At the water's edge: Micromorphological and quantitative mineral analysis of a submerged Mesolithic shell midden at Hjarnø Sund, Denmark

Ingrid Ward\textsuperscript{a,b,c}, Peter Moe-Astrup\textsuperscript{c}, Kelly Merigot\textsuperscript{d}

\textsuperscript{a} College of Humanities, Arts and Social Sciences, Flinders University, GPO Box 2100, Adelaide, SA, 5001, Australia
\textsuperscript{b} School of Social and Cultural Studies, University of Western Australia, 35 Stirling Highway, Crawley, WA, 6009, Australia
\textsuperscript{c} Moesgaard Museum, Moesgaard Alle 15, 8270, Højbjerg, Denmark
\textsuperscript{d} John de Laeter Centre, Faculty of Science & Engineering, Curtin University, Bentley, WA, 6102, Australia

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\textbf{A B S T R A C T}

This study presents the first application of micromorphology and Automated Scanning Electron Microscopy (ASEM) to a submerged shell-bearing midden site in Denmark, one of the few submerged shell-matrix sites in the world to have undergone archaeological excavation. The use of micromorphology in these deposits provides a means to distinguish primary and secondary deposits and degree of preservation. The additional input of quantitative mineral analysis provides an empirical tool for correlation of minerogenic components across the site and assessing change through time. Micromorphological insights into the formation history and post-depositional modification include epizootic infestations within oyster shells at the base of the profile and needle-fibre calcite at the top - the former is indicative of accumulation of at least part of the shell midden below water, whilst the latter is indicative of exposure. Aside from the shell itself, other cultural traces include heated and worked flint fragments, burnt and unburnt hard bone fragments (including fish bone), soft (spongy) bone, charcoal (\textit{Ulmus} sp., \textit{Abies} sp., \textit{Corylus} sp.), and preservation of what could possibly be antler velvet. Quantitative mineral analyses provide support for the successive stabilisation of the midden site by accumulating minerogenic (silica-rich) sands over the glacial clay and detrital gyttja deposits (defined by smaller grain size, greater heavy mineral content), and subsequently between the shell matrix itself, until the erosion of these protective sediments in more recent times. Further micromorphological profiles are needed to fully assess local versus regional signatures within the site, which otherwise provides an ideal context against which to compare the effects of inundation in similar microtidal contexts.

1. Introduction

The Late Mesolithic Ertebølle shell middens or kitchen middens (\textit{køkkenmodding}) of Denmark have been a focus for interdisciplinary research for over a century partly because of their relative visibility and partly because of the many well-preserved cultural and faunal remains within them (Anderson, 2000, 2004; Bailey et al. in press). Over 350 of these midden sites are found above water in northern Denmark as a result of relative uplift associated with ongoing glacio-isostatic adjustments following the melting of the Fennoscandian ice-cover (Anderson, 2000, 2013, see also Rosentau et al., 2017). In southern Denmark, many hundreds of Stone Age sites are now under water, including 37 submerged Mesolithic find spots in the Horsens Fjord system alone (Fig. 1). Few if any of these submerged sites are confirmed shell middens and even fewer have been systematically excavated - only Tybrind Vig, Ronæs Skov, Argus Grund and Mollegabet II (Bailey et al. in press). In the absence of focused excavation and analysis, it remains unclear whether these shell deposits are \textit{in situ} or have been re-deposited by marine inundation, although their preservation is generally favoured by the protective coastlines and low energy (limited wind fetch, and reduced wave height) conditions in inner Danish waters (Rosentau et al., 2017).

One other site to have undergone detailed archaeological investigation is the Stone Age shell-matrix site of Hjarnø Sund (Skriver et al., 2017; Astrup et al. submitted). The site of Hjarnø Sund is located in a water depth of 0.5–2 m on the western shore of the small island (3.2 km$^2$) of Hjarne in the outermost part of Horsens Fjord (Fig. 1). The site was originally situated next to a shallow coastal lagoon represented by deposits of gyttja (Skriver et al., 2017). The midden itself lies across a sloped sequence seaward of a shallow 20 m$^2$ bank (Fig. 1), comprised of glacial clay and over lain by sand, with one end of the midden unconformably overlying glacial clay and the other overlying gyttja.

\footnote{Corresponding author. College of Humanities, Arts and Social Sciences, Flinders University, GPO Box 2100, Adelaide, SA, 5001, Australia. E-mail address: ingrid.ward@uwa.edu.au (I. Ward).}

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Underwater excavation and sediment coring undertaken between 2013 and 2017 has revealed a rich collection of material ranging in age from the Early Ertebølle (∼7300 BP) to the Middle Ertebølle (∼6500 BP) (Skriver et al., 2017; Astrup et al. submitted) and is argued by Larsen et al. (2018) to be one of the oldest-known submerged midden sites in Denmark.\(^1\)

The stratified deposit included layers of edible shell species including mainly oysters (*Ostrea edulis*), as well as cockles (*Carastoderma edule*), mussels and periwinkles (*Littorinalittorea*). Current age estimates of the cockle shells range from 7245 to 6905 cal BP (Astrup et al. submitted), which overlap but are offset by ∼100 yrs from the oyster chronology. This corresponds with previous dating analyses on the Hjarnø site that indicate the oyster-to-cockle shift is chronologically consecutive (separated by as little as 0–163 yr) (Larsen et al., 2018).

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\(^1\) Earlier dates of 7920–7520 BP are reported for the submerged Argus Bank site (Fischer et al., 2007) but this is not a midden site.
Above and below the shell are layers of gyttja, from which artefacts such as painted paddles, dugout canoes, axes, bows, and fishing implements of bone, antler and wood have been recovered (Skriver et al., 2017).

In June 2017, a joint Australian-Danish team undertook further investigation of the Hjarnø shell-matrix site (Fig. 1) as part of the Deep History of Sea Country project (Benjamin et al., 2018; Astrup et al. submitted). The 2017 investigations of Hjarnø Sund included a combination of excavation, photographic and photogrammetric recording, geophysical survey, sediment coring and collection of samples for archaeological, geochronological, sedimentological and soil micromorphological analysis – the latter of which is the focus of this paper. As with previous excavations, virtually all layers in the midden contain flint artefacts, fish bones, hazelnuts, charcoal and an in-situ hearth feature that further attests its anthropogenic origins (Astrup et al. submitted).

Whilst evidence for the cultural origin of the shell-matrix site is strong, there remains some question as to the formation history and post-depositional disturbance of the site by marine erosion (see also Astrup et al. submitted). One means to assess this is through micromorphology, here supplemented by Automated Scanning Electron Microscopy (ASEM) to further aid the identification of minerals and sedimentary processes within these midden deposits (see also Ward and Maksimenko, 2019). Micromorphology has been successfully applied to terrestrial midden sites (e.g. Villagran et al., 2011; Mijares, 2016) and also to submerged wetland and lake dwelling deposits (Lewis, 2007; Ismail-Meyer, 2014). However, the micromorphological investigation of marine inundation on archaeological sites is limited, with the only known published study (Macphail et al., 2010) undertaken on arable terrestrial midden sites (e.g. Villagran et al., 2011; Mijares, 2016) and also to submerged wetland and lake dwelling deposits (Lewis, 2007; Ismail-Meyer, 2014).

2. Methods

2.1. Micromorphology

Sampling for archaeological micromorphology was undertaken by underwater archaeologists during the 2017 investigations of Hjarnø Sund. The 5 × 1 m long excavation runs parallel to the 2015 excavation (Fig. 1), with 1 m² excavation squares excavated by arbitrary units until basal clays were reached. Further details on excavation and survey methods are provided by Astrup et al. (submitted). The sampling strategy for micromorphology involved two sets of samples: (1) a 5 cm diameter x 50 cm long PVC tube core taken ~ 4 m southeast of the midden excavation site, and (2) a series of two box cores (30 × 30 × 10 cm), one immediately below the other, on the eastern side of the second 1 m² excavation square (Fig. 2). The former was taken with the aim of sampling the gyttja-shell transition as this was not present in the excavation itself. In addition, representative sediments were collected by coring from the different sediment facies around the midden site. Sediments were also sampled at 2–4 cm intervals down the box core profile.

The central part of the topmost box core (Box Core A) contained a hearth-like feature (Fig. 3). This central part extracted by cutting away the surrounding sediment, which was retained for associated sedimentological analyses. The remaining ‘heart’ was wrapped in plaster (Fig. 3) and transported to the University of Western Australia (UWA) for resin impregnation (Inset Fig. 3C) and later micromorphological analysis. Two kubiena tins were used to obtain undisturbed sub-samples of the second box core (Inset Fig. 3C and D). The < 2 mm fraction from collected sediment samples were analysed by laser particle size analysis (using Malvern Masterzizer 2000, v 5.6) at UWA.

Large (5 × 7 cm) thin-sections from the box cores’ were produced by Spectrum Petrographics, Vancouver, USA, whilst standard (2.5 × 5 cm) thin sections from the tube core were produced at UWA. Thin sections were analysed at the Archaeology Department, UWA, using a Nikon petrographic microscope at magnifications ranging from 2.5x to 50x, under plane polarized (PPL) and cross polarized (XPL) light. Identification of cultural components, including shell, bone, charcoal and ashes, were made using available reference literature (e.g. Stoops et al., 2010; Nicosia and Stoops, 2017).

2.2. Automated Scanning Electron Microscopy

The eight micromorphological thin sections were analysed by Automated Scanning Electron Microscopy (ASEM) using a TESCAN Integrated Mineral Analyzer (TIMA-X) system at the John de Laeter Centre, Curtin University, to obtain quantitative mineral analyses of the different sedimentary layers. ASEM analyses were conducted at operating conditions of 25 keV using a spot size of 52 nm, a working distance of 15 nm, with a pixel spacing of 10 μm and a field size set at 1500 μm. Modal mineralogy was determined using Version 1.5 TIMA software and presented in terms of pixel area percentages), from representative sets of 5 × 5 fields (7500 μm × 7500 μm) from each of the stratigraphic layers or from the full slide. Mineral identifications are defined by chemical composition and mineral structure as determine from TIMA analyses, using a standard (Astimex Scientific MINM25 + 53 + FC mineral standard Serial 1AQ). Further details on the TIMA operating system can be found in Hrstka et al. (2018), with useful discussions on the application of ASEM to geoarchaeology can be found in Haberlah et al. (2011), Knappett et al. (2011) and Ward et al. (2018).

3. Results

3.1. Hjarnø Sund sediment facies

As outlined above, the Hjarnø shell-matrix site forms part of a sloped and deepening sequence over a glacial clay bank. The clay bank is overlain by a layer of coarse unimodal sands, with variable amounts of reworked shell (mainly Cardium sp. and Mytilus sp.) and reworked cultural material (Table 1). The wider area is covered by poorly-sorted coarse sands with variable amounts of pebbles. These gravelly sands are concentrated around the south-south-western edge of the clay bank, presumably as a result of higher current and/or wave energy. Further offshore, the transition is to grey gyttja at 20–60 cm depth, brown, detrital gyttja and then fine detrital gyttja in the deeper parts of the section, south of the main midden site (Table 1). Within the detrital gyttja are fragments of waterlogged wood, mainly hazel. Grey gyttja is comprised of well-sorted medium grained silty sands that in some parts have a distinct sulphurous odour indicative of anoxic conditions. The shell midden excavated in 2017 overlies this grey gyttja, which itself unconformably overlies culturally sterile moraine clay.

Taken on the northeastern edge of the 2017 excavation, the box core sample (Box Core B) shows a transition from the grey gyttja sediments at the base to a slightly darker (GLEY 1 7/N) unit (5 cm thick) of grey silty sands, with minor shell fragments and a few pebbles. The top of Box Core B overlies with the oyster (Ostrea edulis) layer (7–9 cm thick) from Box Core A, which defines the midden proper. The oyster shells tend to be oriented slightly inclined to horizontal and concave-down in a hydrodynamic stable orientation (Fig. 4). A large flint fragment, shown in Fig. 3B, is present near the top of this thick oyster unit. Above the oyster layer is a thin (1–2 shell thick) mussel (Mytilus edulis) layer, over which is a layer (< 5 cm thick) of cockle (Cerastoderma edule) shells, either inclined or horizontal concave-up, mixed with a few oyster...
and mussel shells (Fig. 4). This orientation of shell, or lack thereof, may imply human discard (e.g. Claassen, 1998; Henderson et al., 2002) and/or greater bioturbation of these uppermost sediments (Salazar-Jimenez et al., 1982). Towards the top of the box core, the interstitial sands become increasingly charcoal-rich, giving a darker colour to the matrix (Table 1). The topmost charcoal feature comprises well-sorted medium-fine dark grey to black (GLEY 1 8/N) sands with large fragments (0.5–1 cm) of charcoal, and a large 2.5 cm flint fragment.

![Fig. 3.](image)

**Table 1**

<table>
<thead>
<tr>
<th>Facies</th>
<th>Short Descriptor</th>
<th>Munsell colour</th>
<th>Modal peak</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Medium sand</td>
<td>GLEY 1 7/N to 6/N (darker = charcoal)</td>
<td>450 μm</td>
<td>Generally unimodal medium grey sand with variable amounts of reworked shell</td>
</tr>
<tr>
<td>2</td>
<td>Grey gyttja</td>
<td>GLEY 1 7/N</td>
<td>445 μm, 60 μm</td>
<td>Well-sorted grey medium silty sand, often with distinct sulphurous odour</td>
</tr>
<tr>
<td>3a</td>
<td>Brown (detrital) gyttja</td>
<td>2.5 YR 4/4 to 5 YR 4/4</td>
<td>60 μm, 550 μm</td>
<td>Soft brown sandy gyttja with variable amounts of waterlogged wood-fragments</td>
</tr>
<tr>
<td>3b</td>
<td>Fine detrital gyttja</td>
<td>2.5 YR 2.5/4</td>
<td>60–100 μm</td>
<td>Loose, watery organic brown mud</td>
</tr>
<tr>
<td>4</td>
<td>Glacial clay</td>
<td>GLEY 2 7/10B to 10YR/1</td>
<td>340 μm, 5 μm</td>
<td>Well compacted grey to white clay with fine sand grit</td>
</tr>
</tbody>
</table>

Fig. 3. (A) Box core A taken around a charcoal feature from upper part of the 2017 midden excavation, with inset (B) showing resin impregnated core with embedded flint artefact. (C) Box core B from lower part of midden site and (D) position of Kubiena samples from Box Core B.
The minerogenic component increases in the underlying sands, with
higher relative percentages of quartz (73%), orthoclase (∼6%), plagi-
oclaste (0.25%) feldspar, muscovite (0.17–23%) and amphibole
(0.14–0.4%) and almost negligible carbonate (< 1%). The anoxic
conditions of these sands are reflected in the higher relative percentages
of pyrite (0.19–28%). In the underlying gyttja, both the relative per-
centage (∼50%) and the median grain size (150 μm) of quartz, as well
as carbonate (< 0.2%), is at its lowest. As might be expected, the
content of defined plant (4%) and pyrite (0.55%) is high in this unit.
Most notable is the significantly greater content (28%) of what has been
defined as rock flour – a very fine-grained silica-rich phase and heavy
minerals including zircon, ilmenite, titanate and rutile that most likely
reflect some input from the underlying glacial clay. Porosity is greatest
in the lower units (10–11%) and is lowest in the top-most unit (5%,
Table 2) possibly reflecting the coarser grain size. The micro-
morphological description of each of the units is described below.

### 4. Microstratigraphy - Tube sample

#### 4.1. ASEM analyses

The tube profile taken adjacent to the main midden excavation
shows three of the four main stratigraphic units (SU) or facies, which
are summarised in Table 3 and presented in Fig. 5. The assemblage
of minerals identified in thin sections is similar throughout the sequence,
comprising mainly quartz, carbonate (mainly shell), feldspar, amphi-
bole and heavy minerals. However, the modal abundance of these
minerals changes downward through the profile as indicated from the
quantitative mineral results (Fig. 5). This shows a decrease in relative
percentage of quartz (from ∼70% to 20%) and increase in carbonate –
mainly as shell (from 12% to 44%) and fine calcite (0.4%–1.1%), re-
fecting the decrease in interstitial sand through the main shell midden
units. ASEM results also show a decrease in the median grain size of
quartz (from 480 μm to 260 μm) and orthoclase (from 300 μm to
70 μm), the most abundant silicate minerals, downwards through the
shell units (Table 2). Larger clasts are predominantly charcoal and flint,
the latter including some artefactual remains.

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higher relative percentages of quartz (73%), orthoclase (~6%), plagi-
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morphological description of each of the units is described below.

#### 4.2. Stratigraphic unit 1 (Samples TC101, TC102)

This unit is equivalent to the main shell-bearing midden unit as
presented in Box Core A. In the tube core it is approximately 20 cm
thick, with a sharp transition between the shell layers and the under-
lying sands (Fig. 6). This unit has an even c/f (coarse:fine) ratio and
single grain to pellicular microstructure comprising well-sorted, mainly
sub-rounded medium sands with a very fine sand component (Table 3).
Shell fragments (~ 1.5 cm) are dominant and include cockle (30%)
(Fig. 6a), mussel (10%) and oyster (10%). The majority of shell is un-
burnt and burnt fragments (~5%), where present (Fig. 6f), are mainly
small (~ 200 μm). Occasional unburnt fish bone is also present
(Fig. 6b). Of particular interest are the bundles of needle-like calcite
near the top of the profile (Fig. 6c and d), with single crystals also
present in the groundmass. Dark charcoal and ash aggregates are
common (no ash rhombs are visible), with the vertical arrangement on
one side of the thin section (Fig. 6, TC_101) a result of smearing along
the tube wall during sampling. Towards the base of the unit, slightly
inclined and aligned charcoal and shell fragments may be indicative of
trampling over a former ground surface (Fig. 6e).

#### 4.3. Stratigraphic unit 2 (Samples TC102, TC103)

This unit is equivalent to the unit below the main shell-bearing
midden unit as presented at the base of Box Core A and top of Box Core
B. In the tube core it is approximately 15 cm thick, with a relatively
sharp transition from the overlying shell midden and a more gradual
transition to the underlying gyttja unit (Fig. 6). As indicated from the
ASEM results (Fig. 6), quartz-rich sand rather than shell is the dominant
phase in this unit, with cultural material still present in the form of
bone (Fig. 6g) and charcoal. Acicular calcite is also present within the
groundmass (Fig. 6h), possibly reflected by the high relative percentage
of fine calcite (1.1%) in the ASEM analyses.

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**Table 2**

Summary of modal peak as determined by Mastersizer, and median grain size
(μm) for quartz and orthoclase as determined by ASEM, and also porosity
(volume %) as determined by ASEM.

<table>
<thead>
<tr>
<th>Tube Core</th>
<th>Modal peak (μm)</th>
<th>Quartz (μm)</th>
<th>K-feldspar (μm)</th>
<th>Porosity %</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC101</td>
<td>nd</td>
<td>414</td>
<td>256</td>
<td>5</td>
</tr>
<tr>
<td>TC102</td>
<td>438</td>
<td>338</td>
<td>170</td>
<td>11</td>
</tr>
<tr>
<td>TC103</td>
<td>nd</td>
<td>440</td>
<td>142</td>
<td>10</td>
</tr>
<tr>
<td>TC104</td>
<td>nd</td>
<td>140</td>
<td>77</td>
<td>10</td>
</tr>
<tr>
<td>Box Core</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BC101</td>
<td>450</td>
<td>371</td>
<td>259</td>
<td>3</td>
</tr>
<tr>
<td>BC103</td>
<td>460</td>
<td>359</td>
<td>283</td>
<td>3</td>
</tr>
<tr>
<td>BC201</td>
<td>440</td>
<td>343</td>
<td>244</td>
<td>2</td>
</tr>
<tr>
<td>BC202</td>
<td>415</td>
<td>415</td>
<td>195</td>
<td>4</td>
</tr>
</tbody>
</table>
Excluding the large (1.5 × 2 cm) angular flint fragment (present in TC103), this unit has a low c/f ratio (Table 3) with an increasing silt component, and a more pellicular and compacted grain microstructure, with iron and manganese precipitates increasing towards the base of the unit. Interestingly the flint fragment contains a planktonic foraminifera (Karen Knudsen, pers. comm.) (Fig. 6i) and at least one calcareous alga (Marcus Key, pers. comm.) (Fig. 6j). Oyster and cockle shell fragments are present albeit in much lower proportions (~10%) than stratigraphic unit 1. Charcoal and plant pseudomorphs are also largely absent, except for a few fragments at the base of the unit (Fig. 6k).

4.4. Stratigraphic unit 3 (Samples TC103, TC104)

This gyttja unit was sampled to a depth of 20 cm, although based on previous coring (Skriver et al., 2017; Astrup et al. submitted) it likely goes to depths of 1 m or more. The unit generally shows an angular blocky structure, with partially accommodated and accommodated intrapedal cracks (Fig. 6, TC_104). However, this blocky/prismatic structure is most likely a result of drying in the oven rather than actual site structure, with the wet sediments otherwise showing a massive structure (see also Mijares, 2016). The minerogenic component comprises coarse sub-rounded to sub-angular sand and silt. Organics include meso-to macro-size plant tissue, with a moderate to weak laminar orientation, with some large fragments (up to 2 mm) showing visible internal structure (albeit insufficient to provide species identification). There is an increase in diffuse manganese and iron precipitates (e.g. Fig. 6m, 7n, 7) indicative of variable saturation of the sediments, and generally anoxic conditions. The latter is also reflected by abundant pyrite framboid aggregates in the groundmass (Table 3) and also high pyrite (0.55%) content from the ASEM analyses. There is no obvious horizontal orientation and packing of plant fragments that may indicate trampling, nor was any cultural material observed in this sample. However, cultural material has been described within gyttja deposits elsewhere on the site (Skriver et al., 2017; Astrup et al. submitted).

5. Microstratigraphy – Box core sample

5.1. ASEM analyses

When combined, the box core profiles through the main shell-bearing midden excavation show four/five main layers or sub-units, which are summarised in Table 4 and presented in Fig. 7. Larger clasts are predominantly shell (cockle, mussel and oyster), pebble-sized flint fragments (including some artefacts), charcoal (20–1000 μm) and bone (some burnt). The assemblage of minerals is relatively homogeneous throughout the sequence, comprising mainly quartz, carbonate, feldspar, amphibole and heavy minerals. Whilst the modal size of quartz (~340–430 μm) and orthoclase (~195–280 μm) remains fairly constant, modal abundance of each mineral phase changes through the profile (Table 2). Quantitative mineral analyses shows a similar modal abundance of minerals in the upper unit of the Box Core (BC101) as in the upper unit of the Tube Core (TC1-1), with 51–53% quartz, 29–34% calcite (shell), ~10% feldspar (orthoclase, anorthite, albite, plagioclase), 0.1–0.15% apatite (bone) (Fig. 7). Modal size of quartz and K-feldspar are also similar (Table 2). This implies these units correspond to the same stratigraphic unit or facies. The greatest difference is shown in the lower section of the shell layers (BC103), which shows much lower...
The abundances of quartz (32%) and higher abundances of calcite (47%), plant (12%) but with similar abundances of apatite (bone) (0.13–0.15%) as in other parts of the shell layers. The total porosity of the Box Core is much lower than the Tube Core (Table 2). However, this is attributed to compaction of a larger overall bulk following sampling compared to an auger sample and is not considered diagnostic. The defined microfacies (mF) and micromorphological description of the Box Core profile is provided below.

5.2. Sub-unit 1a (mF type 1a) (Sample BC101)

The charcoal sub-unit or microfacies type (mF type 1a, Figs. 4A, Figure 8) is characterised by a high c/f ratio, bridged grain microstructure with grains bridged in parts by grey-brown moderately laminated ash aggregates (no ash rhombs are visible) with embedded charcoal fragments, plant pseudomorphs, shell (Fig. 9a) and bone (Fig. 9b). Occasional fragments of detached and burnt fragments of the shell prism layer are present in some ash aggregates (Fig. 9b). Only a very few, small (∼300 μm) sub-rounded cryptocrystalline rock fragments were observed. Charcoal fragments are mostly small (< 60 μm) but with a few larger (up to 2 cm) fragments, generally show some internal structure (e.g. Fig. 9c). Although plant species cannot be identified from a single cross-section, at least one represents elm (*Ulmus* sp.) and others either alder (*Alnus* sp.) or hazel (*Corylus* sp.) (P.H. Mikkelsen, pers. comm. 2018). Both burnt and unburnt fragments of hard bone (< 5%) are present, including one or two (unburnt) spongy bone fragments (Fig. 9d). Despite the marine context, very few foraminifera were observed within the groundmass (Fig. 9e). A small brackish-water snail, possibly *Hydrobia* sp., was also identified (e.g. Fig. 9f).

5.3. Sub-unit 1b (mF type 1b) (Sample BC101, BC102)

This cockle/mussel sub-unit (mF type 1b, Fig. 8) contains a high frequency (40%) of whole cockle shell valves, with variable amounts of mussel (10%) (Fig. 9f) and oyster (10%) shell fragments. The latter two are more fragmented but the majority are interconnected (i.e. broken in situ), with one or two mussel shells showing endolithic boring. In a few shells, the prism layer has been separated or detached (Fig. 9g), with a few smaller burnt fragments of this prism layer evident in the groundmass. Moderate to weakly striated ash aggregates, with embedded charcoal and plant pseudomorphs, burnt bone and/or fine minerogenic (mainly quartz) components, are often concentrated on the upper side of bivalve shells. Occasional fragments of burnt shell are also present within ash aggregates (Fig. 9h) but there is nothing to indicate high temperature combustion.

Also present are a few unburnt fragments of hard bone, including fish bone (Fig. 9i), spongy bone and unknown dark brown cellular fragments (Fig. 10). There is no reference for the latter but one possibility is that it is antler velvet. Although no deer velvet was observed at macroscale, bones of roe deer and tools made of antler are recorded in the midden (Astrup et al. submitted). The minor presence of impregnative iron-oxides associated with some ash features and as hypocoatings around minerogenic grains is possibly indicative of fluctuating redox conditions. Pyritic framboids are present as irregular aggregates around some shells and mineral grains but are not abundant.

5.4. Sub-unit 1c (mF type 1c and 1d) (Sample BC103)

This sub-unit is arguably made up of two main microfacies types, the first (mF type 1d) dominated by sub-horizontal oyster shell and well-sorted sands (Fig. 4B), and the second (mF type 1c, Fig. 8) comprising aggregates of charcoal, ash, shell fragments and moderately sorted sands (Table 4). As with the cockles, the oyster shells in mF type 1d are mainly complete or at least interconnected. Several show evidence of decalcification and separation of the calcitic prismatic layer, and many show evidence of endolithic boring (Fig. 9k). No foraminifera were observed but a micritic pelloid (Fig. 9l) is indicative of shallow-marine tidal conditions. Fabric pedofeatures include pyritic framboids, which occur as individual framboids and irregular aggregates within ash aggregates and on the edge of some shells.

Most plant fragments within the charcoal/ash microfacies (mF type 1c) show Class 2 or 3 weathering, although one charcoal fragment (Class 1) probably represents alder (*Alnus*) or hazel (*Corylus*).
another elm (*Ulmus*) or oak (*Quercus*) (P.H. Mikkelsen, pers. comm. 2018). Although much less abundant than the macro-scale record, a single hazelnut shell is observed in thin section (Fig. 9j). Ash aggregates are still evident along with burnt shell fragments (< 5%), burnt eggshell (1%), burnt bone (< 5%), as well as unburnt bone fragments (< 5%) and spongy bone (1%). A few small (< 300 μm) angular rock fragments (mainly quartz) were also observed.

5.5. Sub-unit 2a (mF type 2a) (Sample BC201)

Contrasting with the overlying shell units, this sub-unit or microfacies type (mF type 2a, Fig. 8) has a higher c/f ratio, an increasingly pellicular microstructure and poorly sorted minerogenic component (Table 4). Oyster shell fragments are infrequent (< 5%), but a cultural presence is still evident in the form of burnt bone (2%) (Fig. 9n), charcoal and plant pseudomorphs (< 5%), and cryptocrystalline flint fragments (~5%). One of these larger (1.5 cm) flint fragments shows heat damage in the form of fine cracks or ‘crazing’ (Fig. 9o), indicative of heating temperatures above 350 °C (Purdy and Brooks, 1971). Also present is an unknown organic, interpreted to possibly be antler velvet, (Fig. 9q). Towards the base of the unit, there are occasional fragments of seagrass, probably *Bangia* sp. (Fig. 9r), and increasing abundance of pyritic frambooids.
Table 4

<table>
<thead>
<tr>
<th>Sub-unit/mF</th>
<th>Description Microstructure Voids c/f related c/f ratio Coarse material Fine fraction Micromass Pedofeatures type distribution b-fabric</th>
<th>Shell</th>
<th>Rock</th>
<th>Bone</th>
<th>Charcoal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a/mF</td>
<td>Charcoal Bridged, grains bridged by simple gefuric 70:30 Fr Vf Vf Fr Grey Parallel striated (ash); Co (ash); pyrite framboids (Vf)</td>
<td></td>
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<tr>
<td>1b/mF</td>
<td>Cockle/mussel Bridged, grains bridged by simple gefuric 60:40 D Vf Fw C Grey Striated (ash); Undifferentiated Co (ash); pyrite framboids (Fw)</td>
<td></td>
<td></td>
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<tr>
<td>1c/mF</td>
<td>Charcoal/ash Intergrain, bridged grains complex enaulic 40:60 Fw D Fw C Grey to black Undifferentiated Co (ash); impregnative Fe-, Mn-oxides; pyrite framboids (Fw)</td>
<td></td>
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<tr>
<td>1d/mF</td>
<td>Oyster Single grain simple coarse monic - 50:50 D Vf Fw Fw Grey Undifferentiated Impregnative Fe-, Mn-oxides; pyrite chitonic framboids (Fw)</td>
<td></td>
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</tr>
<tr>
<td>2a/mF</td>
<td>Sand Increasingly pellicular simple chitonic 90:10 Fr Fw Vf Fw Grey Granostriated in parts HCo (Fe-, Mn-oxide) pyrite framboids (Fr)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2b/mF</td>
<td>Sand Pellicular simple chitonic 80:20 Vf Fw Vf Vf Grey to brown HCo (Fe-, Mn-oxide); No; pyrite framboids brown</td>
<td></td>
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Table abbreviations: Quantity. Vf: very few (< 5%); Fw: few (5–15%); C: common (15–30%); Fr: frequent (30–50%); D: Dominant (> 50%).

5.6. Sub-unit 2b (mF type 2b) (Sample BC202)

The basal unit is a relatively massive sand unit and is distinguished from the overlying unit by an increased silt component and higher Fe- and Mn-oxide content. Presence of at least one pelloid (Fig. 9t) is indicative of shallow water conditions, with fragments of seagrass (Fig. 9s) indicative of the marine context. As in the overlying unit cultural presence is still evident from occasional knapped flint fragments (< 5%) - including one showing ‘crazed’ features (Fig. 9u), burnt bones (2%) (Figs. 4c and 9v) - including one fish bone (Fig. 9w), charcoal, and ash aggregates. A very discrete example of the latter at the base of the thin section shows a clear laminated structure (Fig. 9x). The single displaced and very degraded shell in this and in the overlying unit imply some or all of these cultural elements may derive from the overlying shell midden deposits.

6. Discussion

6.1. Cultural features of midden

The available chronology and macroscopic evidence of the Hjarnø Sund site provides a general sequence of subsistence collection, consumption, and disposal from about 7200 BP, followed by occupational abandonment after a 500 - 300 year period (Skriver et al., 2017; Astrup et al. submitted). This is comparatively short in relation to other large shell midden sites that record use up to 1000 years, perhaps reflecting greater constancy in their natural surroundings (Anderson, 2004). Macroscopic evidence indicates the Hjarnø midden site was located next to lagoonal deposits, with fragments of waterlogged wood within the gyttja deposits indicative of drowned or displaced trees or branches from nearby woodland (Skriver et al., 2017). Although no cultural material was found in the gyttja of the tube core, previous excavations describe quite unique wooden and bone artefacts material within gyttja deposits elsewhere within the Hjarnø Sund site (Skriver et al., 2017; Astrup et al. submitted). These organic remains, along with bone, charcoal and ash, survive in the waterlogged, anoxic conditions indicated by the diffuse manganese and iron precipitates and sulphurous odour of the sediments. No ash rhombs are present and this likely reflects recrystallization of the ash in the wet alkaline sediments (Mallol et al., 2017). There is no visible compaction due to trampling in these organic deposits, although as Ismail-Meyer (2014) highlights, this may be due to swelling within the waterlogged conditions (and perhaps contrasts with terrestrial contexts). Compaction due to trampling can be seen more prevalently on the overlying shell deposits (see below).

At both the macro- and micro-scale there is evidence of flint artefacts, burnt and unburnt bones including fish bones, charcoal and ash that further attest to the midden's anthropogenic origins (see also Astrup et al. submitted). Macrofaunal evidence indicates both marine and terrestrial fauna are represented, with fish bones, particularly cod and flatfish, occurring in concentrations that suggest the use of specific areas of the midden for fish processing (Astrup et al. submitted; see also Anderson, 1989: 26). As in the Argus Bank site, fishing (and shell-fishing) may have been a more important subsistence element than hunting (Fischer et al., 2007). Spongy (cancellous) bone tissue, possibly indicative of shallow water conditions, with fragments of seagrass (Fig. 9s) indicative of the marine context. As in the overlying unit cultural presence is still evident from occasional knapped flint fragments (< 5%) - including one showing ‘crazed’ features (Fig. 9u), burnt bones (2%) (Figs. 4c and 9v) - including one fish bone (Fig. 9w), charcoal, and ash aggregates. A very discrete example of the latter at the base of the thin section shows a clear laminated structure (Fig. 9x). The single displaced and very degraded shell in this and in the overlying unit imply some or all of these cultural elements may derive from the overlying shell midden deposits.

Plant fragments cannot be identified definitively from a single cross-section but given that hazel (Corylus sp.) is the most frequent species...
identified at the macro-scale, it is likely that the same species is represented by at least one of the charcoal fragments in thin section. Alder (*Alnus* sp.), hazel (*Corylus* sp.), elm (*Ulmus* sp.) and oak (*Quercus* sp.) are all contemporary species and were all used for firewood. Charcoal and plant fragments are variably preserved but because of their association with ash features, some of which preserve their laminated structure (e.g. BC101), are generally assumed to be associated with human activity and *in situ*. Given the low specific weight of charcoal (Macphail et al., 2010), it cannot be discounted that isolated fragments of charcoal may have been displaced. Indeed, inverted chronologies from charcoal taken from the base (sample P4) and top (sample P1) of the 2016 excavations (see Astrup et al. submitted) imply some level of displacement of this material. Nevertheless, the charcoal and ash concentrated at the top of the box core profile (mF type 1a) must essentially be *in situ*, preserved through rapid burial. This may represent deliberately dumped material as the underlying sediments show no evidence of rubeification from heating, although rubbed substrates are not a ubiquitous feature of hearths in shell-matrix sites (Villagran, 2018) nor is it known whether rubbed features would survive a long period of inundation.

Microfacies type 2 comprises both mussel (*Mytilus edulis* L.) and cockle, the former with an outer prismatic calcite layer, an inner aragonite (nacre) layer, and a definitive pink colour (Fig. 10b, see also Villagran et al., 2011a) whilst the latter are identified from their ridged surface and concave profile (Fig. 10c). They are distinguished from the oyster microfacies type because of their inclined or horizontal concave-up orientation and greater compaction (see also below), and in the latter correspond more to mF type A1 or mF type 4 of Villagran (2018). Regardless of shell type, very few have a preserved organic layer (periostracum), possibly as a result of cooking at temperatures above 300 °C (Villagran et al., 2011b) and/or from degradation from organic acid in the soil (Villagran and Poch, 2014). However, disaggregated burnt fragments of the prismatic layers are observed (Fig. 8b). These may indicate burning of previously discarded shell and/or burning that occurred at higher temperatures, such as in a hearth laid over a bed of shell. Certainly the isolated ashes in association with the micro-sized charcoals, and high range of alterations of shell, and no visible alteration of substrate tend to support a ‘fire-above’ scenario and/or a dumped shell assemblage as described by Aldeias et al. (2016). Most likely it is a combination of these processes as unburnt interconnected prismatic layers (e.g. Fig. 8g) are also observed in the midden profile, and are indicative of carbonate dissolution.
Fig. 9. Micromorphological sections from the Box Core A (yellow scale bar is 300 μm in all slides), showing (a) fragmented mussel shell and interstitial ash (PPL, 600 μm), (b) burnt and unburnt bone, burnt fragment of prismatic shell layer (red arrow) and plant fragments in ash overlying oyster shell (PPL, 200 μm), (c) charcoal fragment (PPL, 600 μm), (d) spongy bone (PPL, 300 μm), (e) foraminifera (red arrow) and possible antler velvet? in matrix of sub-rounded chitonic sands (PPL, 200 μm), (f) aquatic snail shell and burnt fish bone (red arrow) in monic sands (PPL, 300 μm), (g) separated prismatic layer of shell (red arrow, top) with burnt fragments of the prismatic shell layer (red arrow, below), (h) burnt eggshell in ash aggregate (PPL, 80 μm), (i) fish bone (PPL, 80 μm), (j) hazelnut shell (red arrow, PPL, 300 μm), (k) endolithic boring (arrow) in oyster shell (PPL, 600 μm), (l) pelloid (XPL, 300 μm); and Box Core B showing (m) ash accumulated below shell (PPL, 300 μm), (n) burnt bone fragment (PPL, 300 μm), (o) fine cracks (‘crazing’) within flint fragment (PPL, 600 μm), (p) charcoal (PPL, 600 μm), (q) possible antler velvet? (PPL, 80 μm) (r) seagrass fragment (red arrow) with pyrite framboids developing in chitonic sands (PPL, 600 μm), (s) seagrass fragment (PPL, 200 μm), (t) pelloid (PPL, 600 μm), (u) angular flint fragment in quartz showing ‘crazing’ (PPL, 200 μm), (v) manganese alteration in bone (PPL, 300 μm), burnt fish bone (red arrow) (PPL, 80 μm), (x) laminated ash layers angular microfragment of flint (PPL, 600 μm). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
Observations (by PMA) of the macroscopic bone indicate the majority (> 90%) are unburnt and certainly most of the bones from the larger mammals show no traces of heating. The latter also applies at the microscopic level. What is notable is that many of the bones have been broken to get the marrow, and indeed the meat itself may have been cooked without affecting the bone. Bones that are evidently burnt bones are mainly fishbones, which have obtained a white - blue colour. Thin section shows hard bone fragments throughout the profile (e.g. Figs. 6f, 8b and n, w), many of which show reddish-brown colours and first-order interference colours that are indicative of heating to temperatures of 400 °C (Villagran et al., 2017). Thermal alteration of hydroxyapatite may have allowed better preservation of these burnt bone splinters (Villagran et al., 2011).

The oyster-rich layers correspond to the tossed shell microfacies (mF type F or mF type 3) of Villagran (2018), albeit with a slightly lower c/f ratio, and a dominance of subhorizontal shells and random orientation of bones and other small components. Oysters (Ostrea edulis) are almost wholly calcitic, with a thin outer prismatic layer, and most of the shell comprises a foliated structure (Fig. 11a). Whilst the low fragmentation and sub-horizontal distribution of oyster shells might indicate each of these microfacies represent a single tossing episode (Villagran, 2018), the interdigitation of these with charcoal/ash microfacies implies multiple episodes of shell discard within a period of several hundred years (Villagran et al., 2017). Thermal alteration of hydroxyapatite may have allowed better preservation of these burnt bone splinters (Villagran et al., 2011).

Knapped lithic fragments also occur throughout the profile, even in the layers below the oysters, although the latter probably represent locally reworked material. These fragments are generally composed of cryptocrystalline chert (flint), at least one of which had embedded fossils (Fig. 6i and j), although this is not unusual for this region. A few angular quartz fragments could also be cultural. Most lithic fragments show little or no alteration, however, at least three of these including one in sub-unit 2a (Fig. 9o) and two in sub-unit 2b show ‘crazed’ features from heating at high temperatures (> 350 °C) (Purdy and Brooks, 1971). Alongside the discrete burnt bone and charcoal in these grey sands below the shell midden, this could be interpreted as evidence for pre-midden occupation in the area before 7200 BP. Whilst smaller and more limited finds do occur beneath shell midden deposits (Anderson, 2004), in the absence of more comprehensive sampling it cannot be ruled out that these cultural features were displaced downwards through the profile as a result of mixing.

In summary, it can be argued that the shell deposits largely conform to the classification of Classen (1998, after Widmer, 1989) as a shell-bearing midden site, i.e. site composed of secondary refuse of many kinds of remains, including shell, generated by a wide range of activities, rather than simply a shell midden that shows no other activities. There is evidence of multiple shell building episodes, within each of which is additional evidence of discard of bone, including fish bone, and lithic material, some of which have been heated to high temperatures. Small pieces of worked flint (< 1 cm) found throughout the shell layers indicate activities took place directly on the shell-midden surface (Astrup et al. submitted). In addition there are accumulations of charcoal that may represent hearth features and/or discarded material from a hearth. Hence, as found in other midden sites (Anderson, 2004), multiple activities are being carried out on the surface of the shell heap. However, without further micromorphological analyses in other parts of the shell-bearing midden, it is not possible to define different functional areas as per Villagran et al. (2011a), nor to confirm the representativeness of the microstructure of the midden from the sampled profiles.

6.2. Formation history of shell midden

At the base of the midden sequence are the gyttja deposits that occur in extensive shallow and sheltered areas in many submerged Danish
Preliminary unpublished ASEM analyses indicates small but detectable samples. Unfortunately ASEM analyses are unable to differentiate between the shell and grey sands between the tube and box core deposits (see Astrup et al. submitted; their Fig. 3b). ASEM analyses overlie the difference in the stratigraphic sequence even in the parallel 2015 excavations, where inclined gyttja and grey sand units overlie the shell deposits (see Astrup et al. submitted; their Fig. 3b). ASEM analyses would provide a means to correlate across these sampled units, as evidenced for the shell and grey sands between the tube and box core samples. Unfortunately ASEM analyses are unable to differentiate between different types of carbonate, hence shell species and hence different shell units are identified mainly from their external morphology and internal composition (Kobayashi, 1969). Nevertheless, ASEM is useful in helping to differentiate sub-units and microfacies – e.g. TC1-1 and BC101, TC1-3 and BC202, and generally providing a more accurate and empirical analysis of the sediment profile (see also Ward et al., 2018).

In the 2017 excavation profile, the transition between the sands and the overlying oyster (Ostrea edulis) shell layers is relatively sharp, indicating accumulation over a stable surface. Whilst there is clear evidence of decalcification of shells, the degree and concentration of ‘sacrificial’ shell or secondary carbonates at the base of the oyster layer is much less than occurs in many terrestrial shell middens (see Villagran, 2018). This preferential dissolution of basal carbonate reflects a gradient in physicochemical conditions through the midden profile, and its comparative absence in these submerged deposits implies they were unlikely to have been exposed for any great length of time for such gradients to develop. In its marine context, the midden and its cultural components are not only buffered by the presence of carbonate and siliceous clays but also by seawater itself, even with ash present. Indeed the stability of cultural material and lack of authigenic minerals may partly result from the neutral to alkaline and slightly anoxic conditions, compared to more variable conditions in fully terrestrial contexts (e.g. Karkanas et al., 2000).

Marine borers in the inner part of the oyster shells indicate the midden was located close to the high water mark as such epizootic infestations cannot survive extended periods of aerial exposure (see also Ward and Maksimenko, 2019). The sub-horizontal and concave-down orientation of the oyster shells also support a hydrodynamic stable orientation, with a shallow water context indicated from the presence of pelloids at the base of the oyster layer and in the underlying grey (gyttja) sands. The low concentration of foraminifera indicates that filling sands may have derived from local runoff or from subtidal sand banks and shoals. There is possibly some evidence for an earlier occupation in the localised laminated ash layers at the base of the box core profile (Fig. 9x), and presence of cultural material including burnt bone (Fig. 8w) and heated lithic fragments (Fig. 9u). More likely this cultural material derives from reworking within the saturated sandy sediments (sub-unit 2) in the early phases of accumulation of the oyster layer (sub-unit 1d), with a reworking distance of up to 10 cm indicated by the occasional displaced shell. There is currently no chronology from this pre-oyster phase, although a luminescence age estimate from the base of the 2017 excavation is forthcoming.

The continued accumulation of shell acted as a skeleton to minimise the amount of reworking. Rather reworking, or mixing of cultural and natural deposits, is largely confined to the siliciclastic layers above and to a much less extent below the shell-bearing layers. There is no evidence of major homogenisation of deposits and certainly no features that would be indicative of bioturbation in a terrestrial setting (e.g. excretion fabrics, chamber voids). In the micromorphological profile, discrete depositional phases of oyster and charcoal deposition (Fig. 4) imply continued use of the midden site (see also Claassen, 1991), with current age estimates from the oyster shells ranging between 7345 and 6860 cal BP (Astrup et al. submitted). These may or may not represent smaller spatial units of shell within the larger shell-bearing midden site (Anderson, 2004). Higher resolution chronology and additional micromorphological investigation, aided by ASEM analyses of adjacent deposits, is needed to confirm this observation.

The change in dominant species from oyster to cockle is well documented for this region but whether this reflects changing cultural traditions and/or regional trends in environmental change that affect mollusc habitats (e.g. sediments, salinity) is unknown (Lewis et al., 2016; Larsen et al., 2018; Astrup et al. submitted). Whilst the stratigraphy of the broader midden area shows an overall coarsening upwards sequence that is consistent with shallowing, the modal grain size through the oyster and cockle shell layers is fairly consistent around 450 μm (with a median grain size of 360 μm for quartz) implying a constant source and/or transport process. However, micromorphological evidence does provide evidence for a depositional hiatus or stasis between the accumulations of oyster- and cockle-shell. Nannofossil taxa accumulating in and between the discarded oyster shells would have minimised the effects of trampling that otherwise would have resulted in greater fracturing of the oyster shells, but which is very evident in the mussel (Mytilus edulis) and cockle shells in the mid to upper layers of the midden profile (see also Ward and Maksimenko, 2019). The generally good preservation of the shell, minimal boring by epizoic fauna, and fewer iron and manganese precipitations in the sediments is indication that these layers accumulated in more oxic conditions.

Indeed parts of these shell layers may have accumulated above tide level, as implied by the needle-fibre weathering in the uppermost part of the tube core. According to Villagran and Poch (2014; see also Villagran, 2018), acicular calcite derives from physical weathering, specifically frost action, on the degrading shell matrix (specifically the surface nacre layer) of mussel (Mytilus edulis L.). The observation of similar needle-fibre calcite in the Hjarnø sediments, in a similar climatic context, is likely due to the same processes. During the warmer climatic conditions of the Holocene Thermal Maximum (8000–6600 BP; Rosentau et al., 2017), it is unlikely that the brackish-saline waters of Horsens Fjord would have frozen. The implication is that the deposits, at least in this part of the midden site, may have been exposed (i.e. above sea level) for some period of time before being submerged. Whether this acicular calcite also reflects abandonment (refer Villagran, 2018) is unknown.

Site abandonment may have occurred as a result of inundation, with some minor re-working of the topmost part of the midden before sands buried the midden and surface charcoal deposits and protected them from further erosion. In parts of the midden where shell had accumulated over gyttja, the weight of accumulated shell (and overlying sands) may over time have compacted these deposits and added to the submergence process. Overall indications are that the site originally formed at the lagoon foreshore and continued to accumulate there, even as the site began to become submerged. This does not discount the possible occupation of the supra- littoral zone at the same time, and indeed the combusted wood fragments must have originated from nearby woodlands.

The woodlands have now given way to farmland but below the water, the shell-bearing midden deposits have remained shallowly buried until the more recent erosion of these surface sands. The latter would have minimised the effects of trampling that otherwise would have resulted in greater fracturing of the oyster shells, but which is very evident in the mussel (Mytilus edulis L.), the observation of similar needle-fibre calcite in the Hjarnø sediments, in a similar climatic context, is likely due to the same processes. During the warmer climatic conditions of the Holocene Thermal Maximum (8000–6600 BP; Rosentau et al., 2017), it is unlikely that the brackish-saline waters of Horsens Fjord would have frozen. The implication is that the deposits, at least in this part of the midden site, may have been exposed (i.e. above sea level) for some period of time before being submerged. Whether this acicular calcite also reflects abandonment (refer Villagran, 2018) is unknown.

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4 Preliminary unpublished ASEM analyses indicates small but detectable differences in the major element chemistry of eight reference shell samples that may be diagnostic of species and/or environment.
may be a result of loss of eel-grass (Zostera marina) (Rasmussen 1977) and/or changes in local currents (Skriver et al., 2017). It is also known that sand near the Hjarne jetty was mined for building the foundations for the jetty extension, which itself may have limited longshore transport of sand and further exacerbated any regional effects of erosion. Regardless this recent erosion is impetus for ongoing research on the site, which is likely to continue to provide useful insights into the formation and inundation history of this and possibly other shell-bearing midden sites in Horsens Fjord.

7. Conclusion

Along with other studies of Hjarne Sund, this micromorphological study indicates there is high stratigraphic integrity of what is defined as a shell-bearing midden (shell-matrix) site, which all evidence indicates is anthropogenic in origin (with layers of natural deposition). Whilst the available chronology is fairly coarse, micromorphology provides evidence of more discrete layering within the midden profile as well as insights into both the cultural aspects of midden sites as well as its taphonomy. Although largely limited to a single profile, the micromorphological evidence indicates that the site represents conflagrations of discrete deposits at the water's edge, which remained stable and largely undisturbed by the process of inundation and complete submergence. Local minerogenic sands within and over the shell deposits have more than once helped stabilise the site up until more recent times. These stabilising sands are argued to be natural rather than cultural in origin, and in that regard may differ from some terrestrial shell-matrix sites (see Villagran, 2018).

This study also demonstrates the value of box core sampling in association with excavation of submerged archaeological sites. Much of the sedimentary matrix and especially fine material can be lost during excavation using suction methods. Hence micromorphology combined with ASEM not only helps address this but also provides a largely intact profile to explore sedimentary structures, fine mineralogical features, shell matrix elements and their cultural associations. Additional micromorphological analyses of other concentrated charcoal or hearth-shell matrix elements and their cultural associations. Additional micromorphological analyses of other concentrated charcoal or hearth-like features within the Hjarne site, aided by Fourier transform infrared spectroscopy analyses of the shells and the sediments (see Aldeias el al., 2016), would help better assess the types of shellfish cooking methods used.

Similarly additional micromorphological investigation, aided by automated mineral analyses, of the stratigraphic units and microfacies across the site and over the wider area would aid cross-correlation of chronostratigraphic and archaeostratigraphic units and help assess whether the observations from this single study are more local or regional in nature. As previous studies have demonstrated, ASEM essentially provide a more accurate and empirical analysis of archaeological sediments, and a clear visual representation of mineral associations within these. Comparison with chronologically equivalent terrestrial shell-bearing midden sites and/or experimental work would also help clarify the conditions that preserve shell-matrix sites during inundation, and also the long and short-term the effects of marine inundation on cultural micromorphological features.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jas.2018.12.009.

References


