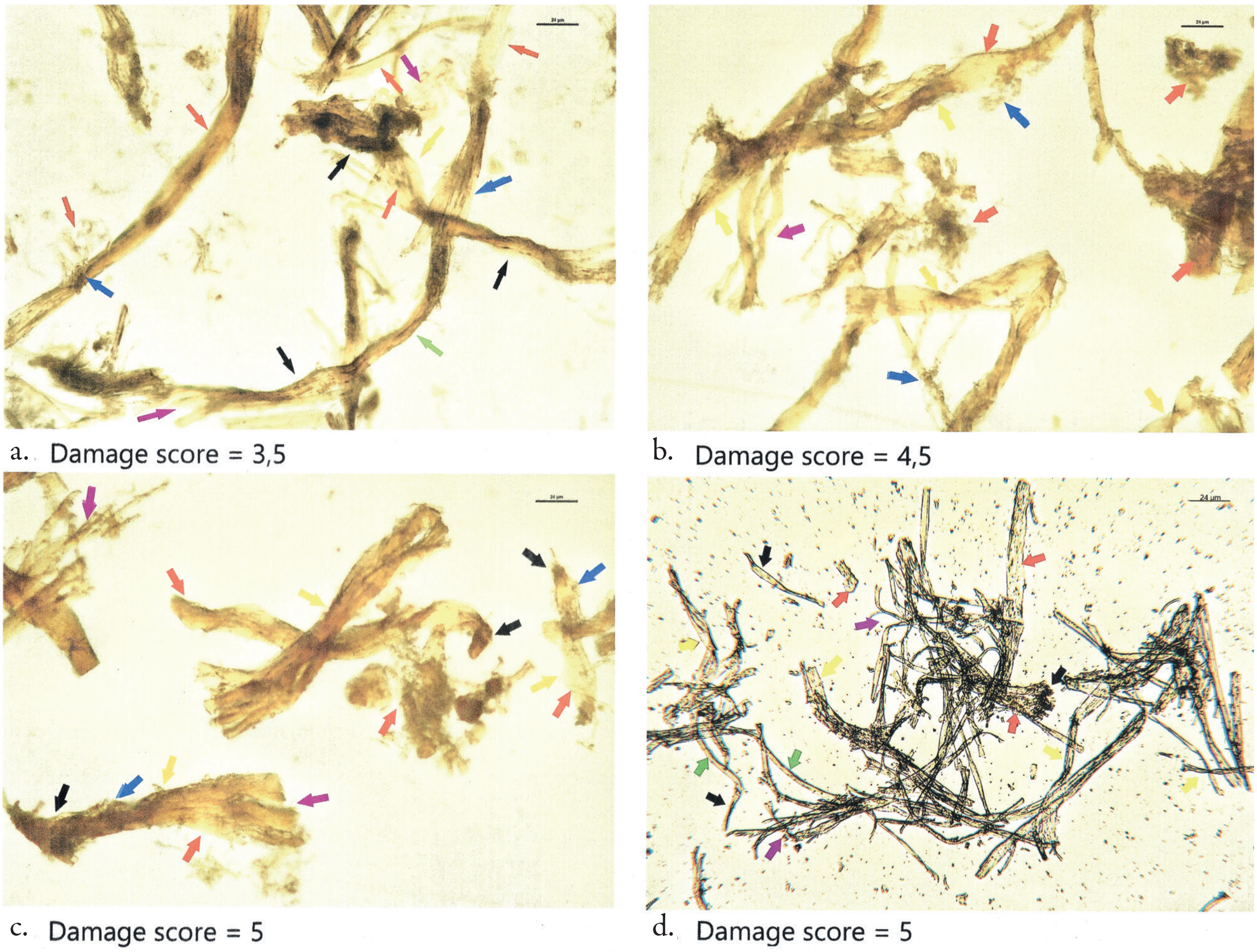

Figure 3. Examples of fibre samples in different degree of deterioration: a.- c. New vegetable tanned leathers deteriorated by hydrolysis and oxidation. d. Historical parchment deteriorated by hot storage condition. Morphological types: Intact Shrunken Frayed Split Pearls on a string Butterfly Gelatinised
(Photos: a-c Bevaring Sjælland, René Larsen and d Kunstakademiets Konservatorskole, Kathleen Mühlen Axelsson).

wear and tear, assessing the Vindum Mose fragments was impossible.

Analysis of Shrinkage Temperature Data

Table 2 shows Ts measured Early Iron Age leathers and skins excavated from bogs. It should be mentioned that the samples from the Grauballe Man were taken from the stomach skin. This bog body was tanned with oak bark extraction in water for 18 months in the years 1953-1954 (Strehle 2007, 43).

As seen, the highest Ts values were measured on samples of Grauballe Man and Tira, the latter of which the fibre morphological analysis and IR spectrum did not show any signs of vegetable tannins (Warming et al. 2020, 188 and 195). Furthermore, there are more than 10°C difference between some of Baunegaard and Tira subsamples.

To test the difference vegetable tannins vs. no vegetable tannins, the data was analysed using a paired samples t-test to test the null hypothesis (H_0) that the population mean of the difference between paired observations equals = 0. The analysis resulted in a probability $p = 0{,}8807$ at a 95% confidence interval and a difference in mean of 0.900. It should be noticed that the accuracy of the method is +/- 2°C. Thus, there is most likely no difference between the Ts values of the samples containing vegetable tannins and those containing none.

Fibre Morphological Analysis

Figure 3 shows comparable examples of fibres from three recently vegetable tanned leathers, aged by

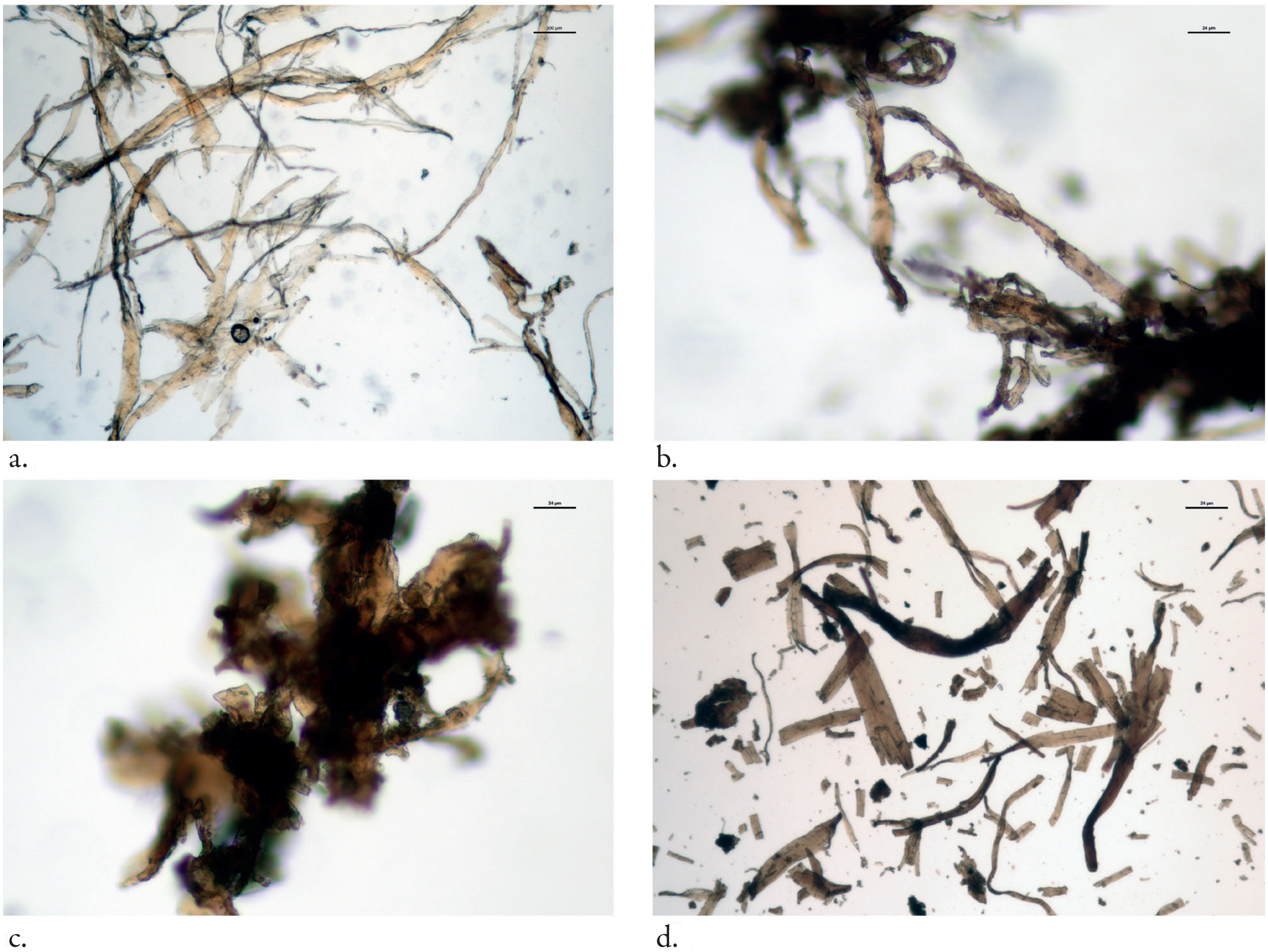

Figure 4. Fibre samples from: a) Baunsø Mose, damage score 3.5, b) Borremose I, damage score 4, c) Huldremose I, damage score 4.5 and d) Vindum Mose, damage score 5 (Photos: Bevaring Sjælland, René Larsen).

accelerated aging (Larsen 2022; Larsen et al. 2021, 6) and a parchment from the Middle East dating from the 17th to 18th century deteriorated by storage in a dry hot environment causing oxidative cleavage as well as crosslinking of the collagen (Mühlen Axelsson et al. 2012, 130). The fibre samples are very similar to samples of the four garments with concerning the degree of deterioration and fibre appearance (Figure 4).

Figure 3.a shows a fibre network with low degree of coherence and high degree of shrunken fibres (wavy and zig zag pattern) and some fibres in process of uncoiling as well as many small fragments. Some fibre parts are blurred due to gelatinising (damage score 3.5). The fibre network in Figure 3.b has a very low coherence with several larger fragments. Fibres and fragments are all gelatinised to various degree and appears in various morphological forms (damage score 4.5). In Figure 3.c, the fibre network is almost completely fragmented and appear mostly as bundles of various morphologies and a randomly shaped gelatinised substance (damage score 5). In Figure 3.d., the fibre network is also completely fragmented appearing in forms of morphologies. Most of the fragments are gelatinised. Though, a few have intact areas and only partly gelatinised (damage score 5).

The Baunsø Mose sample (Figure 4.a) is characterized by relatively long, slightly coherent yellowish-brown fibres, some of which split into smaller fibre units, typical for vegetable-tanned fibres. Some of the long fibres also have preserved intact areas. However, most of the fibres are clearly deformed with clear signs of shrinkage (wave and zig zag structures and pointed ends) also typical of tanned fibres. A partial gelatinization has caused the underlying microfibre structure to blur. Some flat gel like, fragments; typical of decomposed untanned material, indicates lack of tanning. Overall, the sample can be characterized as lighter and incompletely tanned and close to severely damaged.

The Borremose I sample (Figure 4.b) contains bundles of fibre fragments, some with signs of a slight split of the fibres, shrinkage appearing as a wavy structure with a hint of cross-striation. This, together with the faint yellow-brown colour, indicates that the fibres are tanned. In addition, some fragments have morphological structures in the form of pearls on a string, flat and only a few areas of relative intact structure, all characteristics of degraded untanned skin and parchment. The coherence of the fibre structure is most likely due to gelatinised fibres sticking together. Thus, the sample can be characterized as slightly incompletely tanned and heavily damaged.

The fibre structure of the Huldremose I sample (Figure 4.c) can only be separated in small bundles of fragments 'glued' together due to gelatinisation. Thus, the split of the fibre fragments into smaller units, as seen by tanned fibres, are not observable due to dissolution of the fibre structure. The bundles seem to consist of randomly shaped fragments, butterflies and some zig zag structured shrunken fragments. Together with the many butterflies and slightly yellow-brown colour of the visible fibre remains, as observed also by severely degraded vegetable tanned leathers (Figure 3.c), this indicates the presence of tannins. Thus, sample can be described as tanned and severely close to completely damaged.

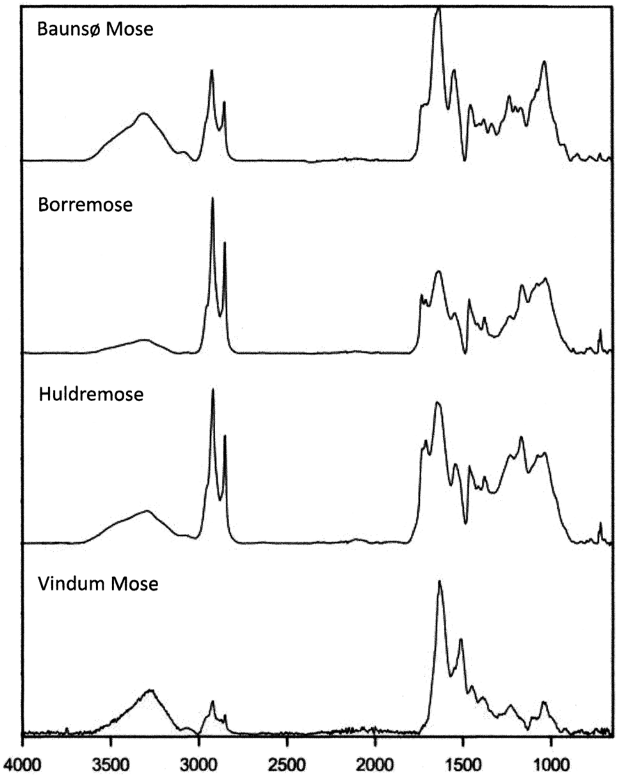

Figure 5. ATR-FTIR absorption spectra of the four cape samples.

The fibres of the Vindum Mose sample (Figure 4.d) are completely degraded and consist of small randomly shaped fragments and longer fragments in the form of partly unfolded flat, pearls on a string and shrunken structures. All are in an advanced state of gelatinisation and without signs of split into smaller fibre units. The morphological characteristics are typical for skin not tanned with vegetable tannins. The many very randomly formed fragments indicate great stiffness in the fibres (Bartoletti et al. 2017, 267-269; Larsen 2007, 18-20). The skin can be described as possibly untanned with a completely damaged fibre structure.

ATR-FTIR Spectroscopy

The absorption spectra of the four samples are shown in Figure 5. The spectra profiles of Baunsø Mose, Borremose I and Huldremose I show the presence of vegetable tannins, whereas Vindum Mose only shows the typical collagen profile and no additional treatments. Previous analyses of archaeological finds of leather weapon shields also revealed both vegetable tanned skins of which one was a find from Borremose (Warming et al. 2020) as well as non-vegetable tanned skins.

Table 3 shows the observed key marker bands for Baunsø Mose, Borremose I and Huldremose I together with 15 published marker bands for historical leathers (Falcao and Araujo 2014, 7; 2018, 16) and 11 markers bands of the weapon shield from Borremose (Warming et al. 2020, 196). All three hides contain both condensed and hydrolysable tannins. The distribution of key markers suggests that Borremose I and Huldremose I may contain the same tanning material used for tanning of the Borremose weapon shield. The deviations in the Baunsø Mose spectrum (Figure 5) may be due to differences in the tanning source, type and/or the presence of other substances, e.g., from conservation. The missing bands may be due to overlapping and/or changes in the spectrum profile due to deterioration.

Vegetable tannins[1]	Historical leathers[2]	Borremose Weapon shield[3]	Borremose I	Baunsø Mose	Huldremose I
Compounds present in all classes of tannins					
1615-1606	1612-1611		1612	1611	1612
1518-1507	1518-1514	1518	1517	1517	1515
1452-1446	1448-1447	1454	1453	1450	1453
1211-1196	1207-1203	1200	1206	1201	1201
1043-1030	1040-1032	1035	1032	1030	1030
Condensed tannins					
1288-1282	1287-1283	1280	1288	1286	1281
1162-1155	1157	1166	1162	1156	1158
1116-1110	1114	1118	1114	1109	1113
976	979-976	972	973	973	976
844-842	842	841	837	835	841
Hydrolysable tannins					
1731-1704	1708-1704	1710	1710	1710	1710
1325-1317	1326-1319	1325	1319	1321	1321
Gallo tannins					
1088-1082	1097-1092		1082	1092	1097
872-870	874-870	874	875	875	875
763-758	765-760		761	766	764

[1] Falcao and Araujo 2018, 16; [2] Falcao and Araujo 2014, 505; [3] Warming et al. 2020, 196.

Table 3. Marker bands (cm-1) for Baunsø Mose, Borremose I and Huldremose I with literature values for vegetable tannins, historical leathers and the archaeological leathers.

Table 4 shows the marker band for Vindum Mose compared to references of collagen I and parchment from the literature including the untanned samples from the weapon shield finds (Warming et al. 2020). It is interesting that the best match of Vindum Mose is with 11 marker bands of the 11 bands of the collagen from Boyatzis et al. (2016, 4).

With respect to the presence of fat, the analysis is based on the detailed study of Nina Naquiah et al. (2017) as the analysis and peak identification of their published spectra resulted in a representative number of key markers for pure cow body fat (26) and pure lamb body fat (22) (Table 5). As seen in Table 5, there is convincing agreement between the 24 markers for Baunsø Mose and that of cow fat from Nina Naquiah et al. (2017), seven of these differs specific from lamb fat and those of the three other furs. Borremose I has 20 out the 22 markers of lamb fat and Huldremose I 19 of lamb and one matching cow fat and Vindum Mose has all 22 matching lamb fat and 3 matching cow fat. Borremose I and Vindum Mose has all 10 of the specific bands which differs from cow fat and Huldremose I 9 of these. As mentioned above, the missing bands may be due to deterioration and masking by bands from other compounds in the skins.

Regarding the possible presence of, e.g., brain lipids, Portaccio et al. (2023, 535) reports 12 major peaks, of which three are found in all four samples. The additional number of peaks found was Baunsø Mose (3), Borremose I, Vindum Mose (7), and

Collagen[1]	Newparchment[1]	Collagen I[2]	Newparchment[2]	Weaponshields Baunegård Surface[2]	Weaponshields Baunegård inner core[2]	Weaponshields Tira S2[2]	Vindum Mose
3321	3302	3305	3292	3293	3290	3289	3292
3072	3072	3076	3073	3073	3073	3073	3072
2958	2926	2931	2926	2928	2931	2931	2936
1644	1640	1631	1631	1631	1632	1632	1645
1545	1538	1548	1538	1535	1536	1523	1546
1454	1448	1452	1448	1449	1449	1449	1450
1405	1408	1405	1405	1402	1402	1406	1407
1340	1334	1339	1335	1334	1336	1335	1337
1241	1230	1238	1235	1233	1235	1233	1237
1082	1084	1082	1081	1080	1081	1082	1082
1032	1031	1032	1031	1031	1031	1031	1034

[1] Boyatzis et al. 2016, 4; [2] Warming et al. 2020, 194.

Table 4. Marker bands in cm-1 for Vindum Mose with literature references for new collagen, new parchment, and untanned skins from archaeological weapon shields.

Huldremose I (6). Four of the brain lipid peaks has no match. Moreover, eight of the brain lipid peaks matches the average position of the peaks of the main lipid components of human cells reported by Portaccio et al. (2023, 534).

There are peaks possibly originating from aluminum (ChemicalBook spectra base) and iron compounds (ChemicalBook spectra base; Veneranda et al. 2018, 71, 73; Wiley spectra base) and mixtures of these (Farahmandjou et al. 2020, 3427-3428) in the spectra of all four samples that do not coincide with the marker peaks for collagen, vegetable tannins and fat. Regarding aluminum tops, the following were found: Baunsø Mose (12), Borremose I (9), Huldremose I (7) and Vindum Mose I (7), which in all cases partially match both aluminum hydroxide and aluminum sulphate. The number of peaks in the spectra of all four samples that may be linked to α-FeOOH, β-FeOOH and γ-FeOOH are: Baunsø Mose (3), Borremose I (6), Huldremose I (5) and Vindum Mose I (6).

The results of the analysis of the deterioration of collagen in the four samples in Figure 6 and Table 6 were based on the ratio between the major amide I (AI) and amide II (AII) bands (AI/AII), the ratio between the amide I band and the carbonyl band at around 1720 cm-1 (AI/1720) as well as the distance between the amide I and amide II bands (Δν). The calculated values show that all samples are degraded to varying degrees from hydrolysis and oxidation, which have led to gelatinisation.

The order of increasing degree of hydrolysis (AI/AII) is 1) Baunsø Mose 2), Huldremose I, 3) Borremose I and 4) Vindum Mose. With respect side chain oxidation (1720 AI) the order is almost the opposite 1) Vindum Mose, 2) Borremose I, 3) Baunsø Mose and 4) Huldremose I. When it comes to the degree of gelatinisation (Δν), the resulting damage caused by the hydrolysis and oxidation is significantly higher for Vindum Mose compared to the three other samples and for Huldremose I it is significantly higher than those of Baunsø Mose and Borremose I. The high AI/AII and Δν values for Vindum Mose may reflect the skin was not tanned, which means that the collagen easily uncoils, fragments and gelatinises in a way typical for deteriorated parchment. However, further studies are needed to reveal if a lower degree of other tannage, e.g., smoke, lipid or aluminum, lead to the same degree and type of deterioration.

Pure cow body fat	Baunsø Mose	Pure lamb body fat	Borremose I	Huldremose I	Vindum Mose	Bovine brainlipids
3000		3002			3005	
2931	2930	2930	2930	2928	2927	
2914	2917	2914	2917	2917	2918	
2868	2872		2872	2872	2870	
1750	1754					
		1739	1739	1739	1737	1742*
		1734	1733	1732	1729	
1705	1704					
		1660	1659	1660	1661	
1654	1655					1652
						1545
1467	1460	1464	1463	1463	1465	1466*
1424	1424	1424	1421	1424	1424	
1417	1417	1410	1409	1410	1411	
		1380	1377	1382	1377	1381*
1375	1372					
1350	1350				1348	
1309	1309	1306	1310	1311	1312	
		1244	1243	1243	1243	
						1234
1238	1238					
		1170	1170	1172	1169	1174
1160	1161	1160	1161	1162	1160	
1118	1118				1119	
1102	1102	1100	1101	1103	1103	
						1084*
1069	1069					
		1060	1061	1060	1058	1064*
1028	1030	1128	1029	1029	1027	
1020	1019	1020			1017	
980	980	980	984	984	986	
						971*
965						
960	961	960	957	954	961	
940	936	940	940		940	
		927	927		929	
884	885			883	885	
	820		820	818	817	822*
726	729					
	719		720		723	720*

Table 5. Marker bands (cm-1) for Baunsø Mose, Borremose I, Huldremose I and Vindum Mose with literature references for pure cow fat, pure lamb fat and bovine brain lipids.

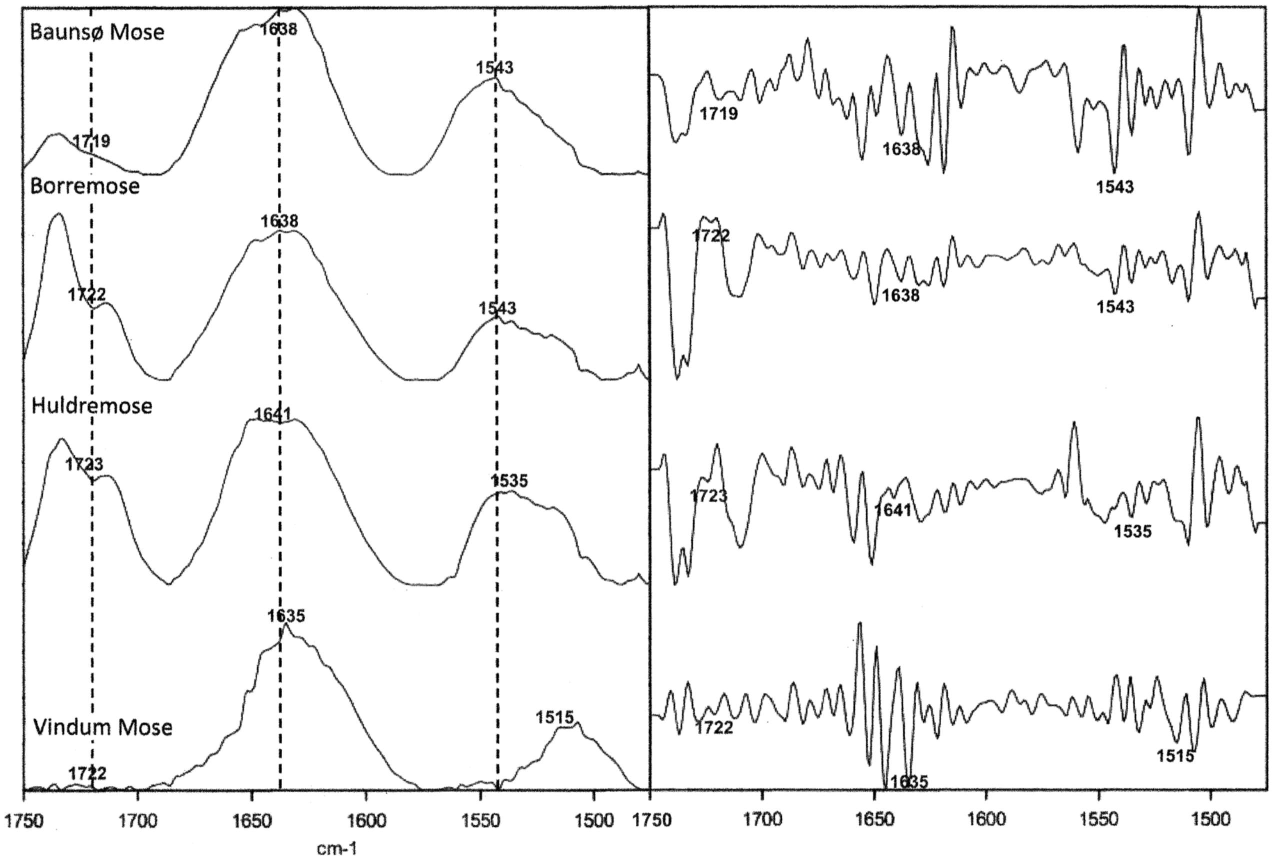

Figure 6. Absorption spectra (left) and the second derivative of these (right) in the wave number region 1775-1450 cm-1.

	Baunsø Mose	Borremose I	Huldremose I	Vindum Mose	
Measured values					**Band type**
AI (~1660) cm^{-1}	1638	1638	1641	1635	Amide I, νC=O
(ABS)	(0,048)	(0,039)	(0,049)	(0,016)	
AII (~1540) cm^{-1}	1543	1543	1535	1515	Amide II, νN-H,
(ABS)	(0,029)	(0,016)	(0,026)	(0,006)	δC=O
~1720 cm^{-1}	1719	1722	1723	1722	Carbonyl, νC=O
(ABS)	(0,034)	(0,024)	(0,037)	(0,006)	
Calculated values					**Damage type**
AI/ AII	1,66	2,44	1,88	2,67	Hydrolysis
1720/ AI	0,71	0,62	0,75	0,38	Side chain oxidation
$\Delta\nu$ (AI-AII) cm^{-1}	95	95	106	120	Gelatinisation

Table 6. Results of the analysis of collagen deterioration based on ATR-FTIR. Data are wave numbers in cm^{-1} and absorption intensity (ABS) without unit of measure.

GC-MS Analysis

Figure 7 shows the total ion count (TIC) chromatogram (top) and a plot of *m/z* 117 (bottom) to highlight fatty acids of Huldremose I. It is seen that glycerol, a phthalate, DDT, cholesterol as well as a range of fatty acids both saturated and unsaturated were detected. The three extracts analysed from Huldremose I, indicated that this sample contained saturated and unsaturated fatty acids, glycerol, cholesterol, DDT and a phthalate. Since no hydrolysis is involved in the first extraction, the fatty acids detected are present as free fatty acids on the sample rather than as glycerides. The glycerol detected could be a product of hydrolysed (degraded) triglycerides on the sample and/or the result of a conservation treatment with glycerol, which has been common practice in leather conservation (Thorvildsen 1935-1953, Part 1, 101, 139. Part 2, 149).

The detected cholesterol is a natural constituent in animal fat which could have been added to the skin or it could be natural fat in the skin itself. A phthalate was detected in all samples which is normal since phthalates are everywhere in our environment and hence also in the samples. DDT was detected as well in Huldremose I. This is the likely result of pest control treatment of the skins or of contact with other DDT treated objects (Schmidt 2001).

In addition to a phthalate, fatty acids and cholesterol were detected in Borremose I. Baunsø Mose also contained phthalates, cholesterol and fatty acids as well as DDT, borate, glycerol and azelaic acid. The glycerol seems to be present both as glycerol and as glycerol derivatives (diethers) which

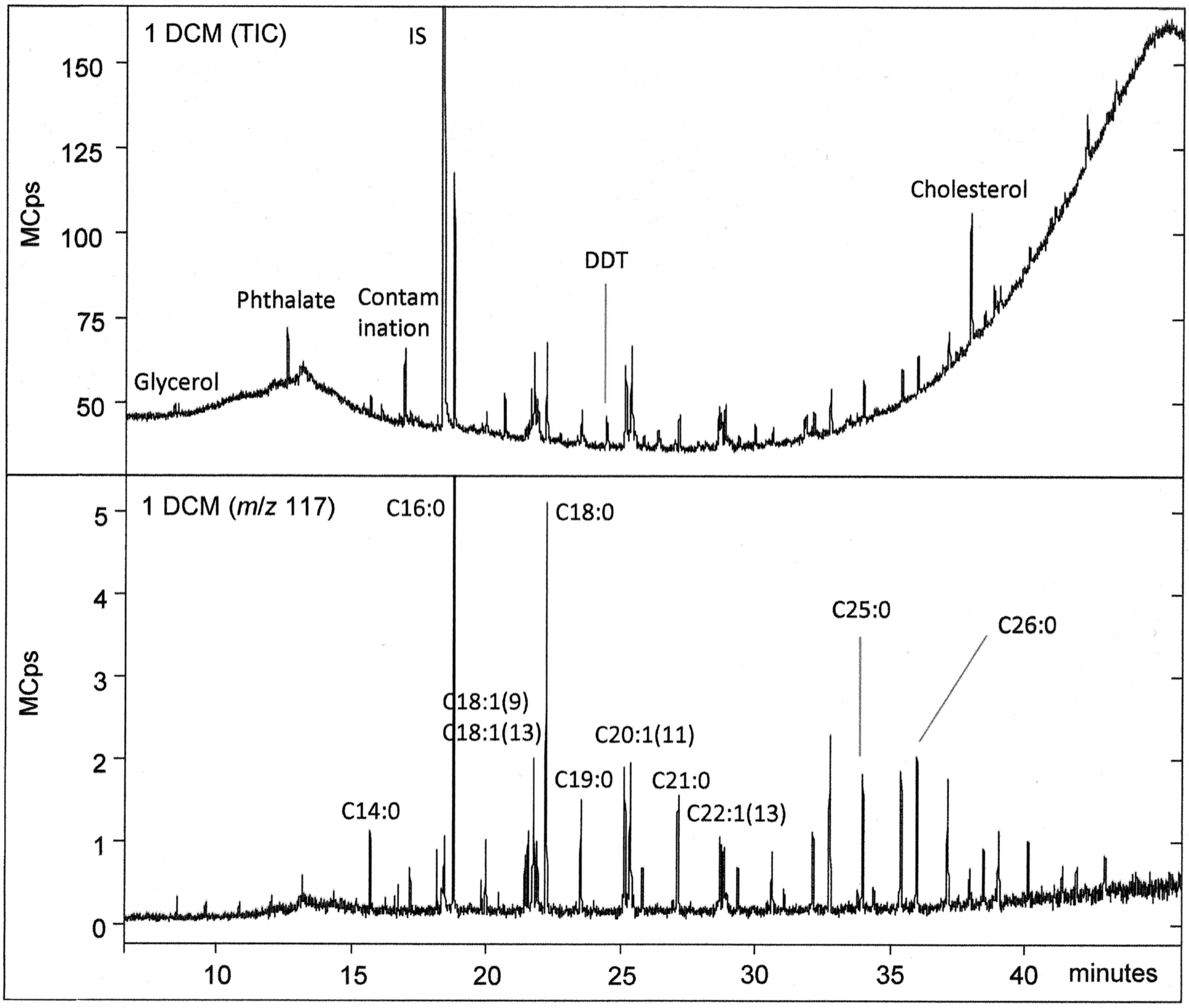

Figure 7. Partial chromatogram by GC-MS for dichloromethane (DCM) extract of Huldremose showing total ion count (top) and a plot of m/z 117 to highlight fatty acids. IS: internal standard, CX:Y: fatty acid with X carbon and Y double bonds, DDT: p,p'-dichlorodiphenyltrichloromethylmethane.

Sample	Dichloromethane (DCM)	Acetone/H2O	MeOH/H2SO4
Baunsø Mose	C14:0, C16:0, C18:1, C18:0, C19:0, C21:0, C25:0, C26:0 Glycerol (and dimers) Azelaic acid Cholesterol Phthalate DDT	C16:0, C18:0 Glycerol (and dimers) Azelaic acid Phthalate DDT Borate	C16:0, C18:1, C18:0 Azelaic acid Phthalate
Borremose I	C14:0, C16:0, C18:1, C18:0, C19:0, C20:1, C21:0, C22:1, C25:0, C26:0 Cholesterol Phthalate	C16:0	C14:0, C16:0, C18:0
Huldremose I	C14:0, C16:0, C18:1, C18:0, C19:0, C20:1, C21:0, C22:1, C25:0, C26:0 Glycerol Cholesterol Phthalate DDT	C16:0 Glycerol	C14:0, C16:0, C18:1, C18:0
Vindum Mose	C14:0, C16:0, C18:0, C20:0, C22:0 Cholesterol (intense) β-sitosterol Phthalate	C16:0 Glycerol Borate	C16:0, C18:0

Table 7. Components identified in extracts by GC-MS.

could be an indication that it has been added to the skin in significant quantities as a conservation treatment. DDT is an insecticide and borates are known biocides which must be why it was added to Baunsø Mose (Peacock 2001, 14 note 1). Azelaic acid is known to form from drying oils (e.g., linseed oil) in paintings (Mills and White 1999). Conservation of Baunsø Mose with such an oil could have led to the identified azelaic acid. Vindum Mose contained fatty acids, a large cholesterol peak, a phthalate, glycerol, borate and β-sitosterol. The latter is a plant sterol, which indicates that a plant oil has been in contact with the skin at some point. Table 7 shows the components identified in extracts by GC-MS.

Summary Discussion

The previously measured Ts of the Baunsø Mose and Borremose I capes and the examined Ts values from the literature clearly show that the Ts is not useful as a criterion for determining the type and degree of tanning of archaeological hides, but rather as a valuable measure of the degree of degradation in combination with the fibre morphological analysis. On the other hand, ATR-FTIR and fibre morphological analysis are obvious techniques for determining vegetable tanning substances in leather and fur. Thus, the results of this and the previous study by Warming et al. (2020) revealed the presence of both vegetable tanned and non-vegetable tanned skins which raises the question of whether full vegetable tannage or tannage by organic components are taking place in the bogs, as the latter would be visible in the FTIR spectra. The effects of bog environment on human skin have been investigated with respect to its ability to preserve bog bodies. Painter (1991, 123-142) points towards a specific component of sphagnum moss (Spaghnan) with tanning and sequestering properties. However, later studies of skin from several bog bodies have not been able to detect this component in the skin samples (Stankiewicz et al. 1997, 1889), nor has it been possible to verify its presence in Sphagnum moss (Ballance et al. 2007, 104-115).

The interesting results of the fat analysis based on FTIR key marker bands are supported by the visual identification of the animal type based on the hair typology as well as the cholesterol and the fatty acids found by the GC-MS analysis. This indicates that the four samples may primarily contain their original fats, and that no other fat may have been applied during the manufacture of the skins. However, a distinction between lipid from different tissues of the animal (Christie 2024), e.g., from the brain (Poitelon et al. 2020, 3) or the liver (Kinsella 1970, 605), can be made by GC-MS and is an obvious topic for further studies. The results on the lipids and the possible presence of aluminum and iron compounds, as indicated in the ATR-FTIR spectra, also calls for an extended study including also smoke compounds as potential tanning agents. The presence of aluminum and iron compounds can be verified by X-ray diffraction (Farahmandjou et al. 2020, 3426-3427; Veneranda et al. 2018, 73-76). Key markers in the ATR-FTIR spectra can finally be determined by comparative analysis of experimental skins and leathers with and without addition of the metals.

The result of the condition assessment of the Vindum Mose fragments agrees with the results of the fibre morphology and IR analyses. On the other hand, the latter results do not agree with the condition assessments of Baunsø Mose, Borremose I and Huldremose I. These were all judged to be in good condition, showing that it can be difficult to judge the condition of the fibre network layer and to differentiate between different degrees of degradation by the naked eye and simple handling. An explanation for this is that the epidermis, which contains the hair layer and is mainly composed of the protein keratin, is more resistant to degradation compared to the corium layer.

The relatively high Ts of Borremose I (42,8°C) and Huldremose I (48,2°C) is probably due to shrinkage of fragments which emphasizes the importance of also using the fibre morphology examination in the damage assessment. With respect to Borremose I and Huldremose I, the epidermis probably ensures the cohesion of the capes, while the corium layer of the Baunsø Mose cape still has some cohesion.

In relation to the condition of the capes and their conservation it should be emphasised that research on degraded historical parchment and leather objects has shown that gelatinisation may take place

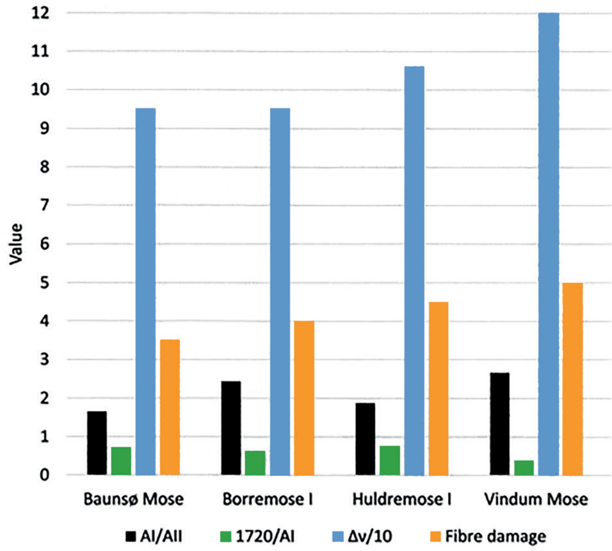

Figure 8. Results of the analysis of collagen deterioration based on ATR-FTIR and fibre analysis. Note that Δv is divided by 10 to obtain a comparable order of magnitude.

when these are exposed to water or alcohol (Derrick 1991; Larsen et al. 2012, 66; Bell et al. 2018) and not least that the degradation can occur spontaneously at room temperature and a low relative humidity (Larsen et al. 2002, 59-60; 2012, 64).

Finally, our results indicates that fibre morphological and ATR-FTIR analysis are complementary in determining the degree and type of damage. The fibre morphology visualise the total chemical modification detected by the ATR-FTIR analysis as illustrated in Figure 8. Despite the small numbers of samples, a strongly significant correlation is found between the fibre damage scores (FDS), assigned in the fibre assessment and the sum of the calculated values based on IR data (Σ_{IR} = AI/AII +1720/AI + $\Delta\nu/10$) representing the total degradation (Figure 9). This constitute a hypothetical relationship that should be verified in a larger study.

Interpretation of the Tanning Methods and Their Sustainability

Our results indicate that the skins have been washed and stretched after skinning, after which the flesh side has been scraped free of muscle remnants, subcutaneous connective tissue and subcutaneous fat (Harris 2012, 12-13; Rahme 1991, 46-51). From here, if the tanning has taken place before burial in the bogs, the treatment of Baunsø Mose,

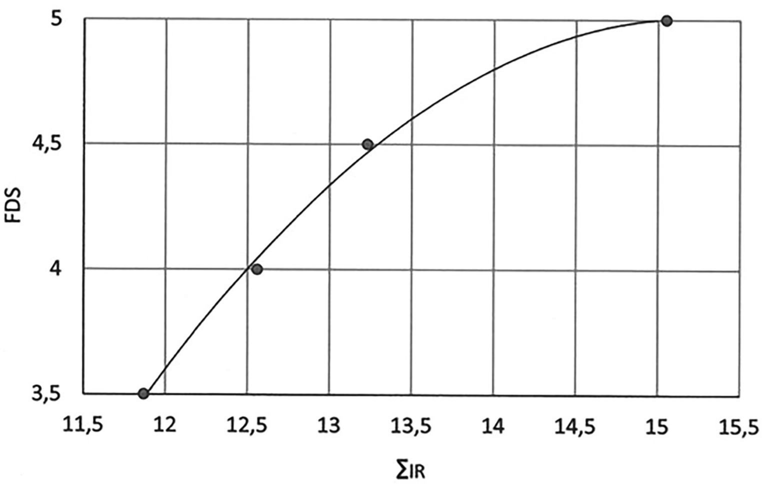

Figure 9. The fibre damage score (FDS) versus the sum of the calculated data from the IR (∑IR). The hypothetical relation follows the quadratic equation FDS = -0,1355*(∑IR)2 + 4,1267*∑IR - 26,406, with a correlation coefficient of R^2 = 0,9973.

Borremose I and Huldremose I differ from Vindum Mose. The first three were probably tanned by rubbing a decoction of locally available bark or other vegetable resources into the flesh side of the wet hide in a stretched state, which facilitates the penetration of the tanning solution into the hide (Harris 2012, 13-14; Rahme 1991, 75). The fibre structure of the skins may have been loosened before they were completely dry, to avoid the fibres sticking together and the skins becoming stiff and inflexible. Skins which are not completely dry are easier to soften manually or with a tool that pulls fixed fibres apart. In the case of Vindum Mose, the scraped hide was probably left stretched until it was halfway dry, after which it was softened manually in the same manner as described above. For both methods, enough of the original fats are left in the skins and distributed more evenly in the skin during the manual treatment. This ensures that the fibres are sufficiently isolated from each other and friction during their movement is avoided.

Assuming that no metal salt or smoke have been used in the production of the capes, the obtained results show that the tanning have been performed using raw materials which are part of the cycle of nature, and therefore has not harmed the surrounding environment. However, a contemporary large-scale production based on bark or other plant parts from slow-growing trees is not sustainable. This requires the use of cultivated fast-growing plants that contain only hydrolysable tannins to also achieve a long-lasting product.

With respect to long term stability, our analyses show that the fibre structure of the four samples range from severely to completely degraded. However, the degree of degradation must be judged in relation to the use of the capes before the burial in the bogs, the long storage time therein and the subsequent storage in the museum. In addition, three of the capes are tanned with condensed tanning substances, which have a strong degrading effect on the collagen structure, even under normal storage conditions (Hulme et al. 1905, 17-27; Innes 1933, 725; Larsen 1995, 69-78; 2000, 94-95).

In summary, the obtained results provide a solid basis for further and more detailed studies and raise, among other questions, the following: Why are some skins found in bogs vegetable tanned and others not? Is it due to differences in the bog environments? Or is it simply because some of the skins were treated with vegetable tannins and others not before burial, and the intended purpose determined the type of leather and fur produced? In this connection, it must be mentioned that Baunsø, Borremose I and Huldremose I were garments (capes), while Vindum Mose possibly had another function, e.g., as a simple body wrapping. This brings us back to the question: Does vegetable tanning occur naturally on skins buried in bogs? It is important to clarify these questions, as well as whether other tanning materials have been used in the production of leather and skins. Moreover, the condition of the examined furs and previously examined leathers and skins from weapon shields calls for studies of the long-term stability of skins tanned with methods assumed to be equivalent to Iron Age methods.

Conclusion

The garments from Baunsø Mose, Borremose I and Huldremose I appeared to be well-preserved by visual inspection, while Vindum Mose was highly fragmented. However, the ATR-FTIR, and the fibre morphological analyses results indicate serious deterioration of the four objects. Baunsø Mose has a damage score of 3.5, Borremose I of 4, Huldremose I of 4.5 and Vindum Mose of 5 (completely damaged). The ATR-FTIR key marker bands show that vegetable tannins are present in relatively slight amounts in the samples from Baunsø Mose, Borremose I and Huldremose I. In contrast, the Vindum Mose sample does not contain vegetable tannins. The tannins are condensed and hydrolysable indicating that tanning based on local plant sources, which was part of nature's cycle, was a well-known procedure during the Iron Age. However, the presence of condensed tannins in the three vegetable tanned capes, is a negative factor with respect to the long-term durability of the products. Moreover, ATR-FTIR key marker bands also indicate that the four samples may primarily contain their original fats. Thus, Baunsø Mose contains fat of calf/cow and Borremose I, Huldremose I and Vindum Mose that of lamb/sheep. However, more detailed analyses are needed to determine the presence of other possibly tanning compounds, such as compounds from smoke, lipids with a high content of unsaturated fatty acids, as indicated by the GC-MS analysis, and non-sustainable compounds from aluminum and iron, as indicated by the ATR-FTIR analysis.

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Declaration of Interest Statement

The authors have no competing interest to declare.

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From Landing site to Local Centre

New Insights into the Developments, Activities and Maritime Networks of Aarhus, Denmark, in the Viking Age c.750-1050

Jette Linaa[1,2,3,4]

[1] JL Consulting, Falstersgade 15B, 8000 Aarhus C, Denmark
[2] Department of Archaeology, Moesgaard Museum, Moesgårdallé 15, 8270 Aarhus, Denmark
[3] Department of Archaeology and Heritage Studies, Aarhus University, Denmark
[4] Corresponding Author (jl@cas.au.dk) ORCID: 0000-0002-6563-769X

ABSTRACT

The Viking Age represents a period of significant dynamism, during which local centres and urban sites participated to varying extents in maritime networks. This paper investigates the development, activities, and maritime engagement during the Viking Age of the Danish town of Aarhus, located on the East Coast of Jutland. In previous research, Aarhus has been portraited on the one hand as a late 10th century town of minor importance, and on the other as a prominent 8th century town with substantial ties to maritime networks between the Baltics and the North. This study contributes to the ongoing discourse through a comparative analysis of structures and artefacts from 20 excavations, contextualised alongside findings from Ribe, Haithabu, and Kaupang. The analysis reveals that in the 8th and 9th centuries, Aarhus was primarily an agrarian settlement centred on coastal resource exploitation, with minimal maritime connections. Although the site was fortified in the early 10th century, its activities largely remained unchanged. It was not until the late 10th century that Aarhus began to take on the characteristics of a town, including local trade, denser settlement, and specialised crafts. Even then, significant maritime connections were still absent, and its strategic location between the Baltic and the North Sea remained underutilised during the Viking Age.

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Introduction

The Viking Age (*c*.750-1050 AD) was a dynamic period characterised by varying levels of engagement in maritime networks among settlements ranging from local centres to towns. Research on Viking Age towns – identified through evidence of trade, specialised crafts, and dense settlement patterns – has evolved over time. Notable Viking Age towns such as Kaupang, Birka, and Haithabu have been extensively studied, with key contributions from scholars such as Arbman (1939), Blindheim, Heyerdahl-Larsen, and Tollnes (1981), and Jankuhn (1986). More recently, research projects employing innovative scientific methodologies have focused on towns such as Ribe, Odense, and Aalborg, yielding significant findings, as highlighted by Lund and Sindbæk (2022), Runge et al. (2020), Runge and Henriksen (2018), Sindbæk (2023a), and Søvsø (2020). Aarhus holds significant potential among these towns due to its wealth of primary sources. The town is rich in Viking Age monuments, with five runic stones, once located in the western part of the settlement, still surviving today. Additionally, a Viking Age rampart, which once encircled the settlement, remained intact until the late Middle Ages, and is still visible in the modern street grid (Jantzen 2013, 103; Roesdahl and Wilson 2006, 210-19). Approximately 250 excavations have been conducted in the city, and several recent publications have examined the town's development, structures, and networks, such as those by Jantzen (2013), Kalmring (2024), Krongaard Kristensen and Poulsen (2016), Linaa (2016), Madsen (1996), Roesdahl (2023), and Søvsø (2020).

Historical mentions and archaeological evidence of Aarhus

Evidence of the status of Aarhus as a Viking Age town first appears in 948, when the settlement is

Figure 1. Major sites mentioned in the text (Map: © MOMU).

referred to as 'Arhuswensis' (Henrichsen 1968, 69-70; Jantzen 2013, 91). However, various publications suggest that the origins of Aros as a town predate this mention by several centuries (Jantzen 2013, 27-32; Skov 1998a, 285-286, 2005b, 16-22; 2008, 2011a). Situated on the Kattegat coast, midway between Haithabu and Kaupang (Figure 1), Aarhus occupied an ideal location for participation in maritime traffic between these significant Viking Age centres. A critical question remains, however: To what extent did the inhabitants of Viking Age Aarhus fully exploit the opportunities presented by this strategic seascape?

Key archaeological discoveries: Excavations and findings

The primary inquiries focus on how and when Aarhus developed into a town, and to what extent its inhabitants engaged in maritime networks. Archaeological investigations in Aarhus have provided early insights. Systematic excavations in Aarhus began in 1963, uncovering a late Viking Age settlement of sunken-featured buildings with evidence of specialised crafts and trade encircled by a rampart, as demonstrated by Andersen, Crabb, and Madsen (1971), and Klindt-Jensen and Madsen (1964). The earliest rampart (Rampart 1) dated to the first decades of the 10th century, was 2-3 m high and 10 m wide and constructed from turf. The rampart was reinforced to a width of about 18 m around 970 (Rampart 2) (Skov 1992; 2003). This led to the interpretation of a foundation of Aarhus in the 10th century (Madsen 1996, 77-90). However, subsequent research has pushed the settlement's origins back to the late 8th century (Skov 2005a, 16-22, 2008, 215; 2011a, 62-63).

Debates on the function of Aarhus: Town or market?

The function of this settlement has been the subject of debate. Krongaard Kristensen and Poulsen (2016), Roesdahl (2023) and Søvsø (2020) characterised early Aarhus as a marketplace that developed into a town in the late Viking Age. Conversely, others, such as Skov (1998a, 1999a, 2005a-c, 2008, 2011a-b), and Andersen and Krants (qouted in Leth Beiter 2024), have interpreted Aarhus as one of the earliest and most significant towns, alongside Ribe, Haithabu, and Birka, functioning as a gateway to the wider world. Corsi (2020) has even included the town among the emporia. Exhibition catalogues from 2005 and 2011, with contributions from Asingh (2005a-b), Skamby-Madsen and Vinner (2005a-b), and Skov (2005a-c, 2011a-b), further emphasised the town's networks, suggesting that as early as the 8th century, Aarhus maintained extensive maritime connections with the Baltic and North Seas. This coastal town is also presented as being safeguarded by a maritime defence system, which included the Kanhave Canal on Samsø, the Helgenæs peninsula to the north – where numerous place names reference Viking Age ships – and the shipyard/harbour site at Snekkeeng along the Aarhus River (Asingh 2005a, 106-112, 106-108; Skamby-Madsen and Vinner 2005a, 85-95; Skov 2005c, 41-42, 2008, 215)(Figure 1).

The perception of Aarhus as one of the earliest Danish towns and a key node connecting the Baltic and North Seas is prominently featured not only in academic publications but also in the permanent exhibitions at Moesgaard Museum (MOMU), the Viking Museum in the town centre, and in current museum plans (Moesgaard Museum 2024, 6-7). The narrative is based on its geographical location, the runic stones, and a small number of imported artefacts. However, an analysis of four Viking Age excavations by Linaa in 2016 provided robust evidence for the exploitation of coastal resources, while offering minimal evidence for trade, specialised crafts, or maritime contacts. This analysis underscored the need for further research in these areas (Bitsch 2007a; Linaa 2016, 71-74; Ritchie 2019).

Aims and Scope of the present study

The 'Vikings' Aros – New Insights into Viking Age Aarhus' project (2021-2024), funded by the Ministry of Culture, aimed to provide fresh perspectives by transforming the collections into new narratives. This was to be achieved through the systematic cataloguing of the many artefacts stored in archives, integrating them into current research for the first time in the town's history.

The first part of the project involved a cross-disciplinary study of a late 10th-century burned-down sunken-featured building in the town centre (Out et al. in press). The second part of the project, which culminated in this paper, aimed to shed light on the development and functions of Aarhus in the Viking Age, focusing on its spatial layout, economic activities, and on the extent of its engagement in local, regional, and interregional maritime networks. The chronological framework of this study spans from the late 8th century to the end of the Viking Age. Simultaneously, its geographical scope covers primarily the area within the Viking Age rampart 1 and the reinforcement, called rampart 2 (Figure 2), encompassing a total of 40,000 m^2. The investigation analysed structures and artefacts from twenty excavations (1964 to 2022), comparing these findings with those from other Scandinavian Viking Age settlements and towns.

Settlement and seascape

Aarhus is situated at the confluence of sea and land, at the mouth of the Aarhus River, three days' sail from Kaupang and one day's sail from Haithabu (400 km and 200 km, respectively) (Skamby Madsen and Vinner 2005b, 98-101) (Figure 1). The surrounding area provided abundant coastal resources, including timber, fodder, game, grazing land, and access to fish, all ripe for exploitation (Fredskild

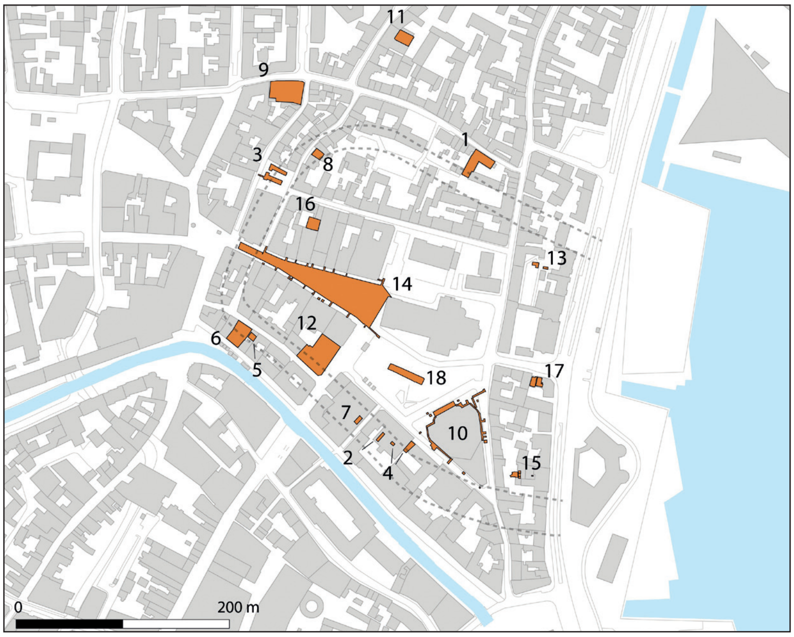

Figure 2. Locations of the excavations in Aarhus.
1: FHM 2664 Rosensgade.
2: FHM 3762 Kannikegade.
3: FHM 3992 Pustervig.
4: FHM 4267 Kannikegade.
5: FHM 4433 St. Clemens Stræde.
6: FHM 4573 St. Clemens Stræde.
7: FHM 5813 Kannikegade.
8: FHM 6211 Volden.
9: FHM 4007 Badstuegade.
10: FHM 4262 Aarhus Teater.
11: FHM 4881 Studsgade.
12: FHM 1393 Aarhus Søndervold.
13: FHM 1600 Katedralskolen.
14: FHM 4880 Store Torv.
15: FHM 4519 Skolegade 19b.
16: FHM 4278 Rosensgade.
17: FHM 4880 Havnegade 2A.
18: FHM 5124 Bispetorv.
Dotted grey lines indicate the location of the rampart (Map: © MOMU).

Figure 3. Map of the hinterland of Aarhus with Aarhus River and Brabrand Sø (Map: © MOMU).

1971; Jantzen 2013, 13-17; Jørgensen 1971; Linaa 2016, 30; Linaa 2020, 41-65; Møhl 1971; Out et al. in press). To the west, the river flows 8 km to the 3 km-long Brabrand Lake, a waterway that connected prosperous Viking Age settlements and magnate farms to the sea (Jantzen 2013, 13-16; Jeppesen 2004, 171-177, 2005b, 52-61, 2011, 87-91) (Figure 3).

Maritime connections and archaeological evidence

This region has long-standing connections to the sea. The Kanhave Canal, which cuts through Samsø at its narrowest point, is one of prehistoric Denmark's most significant engineering feats, indicating the presence of a powerful, possibly royal, authority at the dawn of the Viking Age. The canal, dated to 726, and repaired around 750, has been associated with the movement of ships across Samsø (Asingh 2005b, 116-17; Christensen 1995, 40). Furthermore, the area is rich in names linked to Viking Age warships, such as 'Snekke' (Skamby Madsen and Vinner 2005a, 88-92). Excavations at 'Sneche Eng' [Snekke Meadow], at Brabrand Fjord, uncovered processed wood and a ship's part dated to 797. This site has been interpreted as a shipyard, where the royal fleet may have been assembled (Skamby Madsen and Vinner 2005b, 94-96; Skov 2005c, 41-42).

Approximately 5 km north of Aarhus, a Viking Age agrarian settlement dating to the late 9th and 10th centuries (Skriver 2005) provides evidence of broader contacts. A nearby runic stone, dated to around the year 1000, bears the inscription:

'Alfkell and his sons raised this stone in memory of Manni, their kinsman, Ketill, the Norwegian's estate steward' (Jeppesen 2005a, 79-80).[1] Another Viking Age agrarian settlement, Randlev, located about 30 km south of Aarhus, yielded significant detector finds, evidence of a coastal site that may have connected Randlev to the sea (Jeppesen 2011, 87-90, 2023b). While the surrounding region provides evidence of the significance of maritime contacts, the critical question remains: if, how, and when did the inhabitants of the place later known as Aarhus exploit the opportunities for maritime traffic afforded by its landscape?

Materials and methods

In Aarhus, the past is becoming an increasingly scarce resource. Approximately 8% of the Viking Age settlement has been excavated, with 7% remaining accessible for archaeological investigation. The remainder lies buried beneath medieval and later structures (Jantzen 2013, 30-32; Linaa 2016, 183).

Selection of sites and data criteria

Since 1916, around 250 excavations of varying scale have been conducted in Aarhus. 20 of these were selected for analysis in this project. Given the comparative nature of the analysis, it was essential to select only those excavations, where rigorous and consistent methodologies were employed, to ensure the reliability and usability of the data. The analysis focused on primary occupation layers and secondary waste layers, while tertiary levelling layers were excluded. Based on excavation reports and findings, 18 excavations from Aarhus and two from rural sites were selected for comparative analysis (Table 1). Selection criteria included the nature of the registered structures, recovery methods (e.g., sieving and use of metal detectors), and the quality of reports and documentary materials. The two selected rural sites were the only ones outside Aarhus that met the selection criteria.

Data collection and artefact registration

The excavation reports formed the foundation of the analysis, detailing the year of excavation, site size, methodology, finds, and dating. Few ^{14}C dates were available, so these were supplemented by targeted dating of structures from three excavations (FHM 1393, FHM 4573, and FHM 5124). The artefacts from these excavations, defined as worked items excluding building materials, were catalogued in databases referencing structures and features. These were cross-referenced with site reports to account for discarded objects, with the types of artefacts listed in Table 2. The methodology mirrors that used in previous analyses of Aarhus and has been applied in the study of other towns (Linaa 2016: 42-43, 2021: 333-336).

Specific methods and calculations

The current research includes measurements of the number of artefact types per cubic metre, pottery sherds, and metals to gauge the intensity of on-site activities and facilitate comparison with other sites (Table 2). Cubic metre estimates were derived from the square metres of the excavated area, multiplied by the thickness of the Viking Age deposits, plus an additional two cubic metres of soil per sunken dwelling recorded in the subsoil (Table 1). For partially excavated sunken-featured buildings, a proportional part of the two cubic metres per dwelling was added (Sindbæk 2007a, 121-123).

Limitations and methodological considerations

Comparing the number of items per m^3 involves certain biases, such as soil volume loss due to post-depositional decomposition, uneven or uncontrolled recovery of finds, and changes in preservation conditions over time. To mitigate the uneven recovery of finds, only excavations, where soil was sieved, were included in the analysis. Some material might have been discarded during excavations prior to the 1980s, and to counteract that, the artefact collections from older excavations were compared to the more recent ones. Estimating the post-depositional composition across Aarhus presents a significant challenge. Unlike Ribe, Aarhus

Phase	Site	Year of Excavation	Date	M^3	M^3	Pithouse	Post-built house	Ditch	Rampart 1	Rampart 2
				Sites in Aarhus						
III	FHM 1393	1964	9/10th c	320	245	7			1	1
III	FHM 1600	1969	9/10th c	30	27,5	3				
I	FHM 2664	1982	9/10th c	30	15					
I	FHM 3762	1992	9/10th c	22	26,5					
III	FHM 3880	1994	9/10th c	250	128	7				
I	FHM 3992	1997	8/9th c	15	4				1	1
II	FHM 4007	1998	9/10th c	608	121,6					
III	FHM 4156	1998	9/10th c	50	15	3				
II	FHM 4262	2000	9/10th c	30	37,5	6				
I	FHM 4267	2000	8/9th c	2	17,4			1		
III	FHM 4278	2001	9/10th c	100	30	4				
I	FHM 4433	2002	8/9th c	11	14	2	2	1		1
III	FHM 4480	2003	9/10th c	50	35					
I	FHM 4573	2005	8/9th c	100	85	2	1	1		1
II	FHM 4881	2007	9/10th c	200	154	2	1			
III	FHM 5124	2010	9/10th c	245	197,75	8				
I	FHM 5813	2017	8/9th c	10	2					
I	FHM 6211	2021	8/9th c	6	3		1		1	1
				Rural sites						
III	FHM 4016	2003	9/10th c	3000	30	8	4			
III	FHM 4588	2004	9/10th c	320	48	8	4			
	Total			5399	1236	60	13	3	3	5

Table 1. Selected excavations in Aarhus and rural sites with phase, site number, year of excavation, date, square and cubic metres, and excavated structures. The excavations are ordered by year of excavation, then site number.

has not yet undergone the geochemical analyses that could provide more definitive conclusions as demonstrated by Trant et al. (2024). However, given the small size of the town centre, the sandy subsoil and cultural layers, and the fact that the site is situated on level ground about 1.5 m above mean sea level, it is reasonable to assume that decomposition and decompression levels before the modern period are comparable across Aarhus. Nevertheless, preservation conditions for metals have

Phase	Phase	Local coarseware	Baltic type ware	Reticella glass	Soapstone	Basalt quernstone	Other quernstone	Whetstone	Bone artefact	Glass bead	Segmented/cut beads	Loom weight	Spindle whorl	Smoothing stone	Weight	Coin	Other metal	Total	Finds pr m^3	Pottery pr m^3	Metal pr m^3
I	FHM 2664	31						1									4	36	2,4	2,1	0,3
I	FHM 3762	178						2	1			2						183	6,9	6,7	0,0
I	FHM 3992	12			1													13	3,3	3,0	0,0
I	FHM 4267	80					1											81	4,7	4,6	0,0
I	FHM 4433	107	10					1	6	1		3	1				6	135	9,6	7,6	0,4
I	FHM 4573	1210	22			3	4	2	11	18	1	24	5				13	1313	15,4	14,2	0,2
I	FHM 5813	10			1												2	13	6,5	5,0	1,0
I	FHM 6211	11							22								1	34	11,3	3,7	0,3
II	FHM 4007	87										1					9	97	0,8	0,7	0,1
II	FHM 4262	120					1		18	2		2					1	144	3,8	3,2	0,0
II	FHM 4881	392			4			1	2	2		4	1				3	409	2,7	2,5	0,0
III	FHM 1393	7100	74	1	65	9	5	38	85	60		109	30	1	2		769	8348	34,1	29,0	3,1
III	FHM 1600	439			20		1	8	4	2		7	3			2	127	613	22,3	16,0	4,6
III	FHM 3880	348								1		5	2					356	2,8	2,7	0,0
III	FHM 4156	46							5	25		3	1				10	90	6,0	3,1	0,7
III	FHM 4278	88			4		4	2	2	6		4	1	1			2	114	3,8	2,9	0,1
III	FHM 4480	140			9		23	5	10	15	1	8					56	267	7,6	4,0	1,6
III	FHM 5124	1695			6		11	11	60	121		33	5		1	2	59	2004	10,1	8,6	0,3
	Sum	12094	106	1	110	12	50	71	226	253	2	205	49	2	3	4	1062	14250	12,3	10,4	0,9
	FHM 4016	134			1	2	2	8	1	1		9	7		26	274	362	827	27,6	4,5	12,1
	FHM 4588	550			4		3	5	3	1		12	3		3		325	909	18,9	11,5	6,8
	Sum	684			5	2	5	13	4	2		21	10		29	274	687	1736	22,3	8,8	8,8
	Total	12778	106	1	115	14	55	84	230	255	2	226	59	2	32	278	1749	15986	12,9	10,3	1,4

Table 2. Selected excavations with phase, site number, number and types of artefacts, total number of artefacts and total finds, pottery and metals per cubic metres. The excavations are ordered by phase, then site number.

deteriorated considerably since the 1970s. This shift in preservation conditions is evident in Table 2, where FHM 1393 and FHM 1600, excavated in the 1960s, contain three to four times more metal artefacts than more recent excavations. However, the relative number of non-destructible artefacts has remained consistent.

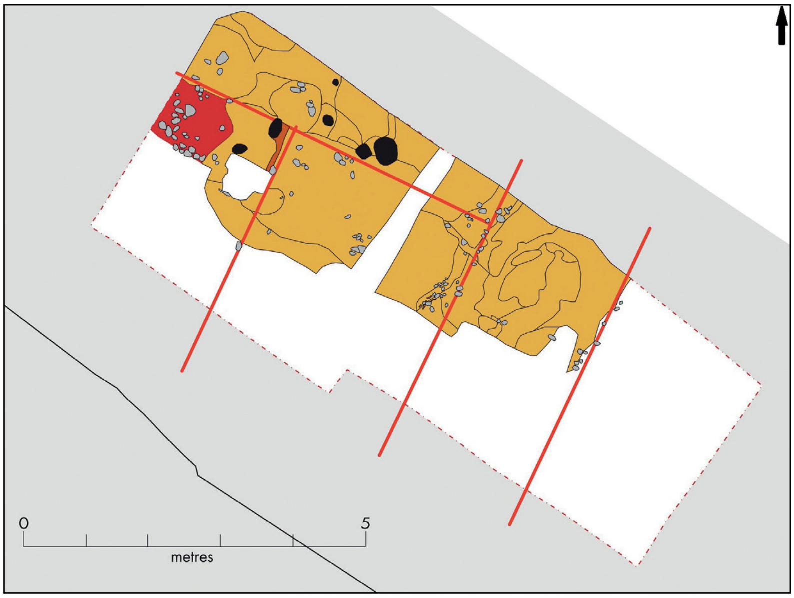

Figure 4. The remains of post-built house at FHM 4573 St. Clemens Stræde. The excavation took place in the basement of a standing building, and the building has been marked in grey. Dotted line marks the boundaries of the excavation. Yellow signature marks a clay floor, and thin black lines mark, where the floor had been repaired during the lifetime of the building. The red square in the west is a fireplace. White indicates disturbances that have destroyed the southern and eastern part of the clay floor. Stones, marked in dark grey, have been interpreted as foundations for partitioning walls, and the position of these walls has been marked as red lines. This house was demolished prior to the construction of the Viking Age rampart (Rampart 1) (Map: © MOMU).

The excavations

The sites are presented below, divided into three phases as established by Skov (2008):

I: Settlement older than Rampart 1

II: Settlement contemporary with Rampart 1

III: Settlement contemporary with Rampart 2

Phase I (c.770-c.900)

During phase I, a ditch was dug at the riverbank, possibly encircling a settlement. The ditch was filled with household waste, and a group of seasonally occupied sunken-featured buildings were constructed on the site. Over time, permanently occupied post-built houses replaced these structures, and further buildings were constructed near the coast to the west and to the north. This settlement has primarily been recovered in excavations that cut through the ramparts.

FHM 2664 Rosensgade (1982) (Figure 2, 1): A rescue excavation in the northern part of the settlement uncovered settlement layers with scattered postholes. Finds included evidence of domestic crafts, such as textile production, small-scale boneworking, and iron fragments (Madsen 1993).

FHM 3762 Kannikegade 12 (1992) (Figure 2, 2): This rescue excavation, located on the eastern part of the riverbank, revealed scattered postholes and fireplaces. The site showed evidence of domestic crafts, textile production, and some comb-making waste (Madsen 1992).

FHM 3992 Pustervig (1992) (Figure 2, 3): Located in the western part of the settlement, this rescue excavation revealed a mixed settlement layer with no registered structures. Activities identified included domestic crafts (Skov 1992; Jantzen 2013, 66).

FHM 4267 Kannikegade 14 (2000) (Figure 2, 4): Another rescue excavation on the eastern part of the riverbank revealed settlement layers dated to the 9th century. Activities at this location were primarily domestic crafts (Larsen 2000).

FHM 4433 St. Clemens Stræde (2002) (Figure 2, 5): This rescue excavation on the western part of the riverbank uncovered an 80 cm deep, 2 m wide ditch running parallel to the riverbank, filled with domestic waste. Oval sunken-featured buildings with fireplaces, possibly permanently occupied, replaced the ditch. These buildings were subsequently replaced by two post-built houses. The activities included domestic crafts and small-scale comb-making (Bitsch 2003). One of the sunken-featured buildings contained a mosaic bead, a type produced around 760-790 in Frisia (X151, Callmer Group G) (Sindbæk 2023b, 272).

FHM 4573 St. Clemens Stræde (2005) (Figure 2, 6): Located 5 m west of FHM 4433, this excavation also revealed a ditch parallel to the riverbank, which was filled with domestic waste and later replaced by two oval sunken-featured buildings. These buildings yielded evidence of domestic crafts and textile production. A 6 m wide post-built house, dated to the 9th century, replaced the sunken-featured buildings (Linaa 2016: 71-74; Out et al. in press) (Figure 4). Activities included domestic crafts, textile production, and possible traces of metalworking (Bitsch 2007a; Linaa 2016, 71-74). A large number of fish bones indicated local fisheries (Ritchie 2019). A segmented bead with metal foil produced in the Middle East, was also found in the house (X1208 A229) (Sindbæk 2023a, 271-272).

FHM 5813 Kannikegade (2017) (Figure 2, 7): This rescue excavation on the eastern part of the riverbank revealed traces of an open settlement, with fireplaces and postholes (Poulsen 2017). The activities included domestic crafts. The settlement was established in the 8th century, with Rampart 1 dating to the late 9th century, according to ^{14}C dates.

FHM 6211 Volden 9 (2021) (Figure 2, 8): Located in the north-western part of the settled area, this rescue excavation uncovered clay floors and postholes. The findings included domestic pottery and corroded metals (Høgsberg 2022).

Phase II (c.900-c.970)

The settlement constructed in phase I was demolished and Rampart 1 was constructed at the start of phase II. Only a few sites contemporary with this rampart can be identified.

FHM 4007 Badstuegade (1998) (Figure 2, 9): This rescue excavation immediately west of the rampart uncovered three wells dated to the 10th century. The findings included domestic pottery, metals, and a loom weight (Jantzen 2013, 115; Skov 1999b-c).

FHM 4262 Aarhus Teater (2000) (Figure 2, 10): Located near the coast in the southern part of the settlement, this rescue excavation revealed fragmentary remains of six sunken-featured buildings dated to the 10n century. The activities identified included domestic crafts and textile production. Gilded mounts for a drinking horn and a buckle were recovered in the area in the 1890s and were initially interpreted as evidence of a Viking Age burial ground, although no further evidence of such a site has been found (Larsen 2001a; Linaa 2016: 163-65; Skov 2008, 218; 2009, 12).

FHM 4881 Studsgade 8-10 (2007) (Figure 2, 11): This rescue excavation immediately north of the rampart uncovered two oval sunken-featured buildings with fireplaces, later superseded by a post-built house measuring 3 by 7 m, dated to the 10th century (Bitsch 2007b; Linaa 2016; 89-91). The activities at this site included domestic crafts and textile production, and a mould for casting Thor's hammers was also found, though no further evidence of casting was discovered (Jantzen 2013, 95; Poulsen 2011, 32, 118)

Phase III (c.970-1050)

During phase III, Rampart 1 was fortified to become Rampart 2, and the area was densely covered with sunken-featured buildings. Evidence for this phase comes from the following excavations:

FHM 1393 Hotel Skandinavien (1963-64) (Figure 2, 12): This rescue excavation on the eastern part of the riverbank revealed remains of Rampart 2, a street paved with wooden boards along the rampart, and seven sunken-featured buildings dated to the 10th century.[2] The activities identified included domestic crafts, carpentry (evidenced by chisels, hammerheads, and axes), and numerous antlers, possibly used for comb production. Other finds included knives, keys, gaming pieces, and weights for scales, suggesting trade activities. A shard of glass with reticella decoration was also recovered from an undated layer. The excavation was published by Andersen, Crabb, and Madsen (1971), including detailed sections on artefacts and biofacts. One of the sunken-featured buildings, CME, was dated by ^{14}C to

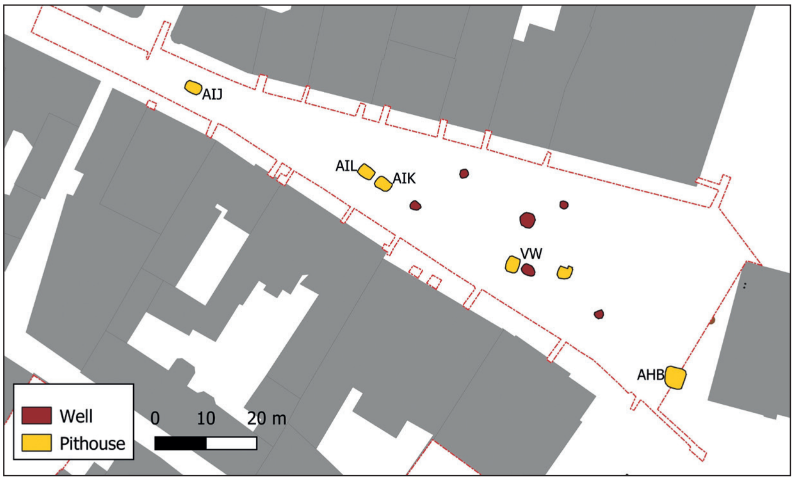

Figure 5. Sunken-featured buildings at FHM 4480 Store Torv (Map: © MOMU).

the late 10th century. Finds from this building included domestic pottery, a key, wooden artefacts, a weight, carpentry tools, whetstones, loom weights, and a comb inscribed with the name *'Hik: uin'*, of Germanic origin. This sunken-featured building is contemporary with a burned-down pithouse at Bispetorv, analysed in Project phase I (Out et al. in press).

FHM 1600 Katedralskolen (1969) (Figure 2, 13): Located in the northern part of the central town, 50 m west of the Viking Age coastline, this excavation covered 30 m^2 and revealed the remains of three sunken-featured buildings along with associated artefacts (Andersen and Madsen 1985; Skov 1997).

FHM 3880 Store Torv (1994) (Figure 2, 14): This rescue excavation in the western part of the settlement revealed seven rectangular sunken-featured buildings (pithouses) with fireplaces, pits, postholes, and wells, all dated to the 10th century (Figure 5). The activities documented included domestic crafts and some comb making (Skov 1994, 1998a, 251, 2005d 652-656).

FHM 4156 Skolegade 19b (1998) (Figure 2, 15): Located at the coast in the southern part of the settlement, this rescue excavation uncovered fragmentary remains of three sunken-featured buildings dated to the 10th century (Skov 1998b). The remaining profiles showed possible clay floors, postholes, and fireplaces. The activities identified included domestic crafts, fishing, and textile production.

FHM 4278 Rosensgade (2001) (Figure 2, 16): This rescue excavation in the northern part of the settlement revealed oval sunken-featured buildings with fireplaces, along with scattered pits and postholes, all dated to the 10th century. The activities included domestic crafts and textile production, evidenced by the discovery of a smoothing stone (Larsen 2001b; Linaa 2016, 66).

FHM 4480 Havnegade 2A (2003) (Figure 2, 17): This site yielded postholes and pits associated with a 10th-century smithy and bronze caster's workshop (Larsen 2004). The findings included slag, corroded metals, and traces of domestic crafts and textile production. A cut bead (Callmer type Q52, X350) was redeposited in a medieval context.

FHM 5124 Bispetorv (2010) (Figure 2, 18): This research excavation, located 200 m north of the riverbank, uncovered seven rectangular sunken-featured buildings with fireplaces (Figure 6). One of these buildings, A334, which was burned, was ^{14}C dated to the last decades of the 10th century and is the subject of Part I of this project (Out et al. in press).[3] The activities identified included domestic crafts and carpentry. A spherical weight for scales and two coins minted by Harald Bluetooth in Haithabu were found, indicating bullion-based trade (Bitsch 2010; Linaa 2016, 99-100).

Rural sites

Two rural sites were included in the analysis for comparative purposes:

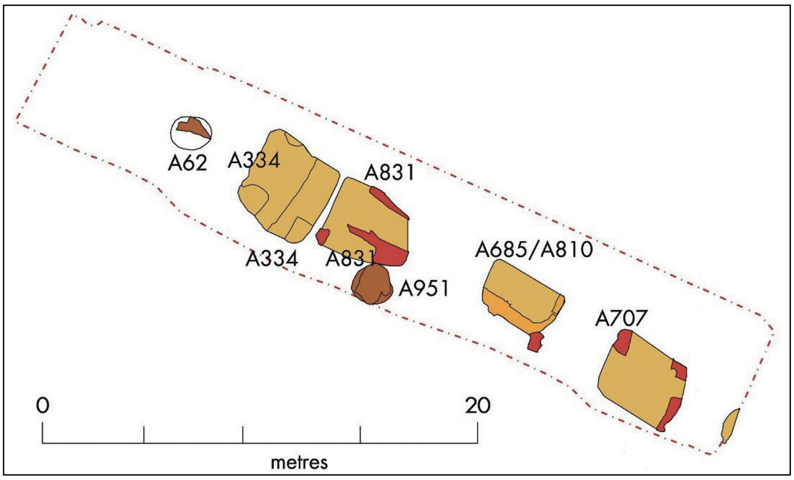

Figure 6. Sunken-featured buildings at FHM 5124 Bispetorv (Map: © MOMU).

FHM 4588 Egå Gymnasium (2004): This rescue excavation, located at the estuary of the Egå River, 5 km north of Aarhus, uncovered longhouses, sunken-featured buildings, wells, and ditches. The activities identified at the site included domestic crafts, textile production, carpentry, and evidence of trade, such as weights for scales. Analysis of the faunal remains indicated on-site meat production (Jeppesen 2005a; Kveiborg 2005; Skriver 2005).

FHM 4016 Randlev (2003): Situated approximately 30 km south of Aarhus and about 2 km from the coast, this rescue excavation revealed longhouses, sunken-featured buildings, and wells. The settlement yielded a large number of metals due to intensive metal detecting, including a miniature sword, a gilded bronze pendant, a bronze belt mount, a silver pendant, hack silver, and 27 weights for scales, all suggesting bullion-based trade. Additionally, three silver hoards containing 237 Arabic coins were discovered at the settlement, with the youngest coin minted in 910/11. A well was dated by dendrochronology to the year 900. The site has been studied extensively by Jeppesen (1998, 2000, 2003, 2011; Jeppesen and Adamsen 2005).

Analysis

The artefacts from the selected excavations

The analysis includes structures and 15,986 artefacts from the selected excavations (Table 2): 14,250 from the 18 selected excavations in Aarhus and 1,736 from the rural sites of Egå and Randlev. On average, the excavations yielded 10 artefacts per m^3, although this number varies significantly: FHM 1393 Hotel Skandinavien yielded 34 artefacts per m^3, while FHM 4007 Badstuegade yielded just 0.7, indicating variations in population density and land use. Pottery constitutes 75 to 98% of the artefacts recovered.

Pottery

The dominant pottery type in the selected excavations is low-fired, hand-shaped, and coiled, featuring hemispherical vessels (Figure 7). In the 8^{th} and 9^{th} centuries, the fabric was thick and tempered with coarse stones, but it became thinner and finer by the 10^{th} century (Andersen, Crabb, and Madsen 1971, 76-87; Knudsen 2023, 35). This pottery type is present in all excavations. The second category in Table 2, Baltic-type pottery, is characterised by incised horizontal or wavy lines. The rims of Baltic Blackware vessels are shaped using a template, and the vessel itself is formed on a slow-turning wheel (Keller 2023, 60; Sindbæk 2014, 280-284; Ulriksen and Brorsson 2023, 1-2). Sherds with Baltic-type decorations are rare, constituting less than 1% of the total pottery. Among the Baltic-type sherds is pottery with Feldberger-type decoration found in phase I in a post-built house on the riverbank (Bitsch 2007a; Linaa 2016, 73). However, these vessels are hand-shaped, and their rims are not template-formed. Comparisons with domestically produced pottery and genuine Baltic Blackware in the study collection of the Department of Archaeology and Cultural Heritage Studies, Aarhus University, reveal that these sherds,

Figure 7. Locally produced, hemispherical pottery vessel from the late Viking Age. Diameter 18 cm (Photo: © MOMU).

Figure 8. Left: Mosaic bead from Frisia, excavated in FHM 4573, dated to the late 9th century. Length 1,2 cm. Right: Reticella glass, excavated in FHM 1393, dated to the 10th century. Length 3,4 cm (Photo: © MOMU).

and similar examples found at the excavation of FHM 1393 Hotel Skandinavien, were produced locally, and were not imported (Linaa 2016, 163-65). This finding is consistent with results from Zealand, where Baltic-type pottery has similarly been shown to be domestically produced (Ulriksen and Brorsson 2023, 9-10).

Quernstones

Quernstones were an integral part of domestic activities, as noted by Baug (2015) and Pohl (2012), and they are among the artefacts from the selected excavations as well. Of the 69 quernstones identified, 55 are made of Norwegian schist, while the remaining are of basalt from the Mayen area in the Rhineland. Norwegian quernstones are present across all phases and in all but the smallest excavations, just as in sites such as Ribe and Kaupang (Resi 2011, 389-391; Sindbæk and Barfod 2023, 87-89). The number of fragments is generally low, possibly representing one to two quernstones per household. Basalt quernstones from the Rhineland were found at the riverbank in phases I and III (FHM 4573 X671, X261, X1294; FHM 1393 CME/EFR), with additional fragments discovered in Randlev.

Whetstones and soapstone vessels

Whetstones and soapstone vessels from Norway are commonly found in both towns and rural areas, and they were frequent in the selected excavations as well. Specific provenance analysis is not possible, as no petrological analyses have been undertaken. These items are primarily recovered from sunken-featured buildings and on floors in post-built houses across all phases and in all but the smallest excavations. They appear to have been a consistent part of Viking Age household equipment, from the settlement established in phase I to the end of the Viking Age in phase III (Baug et al. 2023, 106-110; Resi 2011, 380-393; Sindbæk and Barfod 2023, 91-93).

Glass beakers and drinking glasses

Glass beakers, bowls, or drinking glasses are notably rare in Aarhus. Only one shard, decorated with reticella and possibly produced in Western Europe, has been recovered from the city. It was found in the selected excavation FHM 1393 (Figure 8, right). Similar shards have been dated to the 8th or 9th century (Feveile 2023, 215). Drinking glasses are often associated with an elite drinking culture involving Tating jugs (Feveile 2023, 215-17; Gaut 2011, 183-195; Henderson and Holand 1992, 220-227; Steppuhn 1998, 64-65). The absence of Tating ware and the recovery of only one shard of glass – potentially transported as raw material for bead production – suggests that this practice was not prevalent in Aarhus.

Textile production

Textile production was a fundamental activity in most, if not all households, as evidenced by the presence of loom weights and spindle whorls in the selected excavations. The loom weights are either low-fired or unfired, while the spindle whorls are made of fired clay and are conical in shape. Loom weights have been found in layers predating the earliest sunken-featured buildings, indicating that textile production was a core activity from the settlement's inception. These items are also frequently found in rural settlements (FHM 4573). Smoothing stones made of glass were found in the burned sunken-featured building CME during the excavation of FHM 1393 Hotel Skandinavien, dated to the late 10th century (phase III). Another smoothing stone was discovered in the excavation of FHM 4278 Rosensgade in a sunken-featured building A1, probably from phase III. Similar stones have been found in Ribe, Kaupang, and Haithabu (Andersson 2003, 82; Croix 2023, 352-364; Øye 2011, 343-356).

Bone artefacts

Bone artefacts, such as combs and needles, along with the waste products from their production, are found in all the selected excavations (Andersson 2003, 127-128; Croix 2023, 369-371; Øye 2011, 356-357). The waste is scattered across the floors of dwellings, and a dedicated workshop has never been identified, although concentrations at Store Torv (FHM 3880) suggest that production occurred there. Analyses indicate that the waste is primarily from red deer, while many finished combs are made of reindeer antler and are likely imported from Norway (Ashby, Coutu and Sindbæk 2015).

Glass beads

Glass beads were a staple in households across all phases, and most of the selected excavations yielded some (Skov 2005d, 655). Beads may have been imported, as no bead-making workshop has been identified, although a few finds of glass threads might suggest occasional bead-making in the 10th century. A gilded segmented bead (Callmer Group E) was found on the oldest floor of a 9th-century post-built house in phase I (FHM 4673, X1287, A229). This bead type is known from recent excavations in Haithabu and Ribe, where 190 such beads have been found, dated to the late 8th and early 9th centuries, as well as from landing sites such as Vester Egesborg on Zealand (Sindbæk 2023b; Steppuhn 1998, 40-41; Ulriksen 2018, 218-219). A mosaic bead (Callmer Group G) (FHM 4433, X151), possibly manufactured in Frisia, was discovered in an undated sunken-featured building on a neighbouring plot, about 5 m to the east (Sindbæk 2023b, 259-264; Steppuhn 1998, 51) (Figure 8, left). An eye-bead (Callmer Group B) (FHM 5124, X1247), possibly produced in southern Europe, was recovered from a late 10th-century context. A small cut bead (Callmer Group Q) was redeposited in a medieval context during the excavation of the bronze caster's workshop at FHM 4480 (phase III). These beads are well-known in Ribe, where 158 have been found in contexts dated to the late 8th and early 9th centuries, as well as in Haithabu (Sindbæk 2023b, 272; Steppuhn 1998, 52-53). The majority of the other beads are plain, predominantly green or blue.

Weights and coins

Weights and coins are notably scarce in Aarhus: only three weights, all spherical, and four coins have been discovered in the selected excavations, all found on the floors of sunken-featured buildings dating to the 10th century (phase III). Among these are two cross coins minted by Harald Bluetooth in Haithabu, found in the burned sunken-featured building A334, dated to the 980s (A736 and A813 (P53)) (Out et al. in press). The coins have been studied by Moesgaard (2011). Similar spherical weights have been found in 10th-century contexts in Ribe (Feveile 2023, 117-121; Croix et al. 2019; Søvsø 2020). An unidentifiable coin and an Arabic dirham were also recovered in a sunken-featured building at FHM 1600 Katedralskolen (phase III) (Andersen and Madsen 1985). In contrast, three weights were found in the rural settlement FHM 4588 Egå Gymnasium, and 26 weights, along with 274 coins, primarily dirhams, were discovered at the rural site of FHM 4015 Randlev, dated to the 10th century. The exceptionally high number of coins here results from the discovery of three hoards (Jeppesen 2011, 87-90).

Phase	Site	Textile production	Bone/antler	Trade	Smith	Bronze caster
Phase I 8/9th c	FHM 3762 Kannikegade 12	■	■			
	FHM 4433 St. Clemens Stræde	■	■			
	FHM 4573 St. Clemens Stræde	■				
	FHM 3992 Pustervig					
	FHM 4267 Kannikegade					
	FHM 5813 Kannikegade					
	FHM 6211 Volden 9					
Phase II Early 10th c	FHM 4007 Badstuegade	■				
	FHM 4262 Aarhus Teater	■				
	FHM 4881 Studsgade 8-10	■				
	FHM 5124 Bispetorv I	■				
Phase III Late 10th c	FHM 3880 Store Torv	■	■			
	FHM 4156 Skolegade 19b	■		■		
	FHM 4278 Rosensgade	■				■
	FHM 4480 Havnegade 2A	■				■
	FHM 1600 Katedralskolen	■	■	■	■	■
	FHM 1393 Hotel Skandinavien	■	■	■	■	■
	FHM 5124 Bispetorv II	■	■	■	■	
Rural 9/10th c	FHM 4016 Randlev	■	■	■	■	
	FHM 4588 Egå Gymnasium	■	■	■	■	

Table 3. Occurrence of crafts grouped according to phases. Specialised crafts appear to be introduced in phase III.

Other metal artefacts

The metals listed in Table 2 include tools for carpentry, needles, nails, mounts, and buckles. Although metal artefacts are common in the selected excavations, only one production site has been excavated (FHM 4480 Havnegade 2, phase III). Personal adornments, such as buckles and mounts, are frequently found, particularly in older excavations such as FHM 1393 Hotel Skandinavien (e.g., buckle EQJ from a sunken-featured building, CME, phase III) (Andersen, Crabb, and Madsen 1971, 215-217). A mould for bronze casting in the shape of a Thor's hammer was discovered during the excavation of FHM 4278 Rosensgade 17-19, Studsgade 8-10, but no further evidence of production was registered at other sites (phase III).

Results

Evidence of production, craft, and trade

Evidence of the exploitation of coastal resources such as fishing, animal husbandry, grazing, and possibly agriculture is apparent from the earliest days of the settlement and continues throughout all phases (Fredskild 1971; Jørgensen 1971; Møhl 1971; Out et al. in press; Ritchie 2017). Table 3 reflects the presence or absence of craft and production-related activities. Domestic crafts involving querns, soapstone, pottery, and whetstones are found in all but the smallest excavations across all phases, along with traces of textile production and bone working. A total of 106 combs and associated

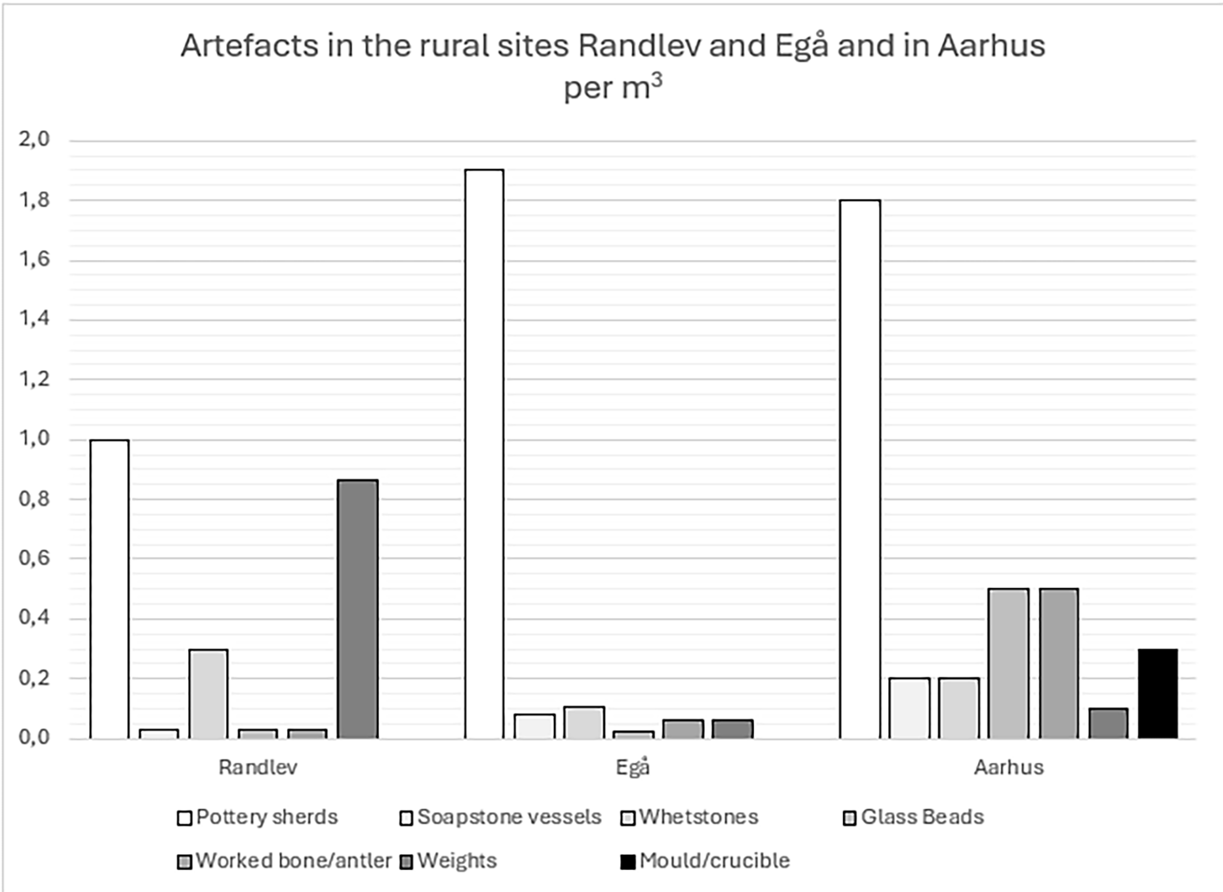

Figure 9. Selected artefacts per m³ in Aarhus and the rural sites of Egå and Randlev. Pottery was reduced by 80% and coin hoards were subtracted from Randlev. Sample size: Aarhus: 1158 m³, 12,3 artefacts per m³, Egå; 48 m³, 18,9 artefacts per m³. Randlev: 30 m³, 18,8 artefacts per m³.

waste material from Aarhus, all from phase III, have been analysed. The raw material for comb production was sourced locally, while a few complete combs were made from reindeer antler, suggesting that these were traded or transported from Norway (Ashby, Coutu, and Sindbæk 2015, 13-14; Out et al. in press).

Bronze casting and metalworking were introduced in phase III, along with tools for trade. However, the number of related artefacts is generally low – constituting less than 1% of the recovered artefacts – and only one specialised workshop has been excavated. All crafts practised in Aarhus were also common in Egå and Randlev, except for bronze casting. Moreover, the evidence of trade-related artefacts in these rural sites surpasses that in Aarhus (Figure 9).

Evidence of imports

Only 255 artefacts, approximately 2% of the 15,986 recovered artefacts, are identified as imports (Table 4). Of these, 245 artefacts (94%) were imported from Norway. Western European imports have been present since the mid-9th century, primarily in the form of basalt querns, while the sole eastern imports are an Arabic coin and a bead. However, most of these imports are also found in Randlev and Egå. Consequently, the only imported artefacts that distinguish Aarhus from the surrounding settlements are a reticella glass shard, two beads from the 9th century, a bead and two glass smoothing stones from the 10th century, and raw material for 10th-century bronze casting.

Phase	Date	Site	Coin	Weight	North: Soapstone	North: Whetstone	North: Quernstone	West: Basalt quernstone	West: Gilded glas bead	West: Glass smoothing stone	West: Reticella glass	East: Cut bead	Total	M^3	Imports pr m^3	No. of artefacts per m^3
Phase I	8/9th c	FHM 3992			1								1	4	0,25	3,3
		FHM 5813			1								1	2	0,50	6,5
		FHM 4433				1							1	14	0,07	9.6
		FHM 4573				5	4	3	1				13	85	0,15	15,4
		FHM 4267					1						0	17,4	0,00	4,7
		FHM 6211											0	3	0,00	11,3
		FHM 3762				2							2	26,5	0,08	6,9
Phase II	Early 10th c	FHM 4881			4	1							5	154	0,03	2,7
		FHM4262					1						0	37,5	0,00	3,8
		FHM 4007											0	122	0,00	0,8
Phase III	Late 10th c	FHM 4278			4	2	4			1			11	30	0,37	3,8
		FHM4156										1	1	15	0,07	6
		FHM 3880											0	128	0,00	2,8
		FHM 4480			9	5	23						37	35	1,06	7,7
		FHM 1600	2		20	8	1						31	27,5	1,13	22,3
		FHM 1393		2	65	38	5	9		1	1		121	245	0,49	34,1
		FHM 5124	2	1	6	11	11						31	198	0,16	10,1
		Sum	4	3	110	73	50	12	1	2	1	1	255	1144	0,22	12,3
Rural	9/10th c	FHM 4016	274	26	1	8	3	2					314	30	10,47	27,6
		FHM 4588		3	4	5	2						14	48	0,29	18,9
		Total	278	32	115	86	55	14	1	2	1	1	583	1222	0,48	13

Table 4. Imported artefacts grouped according to phases. The selected excavations are ordered by phase, date, and site number. Artefact type and provenance are added, along with cubic metres, imported number of artefacts per cubic metres and total number of artefacts per cubic metre.

Figure 10. Conceptual map of the settlement in the 9th century (phase 1). The map depicts Aarhus as a plot-divided settlement, similar to what is known from Ribe and Haithabu, However, so far, no clear evidence of streets or plot boundaries has been found during excavations in the city. Map from Skov 2011, 63 (Map: © MOMU).

Discussion

Intensity and density of the settlement

The excavated structures and the measurement of artefacts per m^3 provide valuable insights into the density and intensity of the settlement. In phase I, the settlement appears to have been most densely concentrated along the riverbank. Approximately 400 m from the coast, four sunken-featured buildings, possibly seasonally occupied, and two permanently occupied post-built houses have been identified within an area of 15 x 15 m (FHM 4573) (Figure 2, 5, 6). Nevertheless, the excavated areas are small, only 80 m^2, which makes the orientation of the houses difficult, and no ditches or plot boundaries have been excavated (Figure 4). The settlement seems less dense towards the coast, with yards and fireplaces recorded during excavations between Kannikegade and the river (FHM 6813) (Figure 2, 7). Traces of clay floors were found at Volden 9 (FHM 6211) (Figure 2, 7), and fireplaces were discovered at Mejlgade 28 (Skov 2003) (Figure 12). On the latest model of the town, from 2011, this settlement has been reconstructed as a regulated and plot-divided settlement with adjoining streets running along the river (Figure 10). Such a settlement structure is characteristic of early Ribe. However, no traces of neither plots nor streets have been excavated in Aarhus, and the settlement may have been unstructured.

The number of artefacts per m^3 in Aarhus is relatively low: the highest number recorded in phase I is 15.4, and in phase III, 34, whereas Kaupang, Ribe, and Haithabu yielded 93, 459, and 171 artefacts per m^3, respectively (Data from Jankuhn 1986; Kalmring 2010; Radtke 2007; Sindbæk 2023a; Skre 2011) (Table 2 and Figure 11). While differences in preservation conditions might theoretically account for some of this disparity, it is notable that Aarhus yielded a maximum of 8 pottery sherds per m^3 in phase I and 29 in phase III, compared to 17 in Kaupang – where no domestic pottery was produced – and 166 in Ribe. Although pottery use may have been more widespread in Ribe than in Aarhus, the significantly lower number of artefacts of any type per m^3 in Aarhus suggests that activities at this site were much less intense than in the 8th and 9th-century towns.

Identifying a settlement contemporary with Rampart 1 is challenging due to the limited availability of ^{14}C dates. Nevertheless, the settlement appears to have been dominated by sunken-featured buildings, one of which was excavated at Bispetorv (Out et al. in press). Scattered postholes may indicate the presence of larger buildings. In phase III, the settlement seems relatively dense, with eight sunken-featured buildings uncovered within 250 m^2 at Bispetorv (FHM 5124) (Figure 2, 14) and seven within 200 m^2 at Store Torv (FHM 3880 (Figure 2, 14) The northern parts of the area might also have been densely built, as indicated by the remains of several sunken-featured buildings unearthed during excavations there (FHM 4157, FHM 1600, FHM 4278). On the latest reconstruction of the town, from 2011, Aarhus is depicted as a plot-divided settlement of sunken-featured buildings and post-built houses organised around a regulated street grid, similar to what is known from Ribe and Hedeby (Figure 12). However, the larger excavations, such as Store Torv (FHM 3880 (Figure 5) and Bispetorv (FHM 5124) (Figure 6), reflect an unregulated settlement of sunken-featured buildings with no traces of streets or plot boundaries.

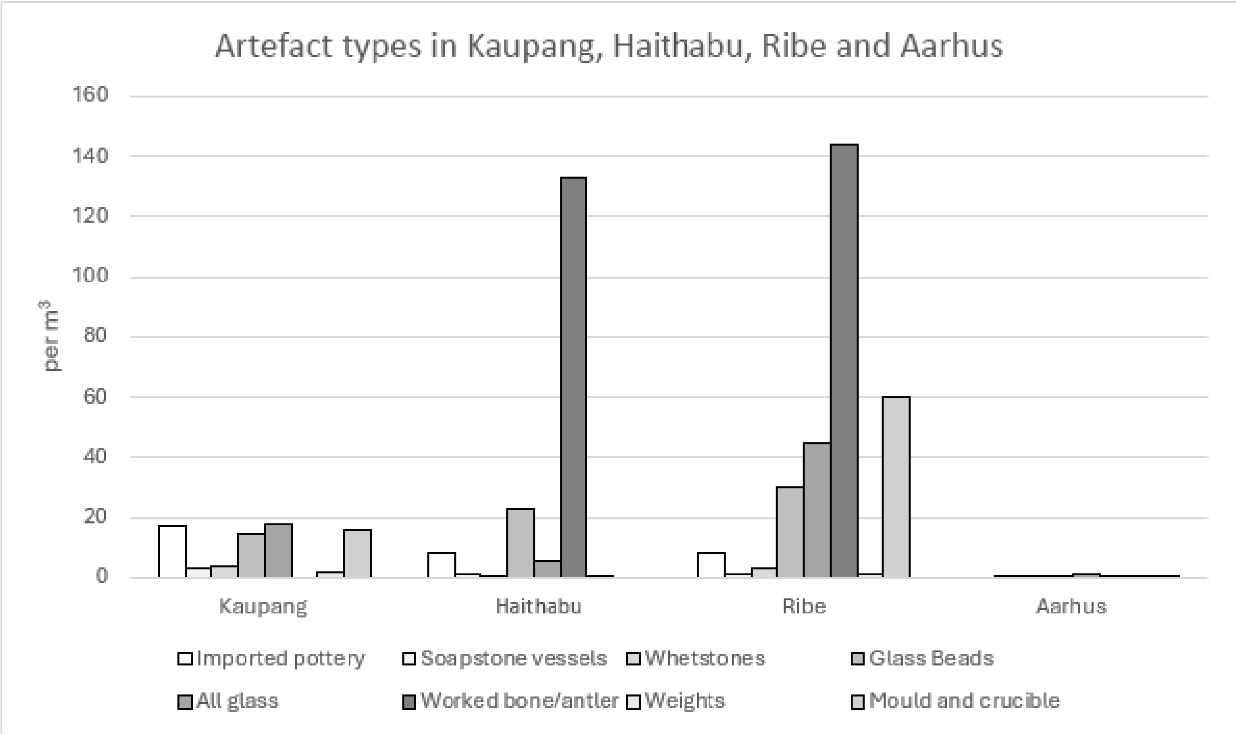

Figure 11. Viking Age Kaupang, Haithabu, Ribe and Aarhus. The proportion of selected artefacts per m^3 of sieved soil. Data: Haithabu after Kalmring 2010. Kaupang after Skree 2011. Ribe after Sindbæk 2023. Sample size: Haithabu: 200 m^3, 171 artefacts per m^3. Kaupang: 215 m^3, 93 artefacts per m^3. Ribe: 160 m^3, 459 artefacts per m^3. and Aarhus 1158 m^3, 12,3 artefacts per m^3.

The number of artefacts per m^3 further illuminates the intensity of the settlement in phase III. Table 2 shows that the number of artefacts per m^3 increased from 15 to 34 from the 9th to 10th century, possibly reflecting an intensification of the settlement and a rise in the number of inhabitants. Additionally, the number of whetstones, loom weights, and spindle whorls doubled during this period, indicating an intensification of the settlement in the 10th century (FHM 4573, FHM 4433,

Figure 12. Conceptual map of the settlement in the late 10th century (phase III). The map illustrates Aarhus as a plot-divided settlement with a regulated street network, comparable to Haithabu and Dorestad, However, excavations in the city have so far not revealed clear evidence of streets or plot boundaries. Map from Skov 2011, 63 (Map: © MOMU).

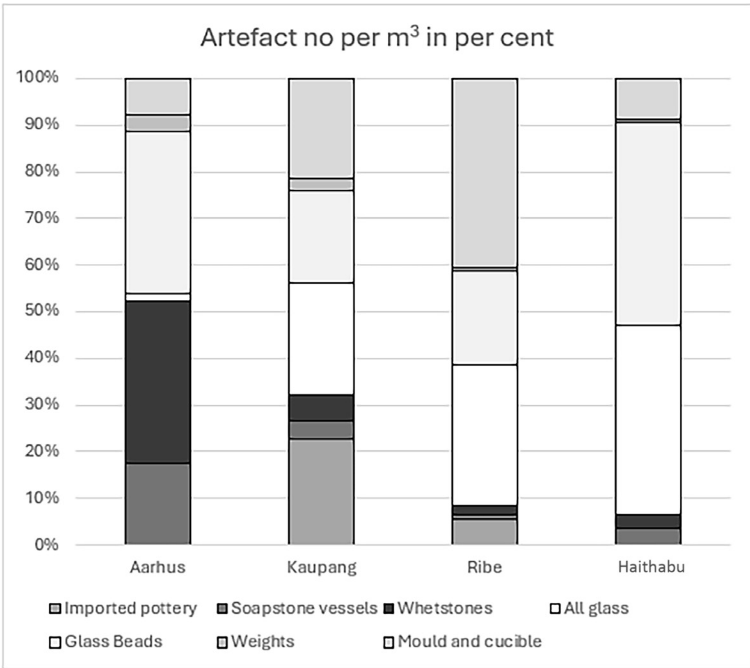

Figure 13. Viking Age Kaupang, Haithabu, Ribe and Aarhus. The relative proportion of selected artefacts per m³ of sieved soil. Data: Haithabu after Kalmring 2010. Kaupang after Skree 2011. Ribe after Sindbæk 2023. Sample size: Haithabu: 200 m³, 171 artefacts per m³. Kaupang: 215 m³, 93 artefacts per m³. Ribe: 160 m³, 459 artefacts per m³. and Aarhus 1158 m³, 12,3 artefacts per m³.

FHM 1393). The 10th-century settlement along the coast north of the cathedral also appears to have been intensively used (FHM 1600), while areas along the eastern part of Kannikegade and the western and northern regions yielded only 2 to 3 sherds per m³, suggesting these areas were less densely occupied.

Despite the increase in settlement intensity from the 9th to the 10th century, Aarhus was still far less intensely occupied than Haithabu, Kaupang, and the slightly earlier Ribe (Figure 11). However, the intensity of settlement at the rural sites of Egå and Randlev, which both yielded 18 artefacts per m³ (Table 2), is comparable to that of Aarhus. The town was hardly bustling with activities compared to these rural settlements.

The development, functions and maritime networks of the settlement

Phase I developments (c.780-c.900): A modest coastal settlement

Archaeological findings indicate that during phase I (*c.*780-*c.*900), the earliest settlement of Aarhus comprised oval sunken-featured structures designed for seasonal use, primarily exploiting coastal resources (Out et al. in press). The absence of plot boundaries suggests a lack of deliberate planning in the site's development (Krongaard Kristensen and Poulsen 2016, 40-44).

In phase I, traces of trade and imports – apart from soapstone, querns, and whetstones found in all settlements – are rare (Table 2). The only exceptions are a few reindeer combs and an eastern bead, possibly brought by visitors (Ashby, Coutu and Sindbæk 2015, 13-14; Out et al. in press). This limited number of imports contrasts sharply with the large volumes found in Ribe, Haithabu, and Kaupang (Figures 11 and 13). Pottery from the Vorgebirge, Mayen, Pingsdorf, and Tating regions account for 25% of the pottery in Kaupang, that had no local pottery production, and 7% in Haithabu and Ribe, yet these West-European pottery types have not been recorded in Aarhus to date (Deckers 2023, 77; Janssen 1987, 27; Knudsen 2023, 25; Linaa 2016: 163-65; Pilø 2011, 285; Pilø and Pedersen 2007, 179-190). The apparent absence of these and other imported artefacts in Aarhus suggests that this settlement had few connections to the maritime networks through which these types were distributed.

Neither the networks linking Ribe, Haithabu, or Kaupang nor the east-west networks extending along the North Sea and through the Eastern Baltic seems to have included Aarhus (Hedenstierna-Jonson 2020, 60-64; Shepard 2008, 143-160; Sindbæk 2007a, 70-71; 2007b, 129. Not only do the imports from Aarhus differ from Ribe, Haithabu, and Kaupang, but the nature of the activities also contrasts with those at the other sites. In these sites, activities are dominated by specialised craft production, such as bead making, bronze casting, and gold-and-silver smithery, often using imported raw materials (Ashby, Coutu and Sindbæk 2015, 4; Feveile 2023, 233; Gaut 2011, 169; Sindbæk 2023b, 245-248; Steppuhn 1998, 82). No such activities have been documented in Aarhus during phase I and II (Figures 11 and 13).

The site in phase I does not share the characteristics of the towns, but it was hardly an important landing site either; key characteristics of such sites, like weight scales, concentrated production remnants, and imported ceramics – evident at Aggersborg, Vester Egesborg, and Lundeborg – are absent in Aarhus (Sindbæk 2009, 100; Ulriksen 2018: 214-15, 340-45; 409-13). Consequently, there is little evidence to suggest that Aarhus served as a hub for interregional trade or specialised craft production at this point in the 8th or 9th centuries. Instead, Aarhus might have been one of many specialised sites with various, perhaps shifting, functions established in the late 8th or 9th century (Krongaard Kristensen and Poulsen 2016, 37-40; Sindbæk 2007a, 123-126; 2014, 152-153.

Phase II developments (c.900-c.970): Rampart and reorganisation

Phase II marked a significant spatial transformation, characterised by the demolition of the earlier sunken-featured settlement. This was replaced by an oval or horseshoe-shaped rampart enclosing an area of approximately 40 hectares (Bitsch 2010). The rampart, constructed from turf and lacking the inner support structure or stockade characteristic of the ring fortresses, shares similarities in dating, construction, and function with a 10th-century rampart found in Ribe (Christensen et al. 2021, 4-5; Krongaard Kristensen and Poulsen 2016, 47-48; Søvsø 2020, 208-211). While the rampart in Ribe was built to protect a significant town, the rampart around Aarhus appears to have served a different purpose. The settlement within the rampart remained primarily a local landing/outfield site, still characterised by sunken-featured buildings, the exploitation of coastal resources, and domestic, unspecialised crafts. Traces of long-distance contact, apart from the ever-present whetstones, querns, and soapstone vessels, have not been identified at this point.

The continuity of building traditions and activities suggests that, if the construction of the rampart was intended as part of a broader initiative to reorganise or urbanise the site, this plan was ultimately not realised at this time (see Table 3). However, some changes did occur, as the site gained a measure of international recognition. By 948, a bishop's seat was established in town by the archepiscopal seat in Hamburg, though the extent of the bishop's presence in Aarhus remains unclear (Krongaard Kristensen and Poulsen 2016, 48; Linaa 2016, 33).

Phase III Developments (c.970-1050): Urbanisation and increasing specialisation

Sometime around 970, the rampart was refortified, marking the beginning of phase III. This refortification, known as Rampart 2, involved cladding the outer side of the rampart in turf and supporting it with a fascine (Bitsch 2010; Christensen et al. 2021, 4-5; Sindbæk 2014, 187-196). During this period, the area within the rampart appears to have been covered with rectangular sunken-featured buildings (Figures 6 and 7). However, the fence-lined, regulated plots and street grid typical of mercantile quarters in Ribe and Haithabu have not yet been documented in Aarhus, although such a layout is shown in models of the town (Figure 12) (Skov 2004; 552-555; 2011a, 62-63; Søvsø 2020, 153-55, 231-237).

The activities might have intensified in phase III, as the increase in pottery sherds per m^3 from 14 to 29 may indicate a more intense occupation in the late 10th century compared to the 8th or 9th centuries. The late 10th century saw the introduction of specialised crafts (Table 4). However, the waste products from these and other crafts were limited, and most activities – apart from smithing – appear to have occurred in dwellings rather than specialised workshops (Skov 2010, 652-656). The primary economic activities continued to focus on exploiting coastal resources. (Andersen, Crabb, and Madsen 1971, 307-319; Fredskild 1971; Jørgensen 1971; Møhl 1971; Ritchie 2017; Out et al. in press). Nevertheless, tools of trade, including coins from Haithabu, a dirham, and weights for scales, have been recovered from sunken-featured buildings dating to the late 10th century (FHM 1600; FHM 1393; FHM 5124; Out et al. in press) (Table 2). The number of coins and weights is small compared to the large quantities found in Randlev, suggesting that the modes of trade, exchange methods, and perhaps the nature of traded goods varied significantly between *this site* and Aarhus (Price and Raffield 2024, 39-42). In contrast, Egå has yielded a significantly smaller number of metals, coins, and weights, indicating that this settlement was likely less active. Nonetheless, both rural sites engaged in craft production, including domestic and unspecialised crafts, small-scale bone and antler working, and some smithing – activities similar to those in Aarhus. However, specialised crafts such as bronze casting have not yet been documented at these rural sites (Figure 9)

What distinguished Aarhus from Egå and Randlev at this point may not have been the activities themselves or their scale, but rather the fortification, the settlement structure, its status as an ecclesiastical centre, and later the establishment of a royal mint under the Kings Hardeknud and Magnus the Good (1035-42 and 1043-47) (Skov 2008, 218). These features suggest that by the mid-to-late 10th century, Aarhus, also known as Aros, had emerged as one of many new towns founded at the end of the Viking Age. The development of Aarhus *does not* mirror that of major early towns; Aarhus diverges significantly from the well-known in terms of import volume, composition, and activities. However, Aarhus *does* show similarities to other towns, e.g. Odense, Aalborg and Lund, where settlements of sunken-featured buildings evolved into towns in the latter part of the 10th century or the early part of the 11th (Krongaard Kristensen 2016, 63; Runge and Henriksen 2018, 16-21; Runge et al. 2020, 75-85; Roesdahl 2023, 252-255; Sindbæk 2007a, 128; Søvsø 2020, 253-255; Vrængmose Jensen and Møller 2009, 99-100). However, the rich detector sites around Randlev and Egå (Jeppesen 2023a, 2023b) indicate that some people in Eastern Jutland were integrated into the Viking Age world of trade, travel, and raids – though these activities did not seem to involve either the 10th-century town or the 8th-9th century outfield site.

Defending Aarhus: The role of ramparts and maritime features

The exposed location of Aarhus on the open coast in the middle of Denmark is atypical for the 8th or early 9th-century town suggested in previous research; in contrast, Ribe, Haithabu, and Kaupang were all founded in border regions along traffic corridors some distance from the sea (Sindbæk 2007a, 129, 2009, 105-106). To explain this unusual location, it has been suggested that an advanced maritime defence system involving the Kanhave Canal, bases on Helgenæs, and a shipyard at the Aarhus River may have existed (Skamby Madsen and Vinner 2005b, 94-97; Skov 2005b, 41-42, 2008, 124; 2011, 64-66). However, the Kanhave Canal, dated to circa 726 and repaired around 750, predates the earliest known settlement in Aarhus by several decades, as demonstrated by Christensen (1995). Although the presence of 'Snekke' names on Samsø and Djursland underscores the importance of maritime activities in the area, no evidence links them specifically to Aarhus, as these names are found throughout Denmark. Moreover, the excavated remains at Snekkeeng do not indicate activities on a scale comparable to the massive deposits known from shipyards such as the late Viking Age Fribrødre River on Falster, excavated by Skamby Madsen (2010) (Skamby Madsen and Vinner 2005a, 94-97). Thus far, the existence of a maritime defence for Aarhus is far from proven. However, future investigations may reveal additional evidence.

A defence might have been needed, as written accounts reveal that Aarhus was attacked by the Norwegian king Harald Hardrada in 1046 (Henrichsen 1968, 158-160). Nevertheless, the archaeological evidence of warfare is sparse so far. The first centuries appear to have been peaceful, as there is no evidence of attacks, such as destruction by fire, in phases I-II. However, this may have changed as Aarhus developed into a town in the late Viking Age, as weapons – possibly from an attack – have been found during excavations at Rampart 2 (Andersen, Crabb, and Madsen 1971, 204; Søgaard 1961, 196). Furthermore, two sunken-featured buildings that burned in the last decades of the 10th century (A443, FHM 5124 Bispetorv, and CME, FHM 1393 Hotel Skandinavien) might have succumbed to an attack (Bitsch 2010; Out et al. in press). Finally, a late Viking Age warrior burial, including a shield and battle axe, may indicate a military presence in Aarhus, as might a runic stone from the late Viking Age that mentions a man named Ful, who died in a battle 'where kings fought,' possibly referring to the Battle of Svolder (Høgsberg 2020; Roesdahl and Wilson 2006, 208-229).[4]

Conclusion: The developments, activities and maritime networks of Aarhus in the Viking Age

This study has provided valuable insights into the development of Aarhus during the Viking Age. By analysing almost 16,000 artefacts from 20 excavations, it is clear that Aarhus did not become a fully-fledged town until the late 10th century. Prior to this, it functioned primarily as a small landing site, focused on exploiting coastal resources, with limited evidence of long-distance trade or specialised crafts. The few imported artefacts, mainly beads and combs, were likely brought by travellers or traders, but they do not suggest that Aarhus played a significant role in broader maritime networks. Such a role might have been played by Randlev and other settlements surrounding Aarhus.

While Aarhus shares similarities with other early settlements, such as Odense and Aalborg, it differs from more prominent Viking Age towns like Ribe, Haithabu, and Kaupang, especially in terms of trade volume and the nature of its activities. Despite its location between the Baltics and the North Sea, which could have been advantageous, the role of Aarhus in interregional trade was largely unexploited until the Middle Ages, when it became part of the Hanseatic network.

The development of Aarhus reflects broader trends seen in settlements like Odense and Aalborg, where small outfield settlements evolved into towns in the late 10th century, without substantial evidence of interregional trade. In contrast, detector finds from Randlev and Egå indicate that people in Eastern Jutland were engaged in Viking Age trade and travel, though Aarhus itself did not seem to participate.

Most of the Viking Age settlement is buried beneath modern structures. What remains of the Viking Age town has been heavily disturbed, while the earlier landing site has been destroyed by modern development. With a significant portion of the settlement inaccessible due to these later constructions, future research will rely heavily on the artefact collections stored in archives. This non-destructive approach offers a valuable means of uncovering new insights. The *Vikings' Aros* project has demonstrated the potential of such studies, activating old collections into new stories about Aarhus in the Viking world.

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Notes

1 The inscription is recorded in the database Danske Runeindskrifter as number MJy 67 (https://runer.ku.dk).

2 AMS ^{14}C Dating Centre Report 2482. FHM 1373, CME, AAR 37191: Charred grain from the floor, ^{14}C age 1050 ± 26: 992-1024 (68.3%) and/or 974-1032 (95.4%). Another charred grain from the same structure and context, AAR37290 ^{14}C Age 1125 ± 29: 979-1022 (68,3%) and/or 973 1026 (95.4%).

3 AMS ^{14}C Dating Centre Report 2842, FHM 5124, AAR37170: charred grain from the flor: ^{14}C age 1062 ± 24, 978-1022 (68.3%) and/or 897-1027(95.4%)

4 The inscription is recorded in the database Danske Runeindskrifter as number MJy 77 (https://runer.ku.dk).

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The call for a responsive approach in Danish field archaeology

Simon Kjær Nielsen[1,3] and Johan Sandvang Larsen[2]

[1] Vesthimmerlands Museum, Archaeological Department, Søndergade 44, 9600 Aars, Denmark
[2] Department of Archaeology and Heritage Studies, Aarhus University, Moesgaard Allé 20, 8270 Højbjerg, Denmark
[3] Corresponding Author (skn@vmus.dk) ORCID: 0009-0005-2900-769X

ABSTRACT

This article advocates for the formal adoption of a responsive approach in Danish field archaeology, utilising a recent case study to exemplify its practical application. In contrast to adhering strictly to predetermined strategies, responsive archaeology underscores the importance of ongoing evaluation and prioritisation during fieldwork to optimise knowledge acquisition and research potential. Despite the informal practice of a responsive approach in many museums within Danish field archaeology, it lacks formal recognition as a legitimate working approach. To accommodate the continual assessment of features, structures, and contexts throughout excavation, guiding methodological choices and preferences, the proposed solution recommends incorporating a prioritisation field into our on-site recordings and then transferring these entries into our archaeological databases and GIS repositories. This would allow archaeologists to self-assess and document the priority assigned to each target during fieldwork, for better post-excavation analysis. This adaptive approach aims to empower excavation teams, enhance transparency, and unlock new potential for future research and excavation strategies.

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Introduction

Acknowledging ‘reflexive approaches’ and recognising the impact of personal perspectives and biases on the interpretation of archaeological findings, as highlighted by scholars like Hodder (1997), Berggren (2001), and, in a Danish context, Jensen (2005), and Borake and Beck (2006), archaeology inherently takes on a subjective nature. As archaeologists, we nominate what qualifies as significant heritage, make choices during fieldwork on what to investigate, how to conduct it, and when to cease and record. Additionally, the recent integration of digital tools, advanced sampling techniques, and increasing interdisciplinary collaborations have introduced numerous innovative methods and altered work processes. Despite these diverse influences and growing subjectivity, a prevailing emphasis on objectivity and standardisation persists in the fieldwork discourse. This is particularly evident in our data repositories, which advocate for the utilisation of extensive datasets to convey a perception of compatibility. Nevertheless, even after Madsen’s (2003a) elucidation of these challenges in Danish archaeology over two decades ago, the issue remains without resolution or effective addressal. In response to the ongoing challenge of balancing subjectivity and streamlined registration, we propose the concept of ‘responsive archaeology’. This adaptable practice focuses on always prioritising the archaeological ‘context potentials’ with the highest scientific potential according to the informed decisions of the responsible excavation team, utilising the excavation and sampling techniques that best align with these goals. The approach embraces a proactive inclination to adjust plans during fieldwork, should it become evident that alternative targets offer superior potentials compared to the initially prioritised ones. Key to responsive archaeology is transparency, emphasising open communication about established priorities within a clear and communicative framework. To enhance efficiency in registration, we propose integrating a novel type of information: As part of archaeological fieldwork, excavation teams should document the overall prioritisation of each feature, structure and context, in addition to all other relevant recordings that one already makes in the field. However, before delving into the implementation of this upgrade, it is crucial to provide a comprehensive understanding of the responsive approach and elucidate its potential advantages.

Definitions

Responsive archaeology

We introduce the term 'responsive archaeology' as a conceptual framework for optimising the archaeological excavations conducted by anyone engaged in archaeological fieldwork, including the Danish archaeological museums. While already informally practised across Denmark, this concept necessitates formal clarification. Responsive archaeology transcends specific methodologies; rather, it embodies a mindset wherein practitioners remain vigilant to unforeseen potentials. While a comprehensive plan is crucial, being responsive entails the ability to adapt the plan when unforeseen opportunities emerge. This may involve reallocating resources for alternative scientific analyses, collaborating with specialists beyond the original plan, or utilising all available means to extract maximum information from a context identified as having significant potential, while transparently communicating the prioritisation choices. A concrete example illustrating this adaptability during fieldwork is presented subsequently.

Context potential

In the practice of responsive archaeology analysing the potential of archaeological contexts is crucial, with the understanding that the contexts themselves do not inherently hold information. Instead, information can be harvested based on the excavation team's priorities and methods. The potential for extraction varies depending on the scientific possibilities related to the layers' formation, taphonomic factors, as well as the methods and expertise of the excavation teams. Therefore, seeking guidance from strategies, experts and fellow colleagues is always advisable, although the promotion of new approaches should also be encouraged. Deliberate downgrading of priority, even when high context potentials are recognised, may occur due to factors such as insufficient funds, time constraints, or the presence of other features, structures, or contexts on the site exhibiting even greater potential. This makes the decision-making process for prioritisation fluid, as different excavation teams with diverse focuses and experiences are likely to prioritise contexts differently. This underscores the subjective nature of our field, highlighting the need for flexibility, openness, and communication in guiding decisions throughout the excavation process.

Nomenclature (translations of our terms)

Responsive archaeology - responsiv arkæologi
Context potential - kontekst potentiale

Discussion

A case-study of responsive archaeology: The Vestrup and Østerbølle Hede-excavations

In 2013, Vesthimmerlands Museum conducted a series of developer led excavations at the village of Vestrup between Aars and Aalestrup, where the museum had previously identified two clusters of late Funnel Beaker stone heap graves (*c.*3100-2800 BCE), 600 metres apart from one another, during preliminary investigations. As is the case for all archaeological structures and complexes, special research questions are also linked to the exploration of the stone heap graves. These include uncertainties in relation to their distinctive anatomy, their construction in long rows possibly reflecting routes of transportation, their regionally constrained distribution to the NW of Jutland, and their relations to structural and thematic counterparts in contemporary cultural complexes in Central and Eastern Europe (Johannsen and Laursen 2010).

Before initiating the Vestrup excavations, the museum forged a collaborative partnership with a specialist from Aarhus University, recognised for expertise in the stone heap graves. Actively contributing to the excavation strategy and during fieldwork, this specialist concurrently authored the excavation guidelines tailored to this particular type of graves.

These guidelines were subsequently integrated into the archaeological strategies published by the Danish Agency for Culture and Palaces, highlighting, among other aspects, the approaches and methods employed at the Vestrup sites (Johannsen 2014). Based on the pre-excavation results at Vestrup a strategic decision was made to focus the investigations on the rear rectangular features of the stone heap graves. Interpreted in recent analyses as human graves, these features strongly indicate that the deceased were laid to rest within a wagon, cart, or a comparable structure reminiscent of such vehicles. The two oblong pits containing a draught pair of oxen, consistently positioned in front of the rectangular features, received lower priority. During excavation, priorities were followed as planned, and valuable outputs were recorded generating new important data. In parallel, and in relation to another key area of inquiry, the intriguing possibility of a prehistoric transport corridor emerged. This corridor hinted at a connection between the Vestrup sites and the contemporary burial sites at Østerbølle Hede, situated on the opposite side of the Lerkenfeld river valley (Nielsen and Johannsen 2014; Johannsen et al. 2016).

In prolongation to the results at Vestrup, and during a continued collaboration by the team, various targeted surveys were carried out in the following years on the other side of the river at Østerbølle Hede; the locus classicus of the stone heap graves (Vestergaard-Nielsen 1952; Becker 1960). During a campaign in 2017, four stone heap graves appeared in a row, instantly capturing the primary focus and priority among the unearthed features. From the outset it had been decided that new finds of stone heap graves should be accorded maximum priority, undergoing investigation with a similar level of detail and emphasis on their rear rectangular feature as had been applied in the Vestrup excavations. Unforeseen factors however meant that this plan was to be completely changed. Firstly, upon closer inspection, the stone heap graves at Østerbølle Hede exhibited signs of previous disturbances, resulting in a less well-preserved state compared to their counterparts at Vestrup. This made it unlikely to improve or even match the results of the previous campaigns undertaken on the other side of the river a few years earlier. Second, the location of the four graves indicated a connection to the same route or path as had been presumed in relation to the Vestrup graves. As part of a (yet not formalised) responsive approach to archaeological field work, according to which it is always sought to maximise the achievable knowledge in relation to the recognised context potentials, our attention was at this point directed to another feature at the site: an elongated indistinctive fill seven meters south of the row of stone heap graves. At first this feature had not been given much attention, but following a cleaning of the surface, it emerged as remnants of a possible sunken road cut into the subsoil and backfilled with light grey sand. A drone was employed for aerial documentation, and by following this initiative (and priority), it became clear that the elongated feature did in fact reflect traces of an old road with clear-cut traces of wheel tracks on the footage. Every plan and perspective regarding the ongoing investigation was immediately changed. Not because traces of an out of context sunken road had been located at some random archaeological site, but because traces of wheeled vehicles had now been identified parallel to a row of stone heap graves, commonly interpreted as vehicle graves, and in this particular case also linked to a potential route connecting the two sides of the larger cemetery area.

With the traces of the road now taking precedence, new decisions had to be made. As part of the new plan, it was decided to try to date the road, because even though the wheel tracks were seen parallel to a row of stone heap graves, the road itself was not necessarily Neolithic. Consequently, invitations were at this time extended to specialists from the Department of Geoscience at Aarhus University to conduct on-site examinations of our discoveries. During their visit, they proposed using the optically stimulated luminescence (OSL) method to potentially date the concealed sediments and rocks associated with the wheel tracks. Following the establishment of this new investigative priority during field work and formalising agreements with the participating labs and scientists, the excavation campaign seamlessly resumed. The road assumed primary focus, with excavations of all other features, including the four stone heap graves, proceeding with adjusted and reduced priorities compared to the original plan[1].

Advancing responsive archaeology: Optimising our data repositories for enhanced knowledge generation

If we accept 'responsive archaeology' as a term and acknowledge that its adaptive approach is already occurring during fieldwork, we can initiate a discussion on its promotion and how to address the fact that pre-established plans and priorities are often changed during excavation. Before engaging in this discussion, however, it is crucial to clarify that the responsive approach complements rather than hinders a simultaneous reflexive approach, wherein self-awareness and critical reflection on one's own role constitute important factors. Additionally, responsive archaeology does not conflict with problem-oriented excavations or predetermined strategies, as exemplified above in the preparations for the Vestrup excavations. Rather, any effort that enhances the given context potential(s) is considered valuable, but the core of the approach lies in the continuous assessment of potentials during fieldwork. This is why we urge excavation teams to engage in ongoing discussions on work progress, priorities, and methods, constantly debating whether certain areas of the excavation should be given higher or lower priority to maximise knowledge and the overall research potentials. Hence, from our perspective, the paramount criterion in any archaeological excavation should consistently be the generation of new scientific knowledge, further emphasising how the excavation constitutes the most important practice within archaeology. It therefore follows, that the most significant part of archaeological research does not take place behind a desk or in the museum storage facility (Madsen 1988; 2003b).

During the progression of any excavation, it consistently remains that the diverse features, structures, and contexts are excavated using varying methods and priorities. Although pre-established strategies and excavation reports routinely capture these details, there is often ambiguity for readers in discerning the specific targets that were actually prioritised (or even excavated) versus those that were not. This is especially prevalent when adhering to an approach, where existing plans and priorities are likely to be changed. Consequently, during excavation, there is an urgent need to implement a systematic registration of prioritisation levels. This documentation should capture the subjective ranking employed during fieldwork, offering transparency regarding the prioritisation processes. Our suggestion is that this task can be most effectively carried out by closely associating it with the individual archaeological features, structures, and contexts, subsequently integrating this information into the database(s) containing the excavation's archaeological data. This addition would not only serve to streamline report-writing by visually conveying prioritisation levels, but also empower other users navigating the extensive datasets, enabling them to immediately identify contexts with inherent potential for comparison. For instance, if intending to study the stone heap graves, our current database searches on existing platforms[2] often come up short, providing only basic information. These searches typically offer rudimentary presence-only data, or, at best, the number of documented stone heap graves found at specific sites. Consequently, researchers intending to create a map showing the spatial distribution of stone heap grave cemeteries on the Jutland peninsula can do so, utilising the clusters of graves from both Vestrup and Østerbølle Hede, as mentioned earlier. However, for a targeted examination of the specific anatomy of the stone heap graves, it would be beneficial for the examiner to immediately identify instances where the excavating teams, based on their own assessments, carried out highly prioritised investigations on the relevant structures. Consider in turn, the potential to distinguish between Bronze Age cooking pits or Pre-Roman Iron Age house plots as part of a database search, facilitating the concentration of attention solely on the features and structures that were highly prioritised by the excavation teams during field work. A further derived effect of this would allow for excavation teams and researchers to seek out and explore current methods and practices according to the different levels of prioritisation; just as we would be given the possibility to ascertain from our data what types of archaeological features, structures, and contexts are mostly prioritised in Danish field archaeology and which types only seldom receive such focus, making it possible to adjust methods and focus more intelligently.

In our proposed solution, we strive to avoid the imposition of new regulatory or bureaucratic measures. Instead, we advocate for a system that enables excavators to articulate and display their prioritisation during field work, meeting both internal needs and contributing to the broader research community. While acknowledging the challenges of retrospectively applying these registrations to older materials, we underscore their potential to significantly enhance future data. Our straightforward proposal involves enhancing our databases by introducing a new field, or drop-down menu, specifically designated for registering priority in relation to the features, structures, and contexts investigated during archaeological excavations. This addition would allow individuals to indicate priority, ranging from No/Minimal priority (1) to Low priority (2), Medium priority (3), and High priority (4). This highly subjective approach would empower archaeologists and excavation teams to assess and highlight their efforts within a simple ranking system. To optimise utility and streamline the process, we further recommend integrating the prioritisation rubric into the GIS data tables (which would also be an easy and effective way to start[3]). This inclusion would enable categorised searches directly within our spatial data, enhancing accessibility, maximising the value of the collected information, and providing a concise summary of the prioritised elements as well as those that were not. Notably, the decision not to register methods alongside the respective priority-levels is based on the inherent complexity and impracticality of managing such information easily in databases (see Berggren and Gutehall 2019).

Conclusion

In conclusion, our paper advocates for embracing the inherent subjectivity of our discipline to a greater extent. We introduce a novel perspective, labelled as responsive archaeology, emphasising the recognition and management of subjectivity through a mind-set that continually assesses and prioritises among the various context potentials uncovered during fieldwork. Although many archaeologists and museums across the country already follow this practice intuitively, it has yet to be widely acknowledged as a valid working method. Consequently, we advocate for a systematic on-site registration and integration of priority levels into our archaeological recordings, databases, and GIS. By adopting this approach, we aim to advance archaeology towards a more dynamic direction, effectively addressing one of the challenges posed by the subjectivity in our field seen in relation to the stereotyped big data that we generate.

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Notes

1) A paper exploring the dating of the road is presently in the active stages of development.
2) Including in a Danish context 'Fund og Fortidsminder', the upcoming 'SARA,' 'MUD,' or other local equivalents.
3) To enhance efficiency, we recommend automating the assignment of 'No/Minimal priority' (1) to each feature documented in the GIS, while allowing for priority level adjustments as excavation progresses. Ideally, these adjustments should occur in real-time during fieldwork, leveraging for instance the MuseumsGIS app for seamless digital data recording (https://www.museumsgis.dk/). Implementing this initiative, or a similar standardised framework for the GIS-tables (including a prioritisation level rubric), could also fulfil another requested objective in Danish archaeology: enabling better cross-case searches between different excavation campaigns (e.g. Løvschal 2016).

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Denmark's Not-So-Oldest Sheep: An Update on Domestic Animals from the Femern Project

Daniel Groß[1,5], Samantha Presslee[2], Ulrich Schmölcke[1,3], Elena A. Nikulina[4], Jessica Hendy[2]

[1] Museum Lolland-Falster, Nykøbing F., Denmark
[2] BioArCh, Department of Archaeology, Department of Chemistry, University of York, York, United Kingdom
[3] Leibniz-Zentrum für Archäologie, Zentrum für Baltische und Skandinavische Archäologie (LEIZA-ZBSA), Schleswig, Germany
[4] formerly Zentrum für Baltische und Skandinavische Archäologie (ZBSA), Schleswig, Germany
[5] Corresponding author (dag@museumlollandfalster.dk) ORCID: 0000-0002-1328-1134

ABSTRACT

Sheep and goats are often considered to be the oldest livestock animals in Denmark. In this contribution, we present the results of ZooMS measurements from seven ovicaprid bones from the Femern project, an excavation in the area of the former Syltholm Fjord (Lolland, Denmark). The bones were morphologically identified as sheep or goats and represented the oldest dated remains of both species in Denmark. However, the ZooMS analysis showed that more than half of the morphological identifications were incorrect. For the other samples, we refined the identifications. Hence, our study confirms that indications of sheep and goat husbandry based on bone morphology alone should be treated with caution. The probability of misidentification in our case was high, even in the case of well-preserved bones.

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Introduction

The extensive archaeological excavations associated with the construction of the Fehmarn Belt tunnel between Denmark and Germany revealed not only significant insights into the prehistory of the Danish Baltic Sea island of Lolland, but are also of general interest for understanding the cultural, economic, and social development from the last foragers to the first metallurgists in southern Scandinavia (see contributions in Groß and Rothstein 2023). Among several remarkable artefacts and features (e.g. Jensen et al. 2019; Jensen et al. 2020; Koch et al. 2024), large assemblages from the transitional phase between Mesolithic and Neolithic lifestyles were uncovered (Gron et al. 2024). In particular, understanding the introduction of the first livestock is crucial for addressing the shift from the regional Late Mesolithic Ertebølle Culture to the Early Neolithic Funnel Beaker Culture in the centuries around 4000 cal. BCE. It is not yet fully understood how these two archaeological cultures represent population exchange (e.g. Allentoft et al. 2024), parallel societies (Jensen and Sørensen 2023), and/or migration processes (cf. Fischer et al. 2024). Current research indicates that the Danish Baltic Sea islands appear to have followed a different pattern regarding the introduction of agriculture and husbandry compared to the continental, western part of the Jutland peninsula (cf. Gron and Sørensen 2018; Lucquin et al. 2023; Philippsen 2023). Hence, knowledge of the first introduced livestock is paramount for understanding this fundamental social, economic, and environmental change in the area in focus.

In this contribution, we present eight recently reviewed species determinations from previously published finds from the Femern project, as well as one new date. All these animal bones were previously morphologically identified as sheep (*Ovis* sp.) or goats (*Capra* sp.) and have been dated to between *c.*4450 and 3100 cal. BCE, hence representing the oldest dated ovicaprids in the assemblages. Two of the specimens predate the previously known presence of elements of the 'Neolithic package' on Lolland, and therefore the traditional Mesolithic/Neolithic transition in Denmark, while seven bones date just after.

Adding another dimension to the population perspective, the selected bones are highly significant, as much understanding of prehistoric socio-cultural development is implicitly embedded in the division between the Mesolithic and the Neo-

Figure 1. Two of the sampled specimens show the different, but generally good preservation conditions (a: MLF00906-II X3691; b: MLF00939-I X3043).

lithic and, accordingly, the introduction of livestock. We use Zooarchaeology by Mass-Spectrometry (ZooMS) as a means of refining the species identification, as sheep, goat, and roe deer bones are often challenging to differentiate morphologically, especially when fragmented (Buckley et al. 2009; 2010).

Materials and methods

The study analysed nine morphologically determined and AMS-dated bones from putative ovicaprids from the Femern project which produced radiocarbon ages between 4450 and 3100 cal. BCE (Table 1). The samples were excavated as part of the Femern project (Groß and Rothstein 2023) during developer-driven archaeology, and dating samples were selected during the project. The analysed samples come from three different archaeological sites and were morphologically identified at Copenhagen University on a contract basis. The preservation conditions for the selected bones were excellent to average with surface damage to the bones (Figure 1). All samples were recovered from the refuse zone of the former Syltholm Fjord, near the northern shoreline (cf. Måge et al. 2023). The selected bones come from large sites with varying osseous inventory sizes (MLF00935-II: n=311; MLF00939-I: n=267; MLF00906-I: n=2784; MLF00906-II: n=2407). A full analysis of the respective faunal data is still pending. The selection of dating samples was generally done based on association and contextualization to obtain ages for the archaeological assemblages or single finds.

For this study, we selected specimens that produced the oldest ages. Additional samples were not obtained for economic and conservation reasons. All selected samples were considered reliably morphologically identified, and the ZooMS analysis was intended as a double-check measure due to the relevance of the finds.

Except for one sample, which was bone powder, all measurements were conducted using collagen extracts obtained during sample preparation for ^{14}C-dating.

Lab ID	Site	MLF-no	Find ID	Sample ID	Species morpho-logical	Bone	Species ZooMS	Samples	Col-lagen yield	14C age	14C STD	d13C	d15N	Reference
AAR-27432	Syltholm II	00906-I	X8821	P202	Ovis/Capra	Pelvis pubis, right, female	roe deer*	collagen	0,012	5194	29	-23.19 ± 0.11	5.15 ± 0.2	Måge et al. 2023
AAR-27434	Syltholm II	00906-I	X10077	P207	Ovis/Capra	Vertebra lumbal, cut marks	goat	collagen	0,043	4765	32	-20.99 ± 0.15	5.92 ± 0.28	Sørensen 2020
AAR-27437	Syltholm II	00906-I	X11371	P201	Ovis/Capra	Vertebra lumbal, cutmarks	roe deer*	collagen	0,05	5122	30	-22.91 ± 0.11	4.98 ± 0.2	Måge et al. 2023
AAR-33777	Syltholm II	00906-II	X3654	P43	Ovis/Capra	Vertebra cervical	sheep	collagen	0,098	5142	33	-23 ± 0.1	5.2 ± 0.2	Måge et al. 2023
AAR-33778	Syltholm II	00906-II	X3697	P44	Ovis/Capra	Tibia, pro-mixal, right, cut marks	roe deer*	collagen	0,072	5313	32	-24.2 ± 0.1	6.1 ± 0.2	Måge et al. 2023
AAR-33779	Syltholm II	00906-II	X4397	P45	Ovis/Capra	Astragalus, right	sheep	collagen	0,066	5122	33	-22.9 ± 0.1	5.3 ± 0.2	Måge et al. 2023
AAR-33781	Syltholm II	00906-II	X4516	P47	Capra hircus	Astragalus, left	roe deer*	collagen	0,105	5040	33	-22.8 ± 0.1	5.7 ± 0.2	Måge et al. 2023
AAR-26547	Syltholm IX	00935-II	X1672		Ovis aries	Humerus, right, cutmarks	sheep	bone	0,04	4506	26	-21.33 ± 0.1	9.9 ± 0.2	Måge et al. 2023
AAR-33747	Syltholm XIII	00939-I	X3043	P16	Ovis/Capra	Femur, diaphysis, left, young individual (unfused)	red deer/elk*	collagen	0,048	5483	40	-22.6 ± 0.1	7 ± 0.3	This study

Table 1. Radiocarbon dates and species identification via ZooMS for the selected samples. Samples marked with an asterisk are corrected species identifications (cf. Måge et al. 2023).

The bone powder was demineralised in 0.6 M hydrochloric acid for 48 hours, followed by three washes, once with 0.1 M sodium hydroxide to remove possible contamination, such as humic acids from the burial environment, and twice with 50 mM ammonium bicarbonate. The bone sample was heated for one hour at 65°C in 100 µL ammonium bicarbonate to denature the collagen into solution. After this step, the rest of the preparation for both the collagen samples and the bone sample was the same. All samples were digested overnight (~18 hours) in ammonium bicarbonate using the enzyme trypsin. Digestion was stopped with the addition of 5% trifluoracetic acid, and the peptides were purified using C18 ZipTip pipette tips before being eluted in 100 µL of conditioning solution (0.1% TFA in 50:50 ACN: Water). 1 µL of the sample was spotted onto a Bruker ground steel target plate and mixed with 1 µL of matrix (alpha-cyano-4-hydroxycinnamic acid). The samples were spotted in triplicate alongside calibration standards, and the plate was run on a Bruker UltrafleXtreme MALDI ToF MS.

The spectra were analysed using mMass, an open-source mass spectrometry tool (Strohalm et al. 2010). The three replicates were averaged, and the resulting averaged spectrum was cropped to 800-3500 *m/z* and peak-picked using a signal/noise of 4-6. The sample spectrum peak list was compared to a list of published markers, allowing for identifications to be made (Buckley and Collins 2011; Buckley et al. 2009; Buckley et al. 2010; Welker et al. 2016). The individual replicate data for all the samples are available via the Zenodo depository.

Results

Three of the nine analysed specimens were positively identified as sheep, and one as goat (Table 1). The results from five samples indicate morphological misidentification, with four specimens attributed to roe deer, and the oldest analysed bone in the assemblage identified as belonging to a large cervid, i.e. red deer or elk (Figure 2). As elk was not present on Lolland in the Final Mesolithic (Aaris-Sørensen

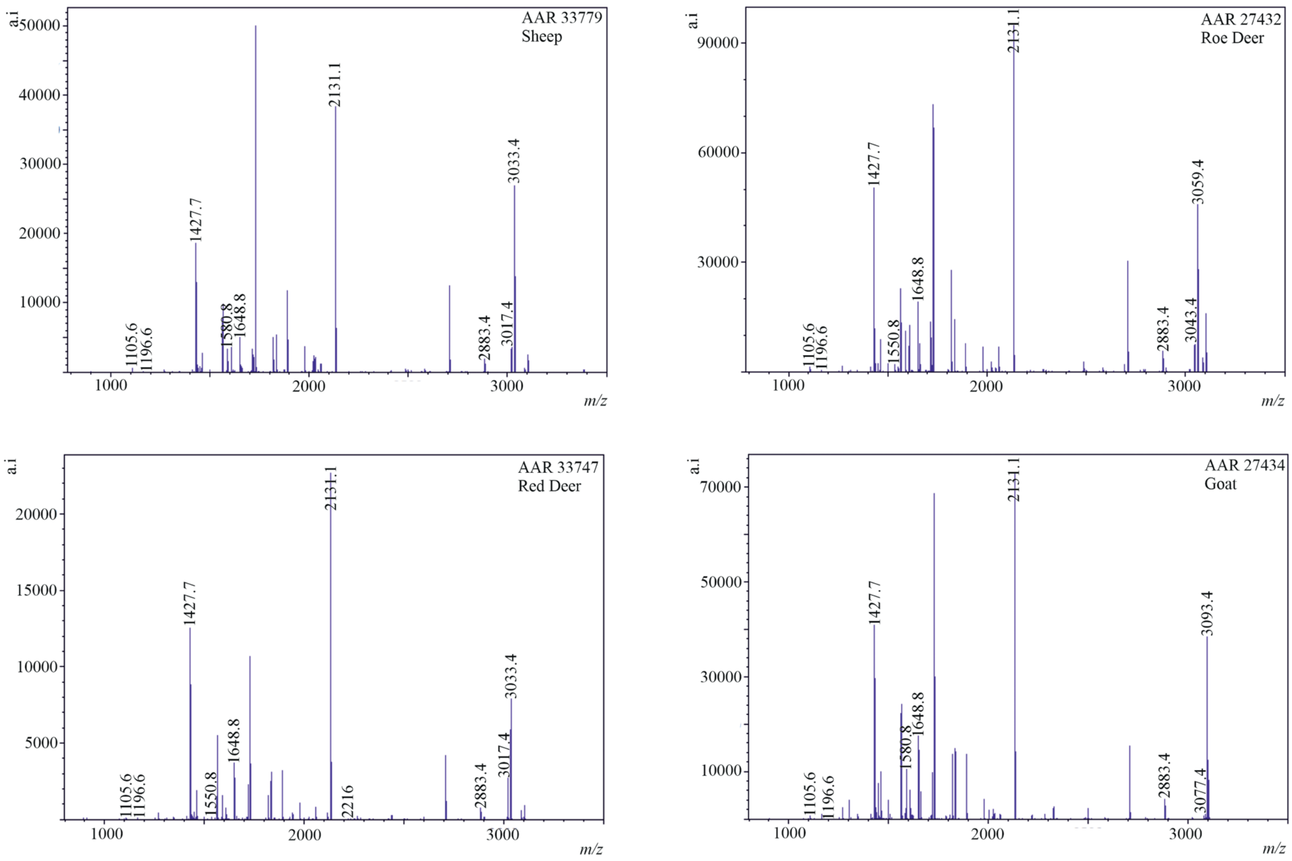

Figure 2. ZooMS spectra for the four identified species from the study.

Lab ID	Site	Morphological species	aDNA species	14C age ± STD	calibrated BCE 2 sigma	Reference
KIA-41338	Rosenhof LA 58	wild boar	pig	5800 ± 25	4720-4583	Krause-Kyora et al. 2013; Rowley-Conwy and Zeder 2014
OxA-27064	Havnø	sheep/goat		5329 ± 35	4313-4046	Sørensen 2014
KIA-7127	Wangels LA 505	sheep/goat		5325 ± 45	4323-3999	Hartz and Lübke 2006
KIA-7129	Wangels LA 505	sheep		5295 ± 35	4242-3995	Hartz and Lübke 2006
KIA-30590	Neustadt LA 156	cattle	cattle	5235 ± 31	4226-3967	Craig et al. 2011; Glykou 2016
KIA-28210	Rosenhof LA 58	cattle	cattle	5231± 25	4221-3970	Scheu et al. 2008
KIA-29091	Neustadt LA 156	goat		5214 ± 32	4222-3961	Glykou 2016
AAR-4998	Wangels LA 505	cattle	cattle	5165 ± 45	4158-3804	Scheu et al. 2008
AAR-4031	Lollikhuse	sheep/goat		5120 ± 55	4045-3781	Fischer 2002
AAR-1459	Rosenhof LA 58	sheep/goat		5110 ± 90	4222-3654	Hartz et al. 2000
KIA-7128	Wangels LA 505	sheep		5085 ± 35	3964-3794	Hartz and Lübke 2006
KIA-30591	Neustadt LA 156	sheep		5060 ± 40	3963-3767	Glykou 2016
KIA-39767	Neustadt LA 156	cattle	cattle	5055 ± 28	3952-3787	Glykou 2016
AAR-3104	Jorløse Mose	sheep/goat		5020 ± 60	3958-3674	Heinemeier and Rud 1999
KIA-29092	Neustadt LA 156	cattle	cattle	5010 ± 34	3943-3706	Glykou 2016

Table 2. Overview of the oldest directly dated domesticates in Schleswig-Holstein and Denmark.

2009), we can assume that the bone is correctly identified as red deer, unless it was imported.

Discussion

Our re-identifications of Stone Age ovicaprid remains from Lolland could not confirm a first appearance of either species in the North before 4000 cal. BCE. We identified the first appearance of sheep in the Syltholm Fjord area around 3900 cal. BCE (between 4040 and 3800 cal. BCE), while the oldest goat is clearly younger and dating to 3640–3380 cal. BCE. Since our sample size is too small to reach solid conclusions regarding the introduction of sheep and goats on Lolland, especially against the background of two-thirds of the samples not being ovicaprids, we cannot conclusively determine that goats were introduced later than sheep, as appears to be the case in southern Sweden (cf. Sjögren et al. 2023). The mismatch between morphological and ZooMS species identification in our case is significant but should not be generalized. However, considering Gron et al.'s (2020) results on interobserver errors, we can conclude that morphological criteria for identifying sheep and goat bones cannot be applied reliably. As in our case, roe deer should also be considered. Our study further emphasises that "If we are to understand the purpose(s) for which caprines were raised, we first must understand whether sheep or goats were present or both"

(Gron et al. 2020, 178) in Early Neolithic assemblages.

It is possible that ovicaprids were indeed the first domestic animals brought to the North, as several bones from Wangels LA 505 (located only 70 km southwest of the Syltholm Fjord in eastern Holstein) and Havnø (Nordvestsjælland), identified as sheep, date to around 4100 cal. BCE (Table 2). Additionally, a goat skull fragment from Neustadt LA 505 (located 100 km southwest) dates to about 4000 cal. BCE. Cattle bones from Neustadt LA 156 and Rosenhof LA 58 (60 km southwest), which have been genetically confirmed as belonging to domesticated animals, are of a similar age to these morphologically identified ovicaprid remains.

As it stands, there is little research on the introduction of sheep and goats into Scandinavia from a regional perspective (Nikulina and Schmölcke 2020; Sjögren et al. 2023). Current genetic studies indicate that the first stock of ovicaprids in Central Europe came from two distinct lineages (Nikulina and Schmölcke 2020). The first, older lineage was the direct successor of animals from early farmers in Greece and the Balkan area and reached Central Europe with the Linearbandkeramik culture. A younger lineage followed one millennium later from southern France and is found at sites from, for instance, the Michelsberg culture and presumably the Swifterbant culture. This lineage appears to be the origin of the first Scandinavian sheep and goats. However, due to the limited data base, these considerations are preliminary and tentative (cf. Brusgaard et al. 2022).

As regional studies have shown (e.g. Gron et al. 2020; Sjögren et al. 2023), a refined evaluation of the introduction of ovicaprids in the Funnel Beaker culture might yield interesting and localized differences. Particularly regarding goats, regional differences seem apparent with them either being absent or at least very scarce in southern Sweden until around 2000 cal. BCE (Sjögren et al. 2023). Additionally, when considering ancient DNA analysis of "cattle" remains (Scheu et al. 2008; Schmölcke and Nikulina 2015), statistical re-analysis of Late Mesolithic and Neolithic aurochs/cattle (Schmölcke and Groß 2020) and criticism regarding the correct attribution of the oldest pig bone in northern Germany (Rowley-Conwy and Zeder 2014), it becomes obvious that the details of the transformation processes throughout the Neolithization of southern Scandinavia and north-central Europe need a critical re-evaluation at the taxonomic level. It is expected that our understanding of the pathways, velocities, and intergroup contacts concerning the introduction of domesticates will be significantly improved, when approached from mixed methodological and source-critical perspectives.

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Declaration of interest statement

The authors declare no conflict of interest.

Data availability

The raw text files from the MALDI-ToF MS analysis are available on Zenodo under the DOI 10.5281/zenodo.13312316

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Experiments reconstructing and using T-shaped wooden Spades

Henriette Lyngstrøm[1,4], Martin Winther Olesen[2] and Lucas Overvad[3]

[1] Saxo-instituttet, Københavns Universitet, Karen Blixens Plads 8, 2300 København S, Denmark
[2] Museum Midtjylland, Vestergade 20, 7400 Herning, Denmark
[3] Sagnlandet Lejre, Slangealléen 2, 4320 Lejre, Denmark
[4] Corresponding Author (lyngst@hum.ku.dk)

ABSTRACT

This article summarizes an attempt at reconstructing and using T-shaped wooden spades as well as reflecting on the connection between structures and resource use around Knudmosen near Herning. However, an important limitation on this process is that very few spades are dated. The conclusion is that the spades are relatively easy to produce and well suited to digging peat.

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Figure 1. A T-shaped spade is a composite tool formed from at least three pieces of wood: the blade, the handle, and one or more pegs that hold the blade and handle together (Photo: H. Lyngstrøm).

T-shaped wooden Spades

A T-shaped wooden spade is a composite tool formed from at least three pieces of wood: the blade, a handle, and one or more pegs that hold the blade and handle together (Figure 1). The spades' blades are preserved as long, thin pieces of wood that are sharpened or worn to a u- or v-shaped edge on one end while the other is shaped so the handle can be attached. The blades are usually widest just under the handle: 6-14 cm. The handles are 26-44 cm long with a circumference of 6-10 cm. Only four of the almost 300 known examples are dated. The dates are between 600-400 BC (Lerche 1985, 216, 1995, 184-185 and 191). The T-shaped spades are all found in bogs and have been associated with peat digging, but their function has never been tested.

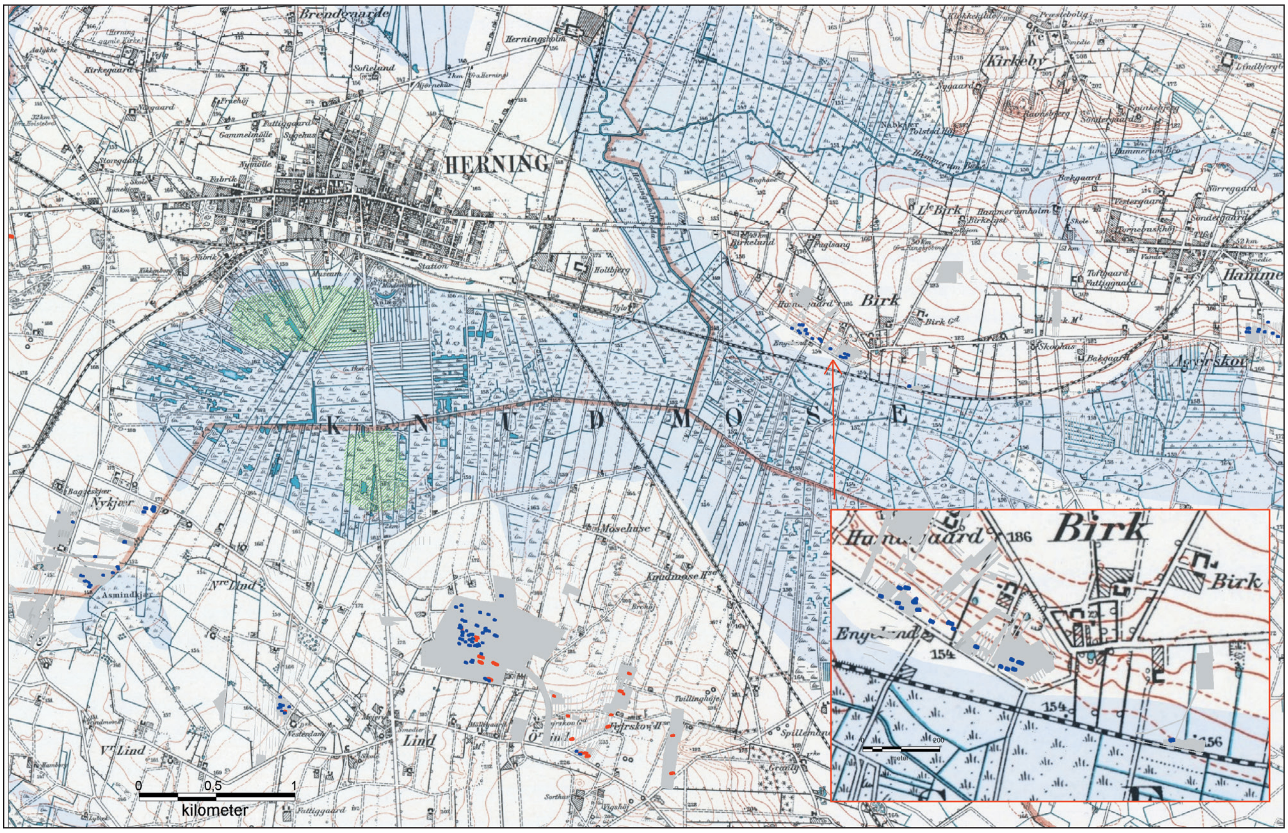

Figure 2. Historic map showing the area around Knudmosen (light blue). The find areas with the located T-shaped spades are marked with a green shading, as well as excavations with finds of houses from the Bronze Age (blue) and early pre-Roman Iron Age (red) (Map: M. W. Olesen).

The Spades from Knudmosen

Museum Midtjylland has the largest collection of T-shaped spades, at least 75, all found during modern peat digging, but almost all with only a general find location, which is often just the name of the bog where they were found. Knudmosen south of Herning is the findspot for 14 of them, making it the locality with the most finds (Lyngstrøm 2016, 102-103).

Knudmosen is an extensive bog area circa 7 km long, 1.7 km wide and covering around 890 ha. Six of the spades are known only as having come from the bog, whereas the other eight have more precise location information in the form of place or road names. One was found in the bog's southeastern zone, three in the southwestern and four in the northwestern. Their find locations are still imprecise but coincide with areas where there was extensive peat digging at the time they were given to the museum. There are two groups: one by the northern edge of the bog and one by the southern. It is not known how far out in the bog they were found and their distribution may reflect nothing more than where recent peat digging occurred.

One spade has both the blade and handle preserved, one has the blade and a fragmented handle, while the remaining 12 consist only of the blades. The spades are 39-45 cm long and 6-8.5 cm wide. Only a single spade varies from the others in size and choice of wood. All of them were preliminarily examined to determine the choice of wood and evaluate their suitability for dendrochronological dating. The spades were split from large oak tree trunks with the direction of the split predominantly radial and done a minimum of 10 cm from the middle of the tree. The wood was generally from older and slow-growing oaks (Larsen and Mikkelsen 2022, table 1) and the uniform quality suggests that raw material for their construction was readily available. Nine spades are suitable for dendrochronological dating and they will be critical for establishing the connection between settlements and the use of Knudmosen where building activity was intense during the Late Bronze Age and Early Pre-Roman Iron Age. Settlement is mostly spread out and high on the moraines overlooking the bog, but along the northern edge there is a row of houses from the Early Pre-Roman Iron Age that are arranged almost linearly. Perhaps the change in settlement pattern happened because of an increased use of the bog's resources (Figure 2).

Experiments making T-shaped Spades

The experiments were aimed at investigating how a spade was constructed, the way in which it wore when used, and especially to reveal the choices made during the process – and the traces these choices leave in the material culture.

The nature of the local soils and available raw materials, in conjunction with conditions of usage, could have had an impact on the spades' form and perhaps led to regional variations of this tool as was known in historic times (Hove 1983, 79). At the same time, the person who made the spade must have had a clear picture of its function and maybe even the individual who would use it. During production there likely was a clear aim to achieve a specific length, width and thickness of the spade's blade and handle, based on how it would be used. Just as the dimensions could have been adapted to the person who would use it.

When reconstructing a prehistoric object, it becomes apparent that there are initially several points to consider. First, a thorough understanding of the raw material is required, as well as an in-depth knowledge of available tools to achieve an end result as close to the original object as possible. Secondly, it is important to search for the 'fingerprints' of the original craftsperson(s). These can be varied, but generally all craftspeople leave a unique signature on the work they create: e.g. an odd angle of a tool mark, a minor 'mistake' or, when similar objects are examined together, some decision in the design and craft process that creates a unique relationship between the different objects (Høgseth 2013, 72).

When looking more closely at the collection of T-shaped spades at Museum Midtjylland some initial observations became apparent.

- The quality of the timber is high.
- The surfaces are well worn from use.
- The joints have low tolerances and generally the work should be considered to be of high quality.
- Most of the blades are radially split, a process that creates more waste, but ultimately produces a stronger plank.
- Many of the blades have been skilfully worked down to an impressive thinness.

With these overall considerations, the next job was to deconstruct the process of making a spade. Unfortunately, given the circumstances of archaeological finds, this process relies heavily on modern sensibilities and logic. Nevertheless, having said that, practical knowledge and knowledge of prehistoric geography, climate, available tools and living conditions can be superimposed onto this process, or at the very least, considered when planning the work process.

It was decided to make the spades from freshly felled wood with a relatively high moisture content. This was decided because oak wood becomes much harder when it starts to dry out. About a month prior to making the spades, an oak tree about 60 cm in diameter was felled and cut into lengths of roughly 1 m, but kept in full rounds with its bark still on. This was done to give the timber some time to relieve stresses as well as letting it mellow slightly. The oak trunks were then radially split with an axe and wooden wedges into eighths, and the weak splint wood was removed so only the strong heartwood remained. The rest of the work was done in a way that corresponded with a production run that involved making several spades at once. The lumber was roughly hewn into spade billets, then all the billets hewn and made into blades of a rough final shape. The same process was used for the handles and once a sufficient number of both blades and handles were finished, we moved on to the assembly of the spades, which required joinery. The work was primarily done using the following tools: axe, adze, knife and spokeshave (Figure 3). An interesting observation was made when then first billet was hewn with a reproduction of an Iron Age adze. The tool marks made with the adze were of similar size: a 90-degree angle on the length of the spade blade like those that could be observed on several originals from the collection of Museum Midtjylland. The tool marks made with the axe were much wider and closer to a 45-degree angle along the length of the spade billet.

Once the two parts were firmly attached together, some final work was done on both, such as

Figure 3. Wood for the blades was produced from radially split blanks that were shaped using an adze to a precise length, with, and thickness (Photo: H. Lyngstrøm).

smoothing out rough bits with a knife and spokeshave. A good deal of attention was devoted to the handles, to allow for personalized handle shapes and sizes, for differently shaped and sized hands.

Experiments digging Peat with T-shaped Spades

Digging peat with a spade is regarded as a simple process that requires a low degree of knowledge and skill. Therefore, many members of the community could do it: women and men, young and old. However, digging requires a variety of levels of physical skill depending on the nature of the peat and the pit's size and depth. Knowledge of both the simple process of digging a pit and the integration of it into the more complex operational scheme of harvesting peat was learned through participation in daily life through observation and imitation (Wenger 1998). Experience from earlier digging experiments showed that the material being dug has an important impact on how a wooden spade wears (Lyngstrøm 2015, 190). However, the way in which it is used also affects the usewear.

The T-shaped spade from Nr. Smedeby was the first example to be published as 'en Tørvespade, en Art Stikspade' (Becker 1948, 96). The very thin blade of the spade points to use in a relatively soft material and the handle would have enabled precise control of the tool while digging (Lerche 1097, 150). Many have compared them to 19th-century peat spades (Hove 1983, 81, Rasmussen 1970, fig. 3) but in contrast with T-shaped spades they had longer shafts and broader blades. Assuming the T-shaped spades were used to dig peat, they would have required a different working stance and produced shorter and narrower slices of peat.

Figure 4. The diggers chose which of the 13 spades they used and when they reflected on what influenced their decision. It was especially the handle that guided their choices (Photo: H. Lyngstrøm).

In the attempt to dig peat in Knudmosen, the spade was both pressed down into the peat and inserted under the peat block. This was done after the turf was removed using modern tools so a clean and moist peat surface was exposed over *c.*15 m^2. Seven people dug for 6½ hours with very few pauses along a clearly visible edge where peat was dug in the 1940s. A small, oblong pit was dug that did not reach the bottom, exactly like the digging strategy documented in Aldersro I and Fuglsøgårds Mose (Christensen and Fiedel 2003, 86-87; Mortensen et al. 2020, 12). The diggers chose which of the 13 spades they used and when they reflected on what influenced their decision it was especially the handle that was important to them (Figure 4). One spade broke at a knot after *c.*450 strokes but otherwise the day's work did not produce any real wear and tear on the spades.

Conclusion

The experiments revealed T-shaped spades to be a specialized tool produced from uniform, carefully selected oak. Wood for the blades was produced from radially split blanks that were shaped using an adze to a precise length, width, and thickness, while handles were more varied to suit the individual who would use them. Two people produced 13 spades in 24 hours. The spades were well-suited to digging peat after the turf had been removed and there were no signs of wear and tear after 6½ hours of use.

The attempts generated a host of new questions, both in relation to dating but also how they were used, as a fragment of a T-shaped spade was also found near the pit zone alignment at Brændgårds Hede.[3]

Notes

1) The reproduction of the spades was undertaken at Sagnlandet in Lejre on May 26th-28th, 2022, by Lucas Overvad, Lindy Wilhardt, Martin Winther Olesen, Sidsel Wåhlin and Henriette Lyngstrøm. Prior to this, the type of wood used in the archaeological specimens was determined at the Department of Archaeological Science and Conservation at Moesgaard Museum and they were examined by Lucas Overvad for traces of the woodworking that had been used to shape them. The spades were used to dig peat in Knudmose near Herning on August 13th, 2022, by Agnete Høj Jensen, Sara Prang, Line Schnoor, Christina Schultze, Sidsel Wåhlin, Mathilde Lundberg Friis, Kathrine Knudsen, Martin Winther Olesen and Henriette Lyngstrøm. The technical reports are archived at Sagnlandet Lejre under HAF journal number 002/2022.
2) The spade HEM 30/42 differs from others as it is made from birch, is 12 cm wide and the wood has been penetrated by insects.
3) The spade RSM 10.010x1012 from Ringkøbing-Skjern Museum.

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