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A drowned Mesolithic shell midden complex at Hjarnø Vesterhoved, Denmark and its wider significance

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ABSTRACT

Anthropogenic shell accumulations (shell middens), often of great size, occur in their tens of thousands around the world's coastlines. They mostly date from the Mid-Holocene onwards and are frequently taken as symptomatic of a Postglacial 'revolution' involving world-wide population growth and intensification in exploitation of marine resources. However, the comparative rarity of earlier deposits may have as much to do with Postglacial sea-level rise and the loss of evidence from earlier palaeoshorelines as with genuine socio-economic trends. Here we investigate the underwater Mesolithic (Ertebølle) shell midden of Hjarnø Vesterhoved in Denmark, one of the first underwater shell middens to be systematically verified as an anthropogenic shell deposit in a region world-famous for its many hundreds of Ertebølle shell mounds on the present shoreline. We show how a combination of geophysical survey, coring, excavation, stratigraphic interpretation and macroscopic analysis of midden contents can be used to identify underwater deposits, to unravel their taphonomic and post-depositional history in relation to surrounding sediments, and to distinguish between cultural and natural agencies of shell accumulation and deformation. We demonstrate the presence of an intact underwater shell-midden deposit dated at 5400–5100 cal BC, one of the earliest in Denmark. We demonstrate the usefulness of such material in giving new information about early coastal subsistence economies and greater precision to the measurement of palaeo-sea levels. We discuss the implications of our results for an improved understanding of the Mesolithic record in Denmark and of biases in the archaeological record of Late Pleistocene and Early-to-Mid Holocene coastal contexts. We emphasise the importance of researching more fully the geomorphological and taphonomic processes that affect the accumulation, destruction, burial, preservation and visibility of underwater archaeological deposits, the need to extend underwater investigations more widely and to more deeply submerged palaeoshorelines, and the combination of methods required to advance such investigations.

1. Introduction

Shell middens, deposits dominated by discarded food shells (mostly marine molluscs) as the main physical constituents by volume, also commonly referred to as shell-matrix sites (Claassen 1998), are a well-known and world-wide cultural phenomenon. Tens of thousands of such sites are known from around the world's coastlines. Many form massive mounds extending over hundreds of square metres, and some reach a thickness of many metres. The great majority of these sites appear from the Mid-Holocene onwards, from about 7000 to 6000 cal BP (5000–4000 cal BC). Since these dates coincide with the time when sea level stabilised after

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Postglacial sea-level rise, they could equally well reflect the increased visibility of shorelines and shell middens rather than a world-wide intensification in the use of coastal and marine resources. Since sea level was lower than present for most of the Last Glacial cycle (Grant et al., 2014; Lambeck et al., 2014), the question arises as to whether we are missing a whole class of earlier coastal sites from the Late Pleistocene and Early Holocene archaeological record because they have been destroyed by marine erosion during sea-level rise or await discovery on now-submerged palaeoshorelines.

Until recently, further investigation of these possibilities has been deterred by two assumptions. The first is the belief that sufficient is known from caves on the coastlines of southern Europe, Africa, Indonesia and Australia about the deeper history of shell-gathering and exploitation of other marine resources to obviate the need for underwater investigations (Bailey and Flemming 2008; (Klein and Bird, 2016); Will et al., 2015). The second is the belief that shell middens would have been washed away by the potentially destructive impact of wave action and water currents during sea-level rise, or so disturbed and degraded as to be impossible to distinguish from marine sediments and natural death assemblages of shells accumulated on the seabed (Andersen 2013; Nutley 2014). However, recent developments in the archaeology of submerged landscapes have led to renewed interest in these questions and renewed optimism about the prospects for discovering underwater sites (Bailey et al. 2017, 2020a; Benjamin et al., 2011; Evans et al., 2014; Flemming et al., 2017).

Denmark is especially appropriate as a regional 'laboratory' for developing this line of investigation, with one of the largest concentrations of mounded shell middens in Europe, famous for their contribution to the definition of the European Mesolithic and the origin of the term 'Kitchen Midden' or *Kjøkkenmødding* (Andersen 2000, 2007; Larsson 1990; Price 1991). Denmark also hosts one of the largest concentrations of underwater Stone Age finds in the world (Andersen 2007; Bailey et al., 2020b; Fischer and Pedersen 2018).

Our aims in this paper are to present the results of recent investigations at the underwater Ertebølle shell midden of Hjarnø Vesterhoved (Hjarnø II). First, we outline the significance of shell middens as sources of cultural information and the inadequacy of current information about the Late Pleistocene/Early Holocene coastal record. We then set out the context for shell mound studies and underwater investigations in Denmark, present details of the depositional context, contents and chronology of the Hjarnø Vesterhoved shell deposit, with emphasis on the evidence that differentiates the deposit as an *in situ* midden from natural shell assemblages or disturbed and mixed deposits, and consider its wider significance and the prospects for future discoveries of underwater shell middens.

1.1. The global record of shell middens and their significance

Shell middens have figured prominently in the history of archaeology for over 150 years and attracted interest for a variety of reasons. The shells themselves provide evidence for the exploitation of marine resources, while the shell deposits create a favourable matrix for the preservation and quantification of artefacts and other food remains including bones of terrestrial and marine vertebrates. Shell middens have high rates of accumulation and can provide well-resolved stratigraphic sequences; they are often associated with secondary features such as human burial and the use of shell debris to create features such as pits, mounds, floors and barriers; they can be used as markers of past shorelines and sea-level positions; and they may have acted as prominent physical features of potential symbolic significance in the cultural landscape of their creators. The largest concentrations, the largest mounds and some of the best-studied sites are associated, with few exceptions, with shallow bays or river estuaries and extensive intertidal zones that supported large supplies of molluscs. Classic examples are the Ertebølle 'kitchen middens' of Denmark and the shell mounds of Portugal, northern France and Scotland, the *sambaquis* of Brazil, the *Anadara* mounds of northern Australia, the 'mega-middens' of South Africa, and the mounds of Jōmon Japan, San Francisco Bay, the Gulf of Florida, Senegal and the Farasan Islands. Most of the largest concentrations of mounds are dominated by bivalves such as oysters, clams, mussels and cockles, occasionally by gastropods as in the Farasan Islands (Bailey and Parkington 1988; Bailey et al., 2013; Bailey and Hardy 2021; Balbo et al., 2011; Erlandson and Fitzpatrick 2006; Erlandson and Jones 2002; Fitzpatrick et al., 2015; Gutierrez-Zugasti et al., 2016; Hall and McNiven 1999; Jerardino 2012; Milner et al., 2007; Roksandic et al., 2014; Thompson and Worth 2011).

Marine molluscs were certainly on the menu for much longer, long before global sea levels stabilised near current levels, back to at least 160,000 years ago, and shell middens or shell-bearing deposits (deposits with shells but not as a dominant constituent) are known from many Late Pleistocene or Early Holocene contexts (Jerardino 2016; Klein and Bird, 2016; Lambeck et al., 2014; Marean 2010; Will et al., 2015). Most belong to periods when sea level was far lower than today and shorelines more distant, but a small number of deposits in the South African caves are associated with the high sea levels of MIS 5. However, these earlier sites are relatively few or contain quite small quantities of shell. Most are in coastal caves or rockshelters on rocky coastlines in southern Europe, Africa, Australia and SE Asia, but include rare open-air deposits. The quantities of shells from all these sites amount in total to tens or hundreds of thousands at most, compared with the billions of shells in Mid- and Late-Holocene shell mounds. Moreover, these early-dated shell deposits were protected from sea-level rise because of locations some kilometres inland from the contemporaneous coastline, or at the top of steep slopes above shorelines that remained nearby even at low sea levels (Bailey and Craighead 2003; Erlandson et al., 1999; Gosden and Robertson 1991; Henshilwood et al., 2001; Kealy et al., 2020; Klein and Bird, 2016; McDonald and Berry, 2016; Sugihara and Serizawa, 1957; Veth et al., 2017). Some of these cave sequences show a progressive increase in shell quantities at the Pleistocene-Holocene boundary as sea level rose towards the present. But it has proved difficult to identify whether this is simply due to progressive reduction of distance to the shoreline, implying the existence of underwater shell middens nearer the shore, to intensification or to environmental change (Bailey and Craighead 2003; Gutierrez-Zugasti et al., 2011).

These earlier examples are what Hausmann et al. (2019) describe as 'post-shore' shell deposits — sites located tens of metres to kilometres inland for optimal access to shelter, fresh water supplies or terrestrial resources. Their study, drawing on a sample of 3000 shell middens on the Farasan Islands, compared contemporaneous post-shore and shoreline middens and demonstrated that the post-shore sites were smaller and the shell quantities far fewer than in the numerous shell mounds on the shoreline where the great majority of the molluscs were processed. This pattern is consistent with ethnographic descriptions and cost-benefit analyses showing that people prefer to conduct bulk processing of molluscs as close as possible to the shoreline because of the high ratio of shell to meat and the labour cost of transport in the shell, but may also carry some unprocessed shells in smaller quantities over greater distances to inland sites chosen because of other attractions or needs (Bird and Bliege Bird 1997; Lasiak 1992; Metcalfe and Barlow, 1992; Parkington et al., 2021). The meat of the molluscs may also be dried and carried far inland, but the shells that are evidence of that practice are obviously left behind on the shoreline (Hardy et al., 2016; Henshilwood et al., 1994). Since the largest shell mounds on shorelines are usually associated with shallow offshore and onshore topography, they would be the first to be destroyed or submerged by rising sea level (Bailey and Flemming 2008, pp. 2155–2156).

It is likely, then, that the known Late Pleistocene and Early Holocene shell middens are not only a very small fraction of the original total, but that they are also systematically biased to specific types of coastlines that exclude the full range of molluscan habitats and inhabited coastlines, especially those that generate the largest quantities of edible molluscs.

1.2. *The regional context*

Denmark has undergone major reconfigurations of land and sea during the Holocene because of a complex interplay between global eustatic sea-level rise and ongoing glacio-isostatic adjustment, and the inner coastal fjords and bays of Denmark did not begin to take their present form as a marine environment until the onset of the Littorina transgression between about 7800 and 6400 cal BC, when a fully marine connection was established between the North Sea and the Baltic (Astrup 2018; Bailey et al., 2020b; Jöns et al., 2020; Rosentau et al., 2017). In northern Denmark (the north of the Jutland Peninsula, and the northern coastlines of the Danish Islands), shorelines have been isostatically uplifted in recent millennia by as much as 12 m or more, whereas southern Danish shorelines have undergone progressive submergence by a comparable amount (Fig. 1). As a result, all the coastal shell mounds are in the north on shorelines at or above the present shoreline, and most of the underwater finds are in the south. Hjarnø is located close to the transition between uplift and submergence, marked by the 0 m contour on the inset map of Denmark in Fig. 1.

The shell mounds in northern Denmark number over 500 (Andersen 2007). They are of varying size, the largest being over 300 m long, and up to 40 m wide and 8000 m^3 in volume (Andersen 2000, 2007). The earliest date from 5600 cal BC and the largest are concentrated in the period 4600–4400 cal BC in association with the middle and late phases of the Ertebølle culture. European oysters (*Ostrea edulis*) are the dominant mollusc. Many shell mounds are considered to be residential settlements, with a wide range of artefact types made of flint, bone and antler, a variety of faunal remains including terrestrial and marine vertebrates and an emphasis on fish as a dominant resource, evidence of the *in situ* knapping of flint artefacts, and features such as pits and hearths. Some of the smaller middens were specialist sites for the hunting of wildfowl or marine mammals, or specialised shell dumps used for the initial processing of molluscs, while the smallest are thin scatters of shells a few metres in diameter and have been compared to the dinner-time camps noted in Australian ethnographies (Meehan, 1982; Andersen 2000, p. 375). Some shell middens continued in use into the Early Neolithic period with evidence of a regional shift to cockles (*Cerastoderma edule*) as the dominant mollusc and a decline in oysters, most probably because of environmental changes (Lewis et al., 2016), and a change in function in some cases to use primarily as processing sites for the removal and discard of the shells. All shell mounds of the Ertebølle and Early Neolithic period are shoreline sites including the largest mounds. Later shell middens are generally small and include post-shore locations up to 2 km inland at sites based on agriculture.

In Denmark's underwater record, at least 1699 find spots have been recorded (Bailey et al., 2020b, p. 47), but most are single artefacts or collections of material that may have been disturbed or redeposited. Relatively few have received systematic sampling and excavation, notably the sites of Tybrind Vig, Ronæs Skov, Hjarnø Sund, Møllegabet II and Argus Bank, all within a depth range of 1–6 m below present sea level, easily accessible to excavation by divers (Andersen 1985, 2009, 2013; Astrup 2018; Astrup et al., 2020; Bailey et al., 2020b; Fischer 1995; Fischer and Pedersen 2018; Skaarup and Grøn 2004; Uldum et al., 2017). The dates of these excavated sites range from about 6000 to 4100 cal BC. Thus,

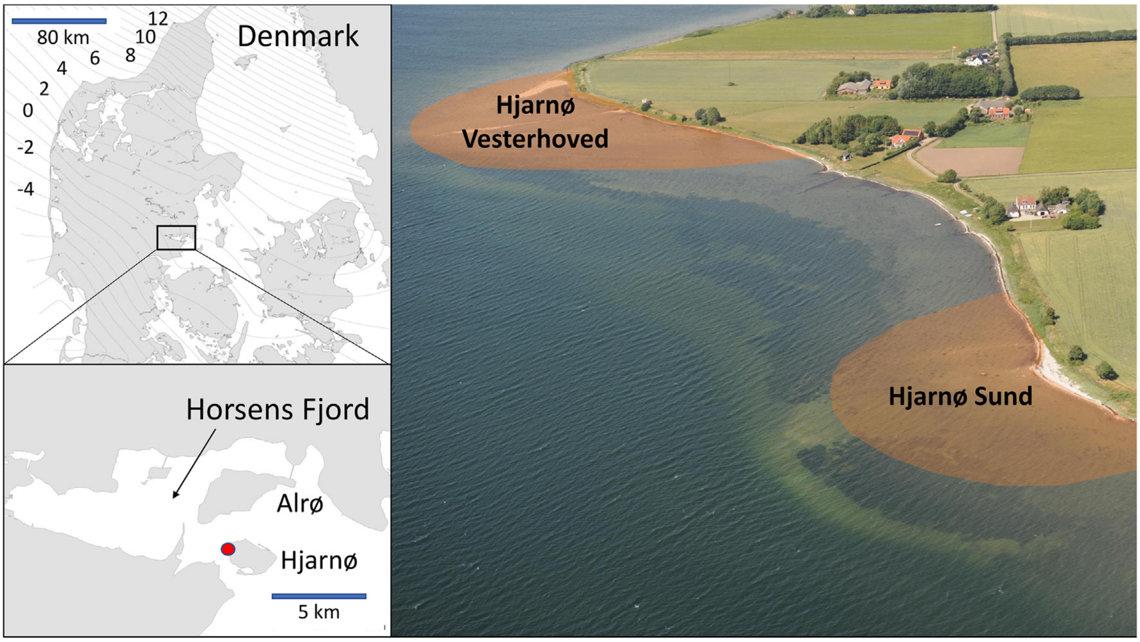

Fig. 1. Map showing the location of the Hjarnø sites in their wider regional context (the red dot on the inset map of Horsens Fjord) and in relation to the local shoreline configuration. The area labelled Hjarnø Sund shows where the Hjarnø I site is located and Hjarnø Vesterhoved refers to Hjarnø II. The inset map of Denmark shows the variation in isostatic uplift/subsidence (elevations in metres) that has occurred since the time when the Hjarnø sites were occupied. The Horsens Fjord is close to the boundary between northern Denmark, where shorelines have been uplifted above modern sea level, and southern Denmark where shorelines have subsided below modern sea level. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the date range of the best studied underwater material overlaps with the dates of the Ertebølle shell mounds in the north but extends further back in time. Even earlier underwater sites are known from more limited sampling of shorelines at greater depth below present sea level back to about 6400 cal BC, including remains of stationary fish weirs, indicating that marine resources were available and exploited from at least this early (Astrup 2018; Bailey et al., 2020b).

These underwater excavations demonstrate that the bulk of the *in situ* cultural material is not from the original area of settlement along the shore. Rather it represents refuse deposits comprising objects thrown away into the water after use, or artefacts originally used in the offshore zone and ultimately abandoned there, such as logboats and the wooden stakes of stationary fish weirs built out from the shore. The presence of soft gyttja sediments in these shallow-water zones ensured that material abandoned there was rapidly encased in anaerobic sediment, and this is the main reason why preservation is so good, including perishable materials such as plant-remains and wooden artefacts. Traces of settlement on the adjacent land surface have been disturbed or destroyed and are limited to stone artefacts and occasional features such as pits, graves and hearths that were either protected from marine erosion or covered quickly enough by marine sediment to resist further erosion. This pattern is typical for other underwater sites of the western Baltic in Germany and Sweden (Jöns et al., 2020; Nilsson et al., 2020).

Shells of oysters and other molluscs are present in some of the excavated underwater sites in Denmark, sometimes in small concentrations suggestive of midden deposits, but it has proved difficult to establish whether these are genuinely *in situ*, or redeposited remnants of anthropogenic middens which may have been much larger, or natural shell banks –death assemblages of shells accumulated on the seabed – or a mixture.

2. Material and methods

Hjarnø Vesterhoved is positioned on the north-west coast of the island of Hjarnø in Horsens Fjord, Denmark, *ca*. 400 m to the north of the site at Hjarnø Sund (Fig. 1). Both sites comprise submerged shell deposits partially buried under marine sediments that have begun to be exposed in recent decades by the disappearance of eel grass and erosion surface sediments that formerly provided a protective cover. Close to these sites are deposits of gyttja. Like the shell deposits, the gyttja appears to have been protected by overlying sediments until recent decades.

Hjarnø Vesterhoved has been known as a prospective site for many years, and while it has never been systematically investigated, it was formally registered by the Danish heritage agency (currently known as The Agency for Culture and Palaces) in 1982. Over a period of many years, local archaeologists have collected large numbers of flint and bone artefacts at low tide mostly eroding from the seabed at depths between *ca*. −0.5 and −1.5 m. The material has been recovered from an area of approximately 31,000 m^2, including a cluster of finds on the western and southern edge of a partly submerged spit or beach ridge, and extends from the western tip of this spit in a south-easterly direction all the way to the modern shoreline (Fig. 2). Most finds appear to be associated with marine deposits. Since the 1990s, the amount of material washed ashore appears to have increased.

These offshore deposits appear to represent a typical refuse area, an extensive distribution of materials discarded into shallow water at the shore edge from a major settlement area located along the shoreline, most of which, on the landward side, has been destroyed. The appearance of shell deposits in places suggesting the presence of a shell midden prompted new investigations, beginning with excavation at Hjarnø Sund in 2016 and experimental work with techniques of underwater investigation and the application of micromorphology (Astrup et al., 2020; Cook Hale et al., 2021; Skriver et al., 2018; Ward and Maksimenko 2019; Ward et al., 2019). Here we discuss the results of the investigations at Hjarnø Vesterhoved, which began in 2018.

2.1. Excavation

A total of five 1 × 1 m^2 trenches (T1–T5) were opened and excavated by divers (Fig. 2). The first trench, T1, was positioned in an area where gyttja was exposed on the seabed to determine whether the gyttja layer represented a refuse layer of cultural material. The remaining trenches (T2–T5) were all positioned 10–15 m south of the first trench on a north–south axis in the expectation of identifying a potential shell midden at the edge of the gyttja layer.

Excavation proceeded by removal of horizontal excavation units using a diver-operated induction dredge mounted on a floating platform (Fig. 3). All material was collected in a 4 mm mesh bag attached to the dredge exhaust and taken ashore, where it was sorted into mollusc shell, lithics, non-artefactual stone, fish bones, other vertebrate bones, and charcoal. Elevations were recorded with a Trimble RTK GPS (Real-Time Kinematic Global Positioning System) using local reference points. The stratigraphic layers were recorded by a combination of methods including simple profile drawings, 2D photography and 3D photogrammetric modelling (see Astrup et al., 2020; Benjamin et al., 2019). Samples for radiocarbon determinations were removed directly from the section wall of the trench to ensure their stratigraphic integrity.

2.2. Coring

In order to better understand the extent and composition of the geological and archaeological layers identified in excavation, a grid at 10-m intervals was established around the excavation trenches and coring was conducted at 23 locations using an Eijkelkamp steel corer with a diameter of 3.5 cm and a maximum depth penetration of 100 cm (Fig. 2). An RTK GPS was used to measure elevations and coordinates. The sediments in each core were described on-site as they were recovered using Munsell Soil Colour Charts and the Troels-Smith standard system for unconsolidated sediments (Troels-Smith 1955). Based on these on-site assessments and comparison with the stratigraphy of the excavation trenches, two master cores were selected for more detailed laboratory analysis of the sediments, 150/500 and 160/520.

2.3. Geophysical survey

Earlier Danish research has demonstrated the value of quite simple acoustic methods both as a survey technique for finding new sites and as a means of obtaining more detail about existing sites (Fischer 2004; Skaarup and Grøn 2004), and new and more sensitive techniques are under constant review (Grøn et al., 2018). In this study, high frequency geophysical instruments were mounted on or towed behind a 4-m boat to investigate the underwater topography and subsurface sediments over a wider area than could be sampled by excavation or coring. Two techniques were applied: sidescan sonar, to identify surface features and changes in the texture of surface sediments; and sub-bottom profiling, to identify variations in sub-surface deposits. The aim was to compare acoustic signals with known sedimentary features as identified from diver observations, cores and excavation trenches, and thus to assess the usefulness of geophysical techniques in the identification and investigation of shallow-water

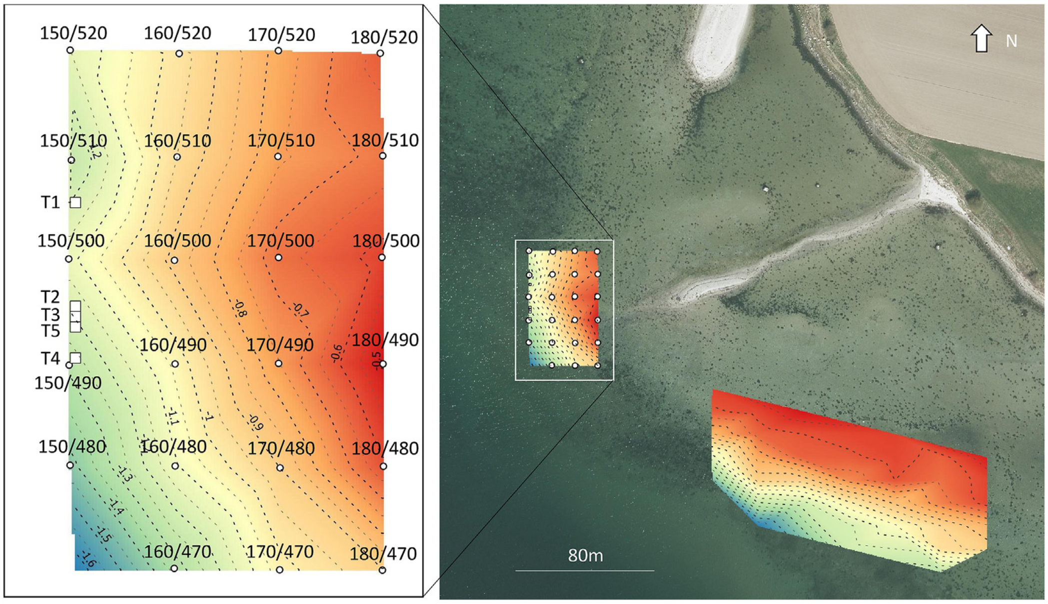

Fig. 2. Site plan showing the position of the excavation trenches, bathymetry and core locations from the 2018 investigation at Hjarnø Vesterhoved. The spit is visible as an irregular white ribbon extending from the modern shoreline towards the 2018 survey area and can also be seen in Fig. 1. The spit and those parts of the seabed at less than 0.5 m of water depth (shown in red) are exposed at low tide. Core locations are labelled with the last three digits of their UTM coordinates. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Fig. 3. Excavation of the shell midden in progress showing the use of the suction dredge. Photo: Jonathan Benjamin.

deposits including shell middens.

A sidescan sonar (Edgetech 4125 dual frequency system 600/1600 kHz) and sub-bottom profiler (Innomar SES 2000, (4 kHz/15 kHz) kHz) were used and integrated with an RTK GPS (Trimble R8) and a motion reference unit (MRU) (Seatex). All data were acquired and processed in the WGS 1984 UTM Zone 32 N coordinate system. Distance offsets on the boat between GPS equipment and laybacks to geophysical sensors were measured and recorded within the navigation software. Location accuracies integrated with the GPS were collected via the RTK unit through a virtual reference station (VRS). The MRU data were integrated with the sub-bottom profiler to counter any motion effects produced by wave activity. In addition, bathymetric data were collected with the fixed sub-bottom profiler, incorporating MRU, GPS and local tide measurements.

The sidescan sonar data were processed and later overlaid in both high and low frequency to ensure optimal coverage and the highest possible resolution. The sub-bottom data, along with the integrated GPS and MRU, were processed in two separate post-processing software programs, Innomar's ISE and Chesapeake Technology's Sonarwiz, to ensure data quality. The geophysical and bathymetric data were then exported from the post processing software and imported into a Geographical Information System (GIS) using ArcGIS.

2.4. Shell analysis

All molluscan material from the five trenches was retained for analysis and sorted taxonomically following the protocols outlined in Szabó (2009). Shells that are clearly modern intrusions were first identified and eliminated from further study, either because they are more recent introductions to the biotope, following Petersen (2004), and have burrowed or been washed into earlier deposits, or because of features such as remnants of fresh flesh or muscle still attached to the shell, or the presence of the periostracum (the proteinaceous layer that covers the external surface of many shells and rarely preserves in the archaeological record).

All the remaining material was identified using a combination of physical reference specimens collected by one of the authors (KW), in conjunction with online identification keys. Care was taken to avoid overidentification, with specimens only identified to a taxonomic level if they possessed features unique to that level (Driver 2011; Harris et al., 2015; Woo et al., 2016, p. 732). To ensure consistency, all nomenclature has been standardised using the World Register of Marine Species (WoRMs Editorial Board 2019).

More detailed analysis concentrated on Trench 3 because the shell layers are thickest in this trench. All shell material was examined for the nature and degree of fragmentation, evidence of surface wear, traces of burning and the presence of epizootic infestations such as barnacles on the shell surfaces. The presence of epizootic infestation is common on exterior shell surfaces, but when present on the inner surfaces of shells is usually evidence of molluscs that died of natural causes. Fragmentation in natural deposits usually results from disturbance by water action and shows up as evidence of rolling and wear on broken surfaces and, in cases of extreme disturbance by wave action, as a hash of tiny fragments. Shells in midden deposits are usually a mixture of whole and fragmented shells, resulting from food processing and physical damage while exposed on the surface of an occupied midden. Evidence of burning is a clear indicator that shells were originally collected as food and discarded on land, since burning of shells does not occur naturally under water. The taxonomic composition of the molluscs may also act to some extent as a discriminator between cultural and natural shell material.

For quantification of taxonomic composition, both Minimum Number of Individuals (MNI) and Number of Identified Specimens (NISP) were used. MNI values were calculated using protocols outlined in Harris et al. (2015). The umbo was used as the NRE (Non-Repeating Element) for bivalves, while the NREs for gastropods included the apex, aperture, and the body whorl. To avoid potential inflations of counts through the subdivision of aggregates (Grayson 1984), a single NRE was selected for each taxon. NREs were selected following the sorting process, with the most frequently occurring NRE used to calculate MNI values.

Three ecological diversity measures were used to examine the richness and diversity of the assemblages: Number of Taxa or NTAXA for richness, and Simpson's Index of Diversity (D) and Shannon's Evenness (H') to measure heterogeneity. All measures were calculated using the Paleontological Statistics package PAST, version 3.26 (Hammer et al., 2001).

2.5. Vertebrate and lithic analysis

Preliminary examinations were conducted on all vertebrate remains recovered during excavation. Remains were subsequently sorted taxonomically and identified using physical reference collections housed at Moesgaard Museum and Museumsinsel Schloss Gottorf. Vertebrate remain were quantified using NISP. Vertebrate remains were also examined for signs of burning/heating, use wear and cut marks. Lithics, predominantly worked flints, were classified according to the standard technological and typological criteria applied to Danish Mesolithic assemblages (Vang Petersen 2014). Flints were also examined for evidence of rolling or edge damage that might indicate post-depositional disturbance by marine erosion. Qualitative assessments of surface patination were also carried out on the principle that unpatinated flints indicate rapid burial and lack of subsequent disturbance, whereas patination indicates prolonged exposure on a subaerial surface.

3. Results

3.1. Midden stratigraphy and composition

All material was provenanced with reference to depth below mean sea level (MSL). The deposits were not always clearly visible during excavation and some of the excavation units cut across several different layers as recognized subsequently (Figs. 4 and 5).

Trench 1 (T1) revealed a stratigraphy that mainly consists of homogeneous brown gyttja (L2) mixed with sand and organic plant fragments from −1.20 m to −1.55 m MSL. Below this layer, at a depth from −1.55 m to −1.70 m MSL, the material mainly consists of brown sand mixed with organic plant material (L3). The excavation in T1 stopped at −1.70 m MSL and no traces of clay material representing the natural subsoil were identified at this depth. All layers in T1 seem to have been accumulated in water under calm conditions, indicating a protected shallow bay or lagoon.

The layer with brown gyttja (L2) was also present in T2, T3 and T5. Here it was found to contain charcoal and patinated and unpatinated flint and pebbles, but only a few shell fragments. A thin layer (L9) of greyish gyttja with sand, gravel and charcoal was found on top of the gyttja layer in T2, T3 and T5. A compact layer (L11) of marine molluscs, sand and archaeological objects (e.g., vertebrate faunal remains, charcoal and worked lithics/flint tools) was recognized on top of the greyish gyttja layer of L9 (Fig. 6). Above this layer is yet another shell layer (L4) in which the shells are much more mixed and fragmented compared to those below. In T2, L8 is a mix of gyttja and shell fragments. The content of organic material suggests that this layer has been formed by re-deposition of material from L4 and L11 in a marine setting. Finally, a thin layer of greyish gyttja with sand/gravel and charcoal as well as unpatinated flint (L7) covered all these layers in T2, T3 and T5.

T4 is located 2 m south of T5. Down to −1.46 m MSL, the sediments consist of a mix of gravel and greyish sand with large amounts of worked flints, but no organic material. From −1.46 to −1.62 m MSL, the material consists of clean sand (without gravel/pebbles). From −1.62 m MSL some poorly visible layers or lenses of brown organic matter could be seen in the sand (L3). Given that organic material is completely absent in Layer 13 in T4, we interpret this as evidence of a former subaerial beach ridge that was forming at the same time as the Ertebølle cultural occupation, and which represents a continuation further out to sea of the modern spit visible in Figs. 1 and 2. The shell deposits and other cultural material are located on the northern side of this ridge and may originally have extended over a larger area of the ridge.

We interpret the position of the shell midden above a layer of gyttja as the remains of activities caried out on the very shore edge and accumulated on a surface that had previously been shallow water but had largely dried out. This could have come about either because of a minor change in relative sea level or because accumulation of other materials − sand, gravel, shells and discarded artefacts as recorded in Layer 9 (Fig. 6) − had created a dry surface sufficiently above the contemporaneous water level to be suitable to live on. Sites in similar locations on the edge of spits close to shallow water have been recorded at other Danish underwater sites, but without evidence of shell-midden deposits, notably at Tybrind Vig (Andersen 2013, Fig. 1.6).

3.2. Cores

The two master cores confirm that the greenish clay sediments that were seen around the site and under the gyttja represent a culturally sterile basement of glacial clay. Core 160/520 was taken in the intertidal area at −0.98 m MSL where this greenish clay was observed immediately below the seabed surface layers (Fig. 7;

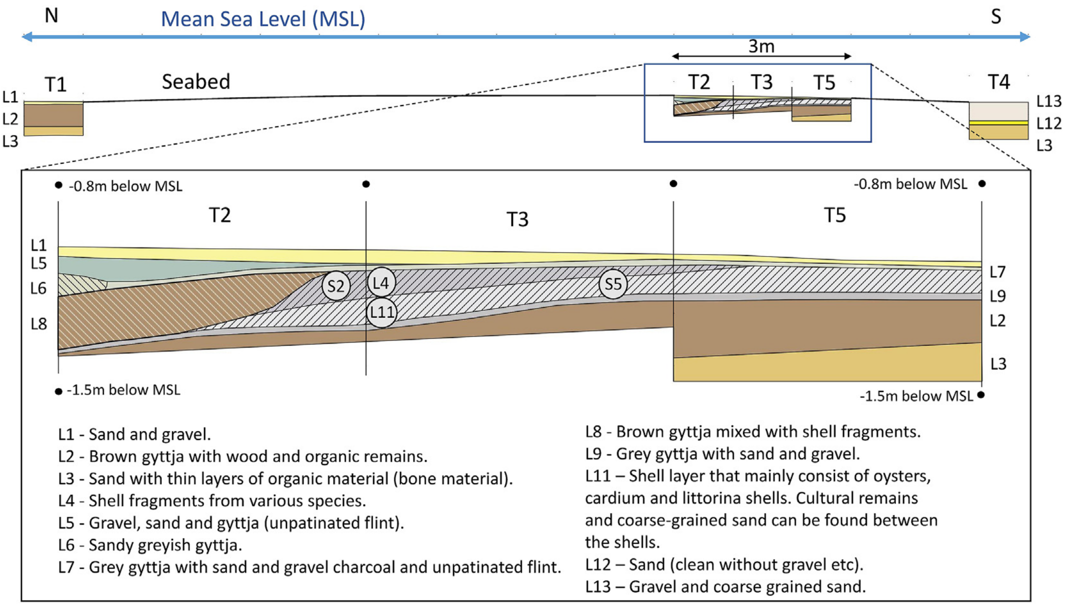

Fig. 4. Stratigraphy of layers in Trenches 1–5. S2 and S5 refer to shell samples that were taken directly from the section for radiocarbon dating (Table 2). See Fig. 2 for location of trenches.

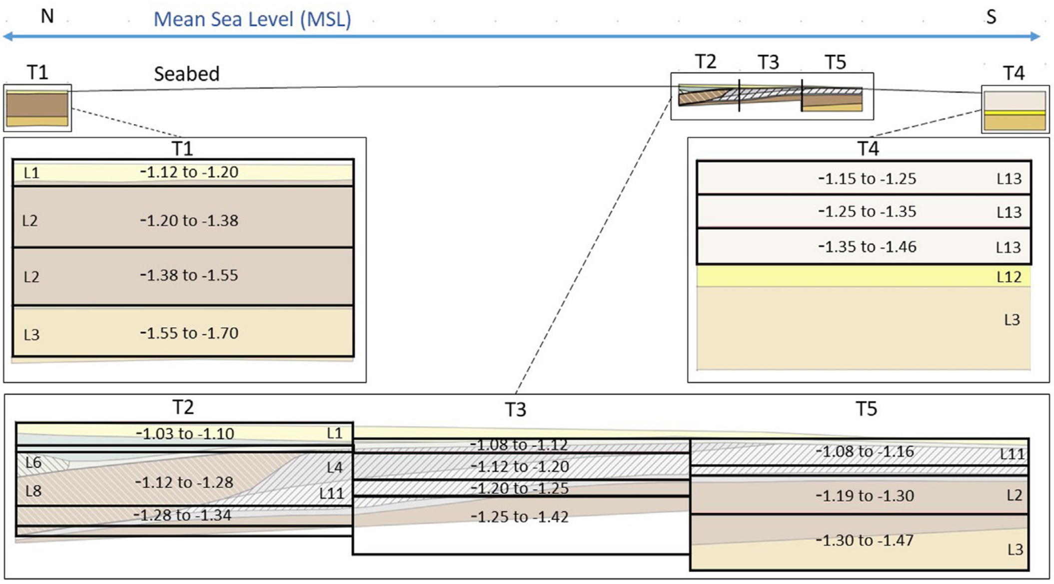

Fig. 5. Correspondence between excavated units and layers in T1–T5. The depth measurements for the excavated units are based on the average of four measurements at the top and bottom of each unit. In some cases, the excavation units cut across more than one layer.

Table 1). This glacial clay deposit has been identified in 14 of the 23 cores, which means that in the remaining 9 cores there is more than 1 m thickness of sediments (often with cultural material) between the modern surface of the seabed and the underlying glacial clay, with the thinnest layer of these post-glacial sediments in the north-eastern part of the site.

The other master core 150/500 was also taken in the intertidal area at −1.15 m MSL (Fig. 7, Table 1). The core was 87 cm long and the sediments contained lithics as well as charcoal fragments, pieces of wood, plant microfossils and molluscs. The stratigraphic composition indicates thick and undisturbed cultural layers in the main body of the core. The surface of the core (0–3 cm) comprised gravel, followed by a layer of dark, sandy gyttja (3–22 cm) filled with recent marine molluscs. Below that, there was a thick layer of gyttja with much reduced sand content and with lithics and visible traces of waterlogged wood (22–79 cm). At the base the sediments were loose and sandy.

The cores have shown that the brown gyttja layer is present in a large area north-east of the five excavation squares. The layer varies in thickness. It is thickest to the west where the water is deepest and thins out to the east either because of erosion or proximity to the former shoreline. The gyttja must have been deposited in calm waters and is not found forming on the exposed present-day coasts, where wave action deposits sand and forms beach ridges instead. The gyttja deposits therefore reveal a coastal morphology very different from that of today. This gyttja deposit is present only

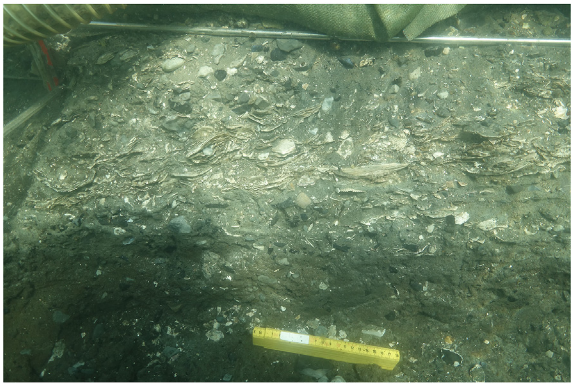

Fig. 6. Close up of the section in Trench 3, showing the contact between the shell deposit of Layer 11 and the dark-coloured underlying gyttja layer (Layer 9). A line of cockles is visible at the base of the shell layer. Artefacts are visible both in the shell layer and in the gyttja deposit.

north of T4. The massive layer of gravel observed in T4 is believed to represent a beach ridge that was forming at the same time as the Ertebølle cultural occupation, and which represents a continuation further out to sea of the modern spit. This beach ridge would have provided a protective barrier and facilitated calm shallow waters suitable for the accumulation of gyttja north of T4. The area south of the beach ridge system merely consists of marine sand with shell fragments and organic material situated on top of glacial clay.

The protective sand barriers including the beach ridge in T4 were not permanent features, and the core samples revealed thick sand layers interleaved with the gyttja, showing that it had been inundated on several occasions and perhaps also partially eroded by the sea. Several thinner sand layers are presumably the result of brief transgressions caused by local storms or tidal surges. The position of the excavated shell layers shows that they formed at the very the edge of shallow water and consequently some of the shells became embedded in the gyttja layers.

3.3. *Geophysical results*

The geophysical operations were split into two phases: 1) sidescan sonar data collection; and 2) sub-bottom and bathymetric data collection. The data collection and interpretation were divided by process and then integrated to study the environmental context of the archaeological materials and surrounding palaeolandscape.

In water depths of <0.5 m, distortion was observed in the outer beams of the sidescan images. This made it difficult to identify features near the excavation site and further east. In deeper waters, ≥1 m, the sidescan was effective in identifying distinct sediment textures, including transitions from sands to gyttja. However, differentiating between small pebbles and shells was not achievable, since these two types of material are similar in size and hardness and return similar acoustic signals. In addition, observation by divers showed that scattered shell and gravel were intermixed with softer sediments. This intermixed material was found to attenuate the return signal, compromising the identification of any potential shell deposits.

The high frequency parametric sub-bottom equipment was deployed along track lines that extended through the area of the excavation trenches and the core locations, and beyond (Fig. 8). The seismic profile on the NW–SE transect passes a few metres west of the excavation trenches, and the NE–SW passes through the area of Trench 1. Comparison with known deposits identified in the cores

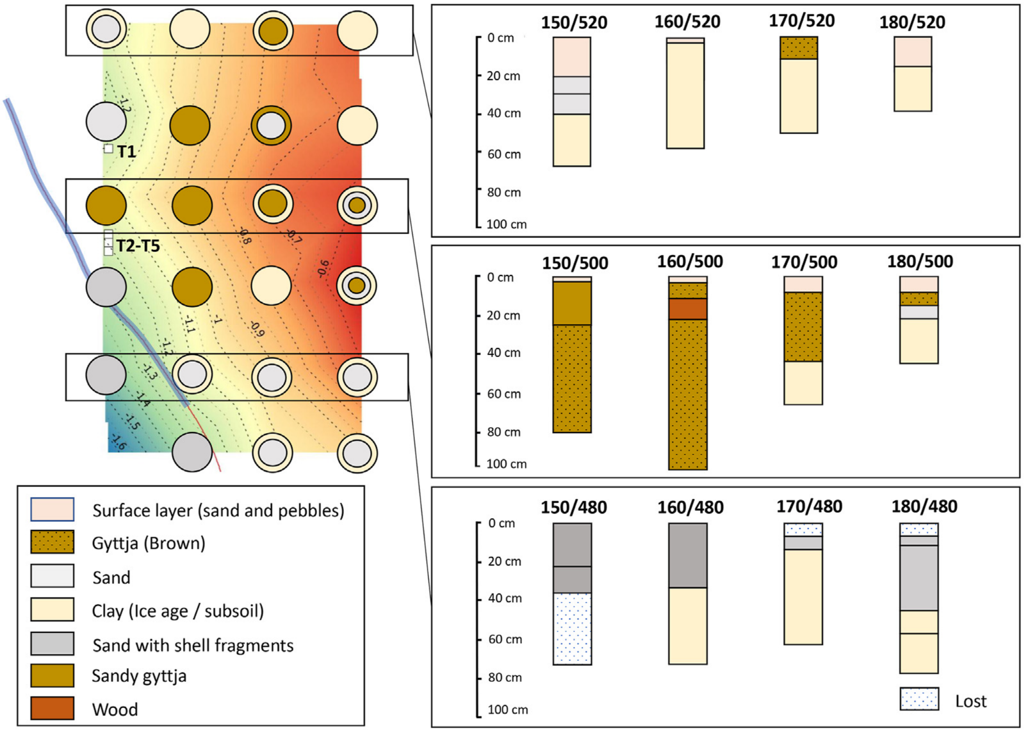

Fig. 7. Interpretation of cores, showing their location in relation to the excavation trenches and the sequence of deposits recorded within them. Top left, the location of the cores in relation to the excavation trenches with a simplified coding of the dominant deposits in each core. Bottom left, legend for the colour codes. To the right, the more detailed stratigraphy of selected cores in three transects. Cores 160/520 and 150/500 are the master cores selected for more detailed analysis and detailed descriptions of sediments (see Table 1). The blue line marks the track line of the sub-bottom profile (see Fig. 9). Core 150/490 is immediately next to Trench 4 and both are close to the blue line (Fig. 2). The sequence of deposits is shown in simplified form here and in more detail in Fig. 3. Both the core and the trench indicate sand as the dominant deposit at this location. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Description of changes in sediment composition in master cores 160/520 and 150/520, using the Munsell soil colour chart (Munsell Colour Co. 1992) and the Troels-Smith standard system for describing unconsolidated sediments (Troels-Smith 1955). The Troels-Smith system uses abbreviations in Latin to describe sediment characteristics: Darkness (Nig.); Stratification (Strf.); Elasticity (Elas.); Dryness (Sicc.); and Contact (Lim.). Sediment components are: Clay (As); Fine sand (Ga); Coarse sand (Gs); and Herbaceous peat (Th). Both the characteristics and components are estimated on a scale of 0–4. The Finds column refers to the presence of cultural materials, mostly worked flint, and the depths within the core where they were found.

Interval (cm)	Description	Munsell	Characteristics					Components	Finds (cm)
			Nig.	Strf.	Elas.	Sicc.	Lim.		
Core 160/520									
0–40	Greenish clay	GLEY 1 5/10Y	1	1	0	2	0	As3 Gs1	–
Core 150/500									
0–3	Rock	–	–	–	–	–	–	–	–
3–22	Sandy Gyttja	7.5 YR 2.5/1 black	4	1	1	1	1	Th2 As1 Ga1	–
22–79	Gyttja	5Y 2.5/1 black	4	1	3	1	1	Th3 As1 Ga+	23–24 24–25 32–33 35–36 38–39 39–40 46–47 47–48 48–49
79–87	Contaminated	7.5 YR 2.5/1 black	5	1	1	1	–	Th3 As1 Ga+	–

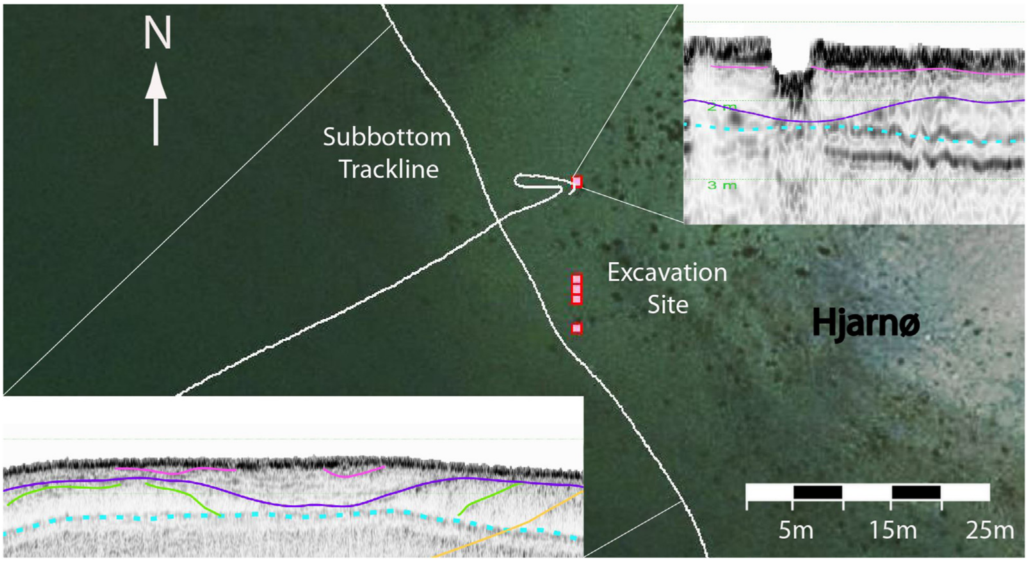

Fig. 8. Map of sub-bottom track lines, showing their relationship to the excavation trenches and the position of two detailed profiles, shown as insets. For enlarged versions of the profiles and explanations of the features, see Figs. 9 and 10.

shows that the geophysical signals were able to distinguish between gyttja, sand, and layers consisting of shell or gravel, although they could not reliably distinguish shell from gravel. At shallow depths of <0.5 m, signal noise obscured the interpretation of features, so that it was not possible to directly compare the features in the seismic profile with the layers identified in the excavation. Increased signal noise also made interpretation more difficult at depths greater than about 2 m. The resolution of these profiles, then, cannot provide the same level of detail as the examination of deposits in the cores or in the excavation trenches, and their interpretation depends on direct observations of these deposits to help calibrate the sedimentary significance of the acoustic signals. The main advantage of the seismic profiles is that they were able to reach to greater depth than the cores or the excavation trenches and to track changes in sub-surface features over a larger area.

The principal feature visible in both profiles is reflectors that we interpret as the upper and lower boundary of a basin-shaped or

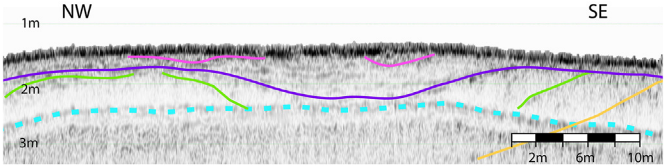

Fig. 9. Sub-bottom profile on the NW–SE transect with interpretation of features. The depth scale is in metres below Mean Sea Level. The thick black line at the surface indicates the zone within which detail is obscured by the first return of the acoustic signal after hitting the seafloor. Coloured lines represent reflectors indicating changes in the sub-surface sediments. These are interpreted as follows: Pink, change from coarse sediments to gyttja, detail above the gyttja is obscured but may include shell deposits at the SE end; Purple, base of shallow channel marking lower boundary of gyttja; Green and Yellow, continuation of channel to greater depth but marked by different types of sediment infill, possibly re-worked sediments. The dotted blue line is the seabed multiple, the depth at which the acoustic energy bounces between the seabed and the sea surface, and therefore the limit below which the acoustic signals become difficult to interpret with confidence. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

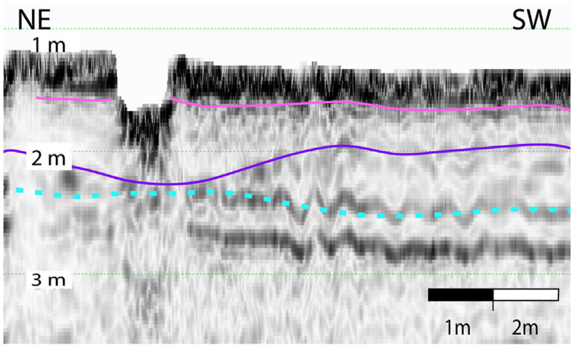

Fig. 10. Sub-bottom profile on the NE–SW transect. Note the cut at the surface, which is Trench 1. Trench 1 shows sand at the base of the section between −1.55 and −1.70 m MSL (Fig. 5). The signal noise at the base of the trench makes it difficult to interpret the relationship between this sand deposit and the surrounding features in the sub-bottom profile or to be confident that the pink line is a consistent marker for the upper boundary of gyttja sediments. Interpretation of other coloured lines as for Fig. 9. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

channel-shaped deposit of gyttja (Figs. 9 and 10). The upper boundary (shown in pink) marks the transition from coarse material (shell or sand) to gyttja sediment, and the lower boundary (shown in purple) marks a transition to a different type of deposit that we interpret as re-worked gyttja. The maximum thickness of the gyttja deposit observed in the profiles is about 1 m, and the deposit thins out towards the shell midden deposit and the palaeoshoreline. The same feature in its wider context can be seen in the 3-D image showing the intersection of the two profiles (Fig. 11).

3.4. Chronology

Three radiocarbon dates on shell material give dates ranging between 5471 and 5080 cal BC for L4 and L11 (Table 2). In terms of the Danish cultural chronology, this represents the early stage of the Ertebølle period. However, Ertebølle ceramic sherds, which represent a late phase of the culture, have been found in other parts of the Hjarnø Vesterhoved area. This demonstrates that the wider area around the spit was occupied if not continuously, then at least repeatedly, throughout most of the Ertebølle culture. The dates on the shell layers from Hjarnø Vesterhoved are contemporaneous with the shell midden from Hjarnø Sund (Astrup et al., 2020).

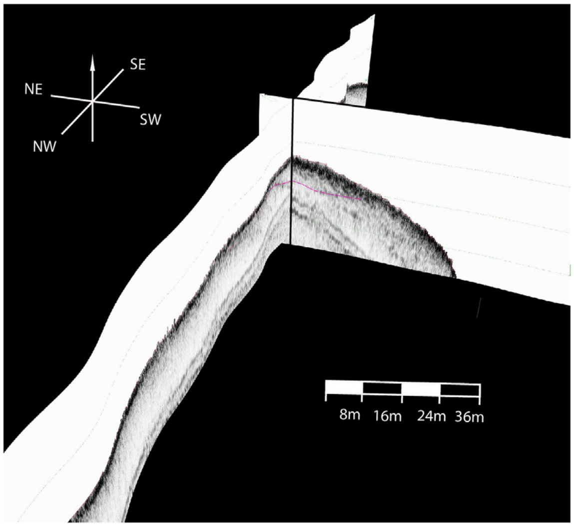

Fig. 11. Three-dimensional view of the two sub-bottom profiles shown in Figs. 9 and 10. This figure shows the point where the two profiles intersect and illustrates the consistency of the two profiles and the correlation between them. The feature shown by the purple line and interpreted as the base of a channel filled with gyttja lines up in the two profiles. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.5. Artefacts and vertebrate fauna

In T1, 250 pieces of flint debitage were found together with 6 blades and 2 cores (Table 3). Much of this material was patinated and found in the uppermost part of the trench and might therefore have been redeposited from elsewhere. In T2, T3 and T5 a total of 1125 pieces of flint debitage were found together with 8 transverse arrowheads and 21 blades. Most of this material came from the two shell layers (L11 and L4) and most are unpatinated, which means they are likely *in situ*. The transverse arrowheads are diagnostic of the Ertebølle culture. T4 also contained large quantities of worked flint (267 pieces of flint debris; 5 blades and 1 flake axe). However, the flint from T4 is patinated, indicating that it was exposed on a sub-aerial surface over long periods of time. Therefore, it seems plausible that it was re-deposited from the former beach ridge. This is also suggested by the fact that the material in T4 mainly consists of a gravel layer that is likely to have been formed by wave action. It is a characteristic feature of deposits that were formed in a high-energy environment that light sediments and very small objects are removed, leaving behind only the heavier material. This interpretation is supported by the very low content of fine-grained sediments/sand and the average weight of the flint specimens, which is 10 g in T4 compared to 4.4 g in T1, 5.9 g in T2 and 5.2 g in T3.

The vertebrate faunal assemblage consists of 2167 individuals (NISP) and 23 taxa (Table 4). The majority are from the shell deposits. They include a variety of marine and terrestrial taxa and conform to what has been identified from terrestrial Ertebølle shell middens of later date, especially the settlements, and from other underwater excavations. These show evidence for hunting of land mammals such as red deer (*Cervus elaphus*) and wild boar (*Sus scrofa*), marine mammals such as seal (*Halichoerus grypus*), porpoise (*Phocaena phocaena*) and dolphin (*Tursiops truncatus*), fishing especially for cod (*Gadus morhua*) and eels (Anguilla anguilla), and fowling. The proportions of these different types of resources vary according to the particular location, but fish are almost always represented in large numbers.

All these categories of animals are represented in the Hjarnø faunal list, though some only in small numbers. Sea mammals appear to be least well represented with only two identifiable bones, followed by birds (5 identifiable bones and 27 unidentifiable) and terrestrial mammals (24 identifiable bones and 141 unidentifiable, of which most are probably terrestrial). Fish bones dominate with 1253 identifiable to genus or species and 727 unidentifiable fish bones, and the identifiable remains are dominated by cod (*Gadus morhua*) and flounder (Pleuronectidae). This is consistent with the evidence for an emphasis on fishing in the settlements of the later Ertebølle period. The fish bones were found primarily in T2, Ts and T5 with large concentrations in Layer 11 (Table 3). Minimal amounts were found in trenches T1 and T4, with only 37 fish bones.

As with the fish bone, remains from terrestrial taxa were concentrated in the shell layers, with the largest assemblages in trenches T2, T3 and T5. The large concentration of bone in the shell layers, with a comparable range of taxa to what is found in on-land shell middens, together with evidence of burning on 45 bones, further supports the argument that the Hjarnø Vesterhoved shell

Table 2
Radiocarbon dates from Hjarnø Vesterhoved (Hjarnø II). All samples have been corrected for the marine reservoir effect by subtracting 369 years from the radiocarbon age. The reservoir age of 369 years for Hjarnø has been estimated by Larsen et al. (2018) on the basis of samples from the Hjarnø Sund site. Dates have been calibrated using the terrestrial calibration curve IntCal20 in OxCal version 4.3. For further detail on the depth and provenance of the samples see Fig. 3.

Lab code	Sample name	Material	Radiocarbon Age BP	Reservoir corrected Age BP	Calibrated date BC 95.4% probability
SUERC-85824 (GU50776)	Sample 2 Layer 4.	*Ostrea edulis*	6745 ± 30	6376 ± 30	5471–5224
SUERC-85825 (GU50777)	Sample 5 Layer 11	*Ostrea edulis*	6659 ± 30	6290 ± 30	5324–5210
SUERC-85826 (GU50778)	Sample 5 Layer 11	*Ostrea edulis*	6635 ± 30	6266 ± 30	5316–5080

Table 3
Chart showing the stratigraphic distribution of artefacts, fish bone, other vertebrate bone, bone artefacts and charcoal by trench. Provenance shows excavation unit including data on unit thickness, layer, and principal type of deposit. Abbreviations: Trans arrow, Transverse arrowhead; Decor. Bone, Decorated bone.

Trench No.	Elevation	Thickness	Layer	Deposit	Flint debris	Flint debris	Artefacts	Charcoal	Fish bone	Other Bone	All Bone
	m MSL	Cm			N	g	N	g	N	N	G
T1	−1.12 to −1.20	8	L1	Sand/Gravel	104	357	3 Blades	0	0	0	0
	−1.20 to −1.38	18	L2	Gyttja	107	501	6 Blades	31	39	17	42
	−1.38 to −1.55	17	L2	Gyttja	35	178	1 Core	0	0	0	0
	−1.55 to −1.70	15	L3	Sand	4	80	1 Core	0	0	0	0
SUM T1		**58**			**250**	**1116**	**11**	**31**	**39**	**17**	**42**
T 2	−1.03 to −1.10	7	L1, L5	Sand/Gravel/Gyttja	65	475	0	14	130	17	20
	−1.10 to −1.12	2	L5, L7	Gyttja/Sand/Gravel	48	426	1 Trans arrow	10	314	17	15
	−1.12 to −1.28	16	L4, L6, L7, L8, L11	Shell, Gyttja	87	434	2 Blades	23	82	17	13
	−1.28 to −1.34	6	L8, L11	Gyttja, Shell	40	188	0	6	102	5	3
	−1.34 to −1.37	3	L2, L9, L11	Gyttja, Shell	37	136	1 Trans arrow	17	65	12	7
SUM T2		34			**277**	**1659**		**70**	**693**	**68**	**58**
T3	−1.08 to −1.12	4	L7, L4	Shell	38	280	1 Blade; Decor. Bone	9	89	7	12
	−1.12 to −1.20	8	L4, L11	Shell	23	123	0	17	348	8	10
	−1.20 to −1.25	5	L2, L9, L11	Gyttja, Shell	86	294	0	34	265	20	29
	−1.25 to −1.42	17	L2, L9, L11	Gyttja, Shell	125	728	1 Trans arrow; 3 Blades; Bone point	55	12	29	30
SUM T3		**34**			**272**	**1425**		**115**	**714**	**64**	**81**
T4	−1.15 to −1.25	10	L13	Gravel/Sand	138	1650	1 Flake Axe	0	16	4	2
	−1.25 to −1.35	10	L13	Gravel/Sand	79	620	2 Blades	2.5	1	2	2.5
	−1.35 to −1.46	11	L13	Gravel/Sand	50	564	3 Blades	0	0	0	0
SUM T4		**31**			**267**	**2834**		**2.5**	**17**	**6**	**2**
T5	−1.08 to −1.16	8	L1, L7, L11	Sand/Shell	64	162	0	14	0	0	0
	−1.16 to −1.19	3	L11	Shell	57	402	2 Trans arrow	11	82	8	5.2
	−1.19 to −1.30	11	L9, L2	Gyttja	390	1767	3 Trans arrow; 3 blades	57	291	15	23
	−1.30 to −1.47	17	L2, L3	Gyttja/Sand	65	315	2 Blades	20	144	9	9
SUM T5		**39**			**576**	**2646**		**102**	**517**	**32**	**32**

Table 4
Faunal remains from the excavation trenches T2, T3 and T5 at Hjarnø Vesterhoved. The faunal material has mainly been found in Layers 4 and 11 (See Table 3). Determinations have been made by Kenneth Ritchie, Moesgaard Museum.

Taxa	Common Name	NISP
Anatidae cf. *Anas platyrhynchos*	Mallard	4
cf *Haliaeetus albicilla*	White-tailed eagle	1
Unidentifiable bird species		27
Bos primigenius	Auroch	1
Bos/Alces	Auroch/Elk	1
Capreolus	Roe Deer	2
Cervus elaphus	Red Deer	5
Canis familiaris	Dog	1
Vulpes vulpes	Red Fox	1
Equus caballus	Horse	6
Felis sylvestris	Wild Cat	1
Lutra lutra	Eurasian Otter	1
Martes martes	European Pine Marten	1
Sus scrofa	Wild Boar	2
Cetacean	Cetacean	2
Unidentified mammal remains		141
Chondrichthyes	Cartilaginous Fishes	1
Anguilla anguilla	European Eel	9
Clupea harengus	Atlantic Herring	2
Esox lucius	Northern Pike	1
Gadidae	Cod	841
Gadus morhua	Atlantic Cod	25
Myoxocephalus scorpius	Bull-rout	18
Pleuronectidae	Flounder	353
Salmo sp.	Salmon/Trout	1
Scophthalmidae	Flatfish	1
Trachinus draco	Great Weever	1
Unidentifiable fish species		717
Total		2167

layers are anthropogenic deposits.

A variety of bone tools have also been recovered eroding out from the marine deposits in the wider area. These include knives, antler axes, fabricators, fishing hooks, points, needles and polished and decorated antler handles/shafts. However, most are not in stratigraphic context and it is not possible to determine their relationship to the layers identified in excavation without direct radiometric dating of individual specimens. The notable exceptions are a fragment of a bone point or needle and a decorated bone found in the shell layer in T3 (Table 3).

3.6. *Shell analysis*

Detailed analysis of the molluscan remains in T3 focussed on identifying whether or not the shells are the by-product of human food consumption or naturally accumulated materials, and on any evidence for time trends in taxonomic composition within the deposit. One complicating issue is that the high suction level of the induction dredge used in excavation caused additional fragmentation of the shell material. This is demonstrable from comparison of the shell material on the laboratory bench with observations of the shell layers *in situ* before excavation. The resulting high degree of fragmentation has not seriously impeded taxonomic identifications, and since it is a constant for all deposits analysed, any variation in degree of fragmentation between layers can be attributed to other variables. Nevertheless, the damage caused during excavation is a factor that needs to be taken into account in evaluating the taphonomic history of the material and the development of future methodologies.

When the intrusive, modern shells are removed from the assemblage, only five taxa are present in the T3 sample: *Cerastoderma edule* (cockle), *Ostrea edulis* (oyster), *Mytilus* spp. (mussel), *Littorina saxatilis* (periwinkle) and *Littorina littorea* (periwinkle). This list conforms with what is typically noted for other Ertebølle middens (Andersen 1995, 2000, 2007, 2008, 2018; Milner 2002, 2005, 2013; Nielsen 2008), and what has been reported from the nearby submerged midden site of Hjarnø Sund (Larsen et al., 2018).

There is limited evidence of epizootic activity, such as sponge boring or barnacle infestation, with less than 1% (by NISP) of the specimens showing such evidence. Moreover, where present, epizootic infestation was only found on the exterior surface of the shell, suggesting that these specimens were harvested live prior to deposition. Finally, burn marks were noted on some of the specimens in the assemblage, providing another line of evidence that the shells were processed on land prior to consumption. However, the high rates of fragmentation hindered the identification of burning, especially for the oyster and mussel shells. This is largely due to their relative fragility and the removal of much of the outer shell layers. It is therefore possible that burning is more frequent than indicated by our observations, and further research is needed to ascertain if other markers for burning can be established.

Additional evidence confirming that the shell deposits were accumulated on land, or at the very least spent a period of subaerial exposure before inundation, is the presence of a terrestrial snail species (n = 3) in excavation unit −1.12 to −1.20 m in T3 (see Fig. 5). The size of the land snails (<5 mm) indicates that these individuals were not collected for consumption but crawled onto the accumulating surface of the shell deposit while it was still located on dry land and died *in situ* (see Nielsen 2007).

As observed during the excavation of this site, Layer 4 displayed a higher level of fragmentation compared to shell found in the underlying Layer 11. An examination of the NISP:MNI ratios for the four most abundant taxa in this assemblage, confirms this observation, with these ratios showing a constant rise in values as one moves from the bottom of the trench to the top (Fig. 12).

The molluscan remains suggest a change in dominant species over time (Table 5: Figs. 13 and 14). In the lower shell deposit (Layer 11), *C. edule* and *O. edulis* are most common, with the former being marginally more abundant. *L. littorea* and *Mytilus* spp, while less abundant, also make a sizable contribution to the assemblage during this period. Over time, however, oyster gradually shifts to become the single, dominant taxon within the assemblage, contributing to over 85% of the assemblage by MNI in the upper part of the shell layer.

This is different from other shell middens in Denmark, which, as noted earlier, show a consistent dominance of oysters throughout the Ertebølle period, shifting to a dominance of cockles only in the

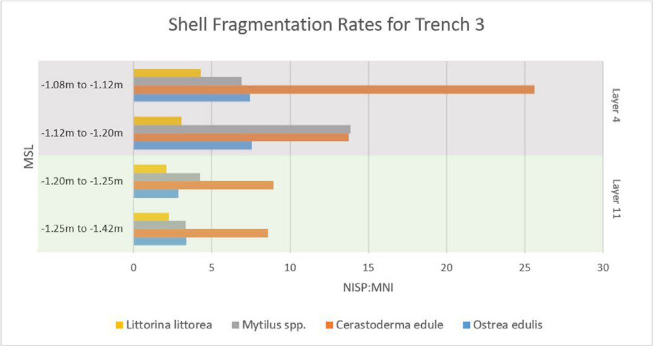

Fig. 12. Graph showing the change in rates of fragmentation for the four most abundant taxa found in Trench 3. Note that the fragmentation rates for the molluscs increase significantly in Layer 4.

Table 5
The raw MNI and volume corrected MNI for the molluscan material from Layers 4 and 11 in Trench 3. The row sum gives the proportional taxonomic representation for each excavation unit. Note that *O. edulis* is the dominant taxon except in the upper unit of Layer 11, where *C. edule* is proportionately more abundant. See text for further discussion.

Layer	Taxon	*Ostrea edulis*			*Cerastoderma edule*			*Mytlilus* sp.			*Littorina littorea*			*Littorina saxatilis*			All	
	NRE	Base			Right umbo			Right umbo			Base whorl			Apex			Row Sum	
	Depth	**MNI**	**MNI/m^3**	**Row %**	**MNI**	**MNI/m^3**	**Row %**	**MNI**	**MNI/m^3**	**Row%**	**MNI**	**MNI/m^3**	**Row %**	**MNI**	**MNI/m^3**	**Row %**	**MNI**	**%**
4	−1.08 m to −1.12 m	328	8200	***86***	33	825	***9***	11	275	***3***	10	250	***3***	0	0	***0***	382	*101*
	−1.12 m to −1.20 m	852	10,650	***63***	305	3813	***23***	128	1600	***9***	61	763	***5***	9	113	***1***	2355	*101*
11	−1.20 m to −1.25 m	297	5940	***35***	373	7460	***45***	61	1220	***7***	107	2140	***13***	0	0	***0***	838	*100*
	−1.25 m to −1.42 m	40	2353	***57***	20	<1	***29***	6	353	***9***	4	<1	***6***	0	0	***0***	70	*101*

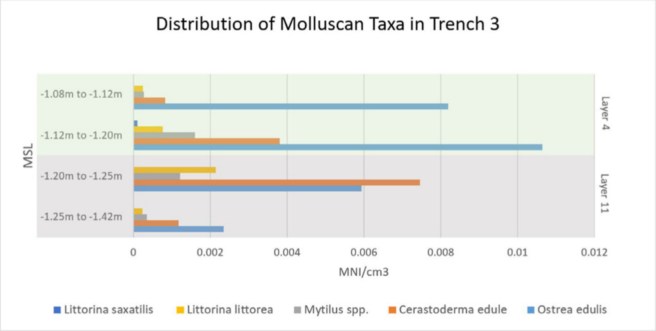

Fig. 13. Graph showing the volume-corrected MNI values (MNI/m^3) for the archaeological molluscan material from Trench 3 (Layers 11 and 4). Taxa deemed to be ‘modern’ or ‘ambiguous’ have been excluded from the dataset. This graph indicates that there is a shift in the representation of taxa, with the dominant taxon switching from *C. edule* in the upper part of Layer 11 to *O. edulis*. in Layer 4. See Table 5 for full data and text for further discussion.

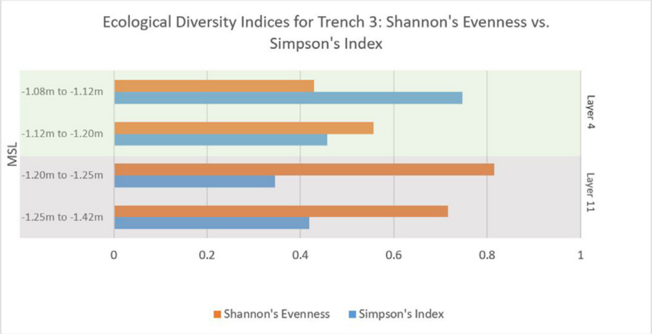

Fig. 14. Graph showing the shifts in Shannon’s Evenness and Simpson’s Index values for the mollusc contents of T3 (Layers 11 and 4), using the unadjusted MNI values per spit. The gradual increase in Simpson’s Index and the decrease in Shannon’s Evenness highlights the progressive increased dominance over time of the oyster species *O. edulis*. The mirroring of values indicates that these trends are real.

Neolithic period. Four hypotheses might account for this difference:

1. Since Hjarnø Vesterhoved is earlier in date than most other middens in Denmark, the deposits could be sampling an earlier regional trend from cockle-dominated to oyster-dominated marine environments that is missing from the other shell middens. The main argument against this hypothesis is the sequence at the nearby site of Hjarnø Sund, where an oyster-dominated layer is stratified beneath a cockle-dominated layer, even though these deposits are of a similar early date to the Hjarnø Vesterhoved shell midden (Astrup et al., 2020). Oysters are also the dominant species in other early-dated shell middens, notably at Brovst (Andersen 1970; Bailey 1975).

2. The dominance of cockles in the upper part of Layer 11 represents a preferential selection of cockles for a short-lived event, perhaps a dinner-time camp or a single meal or group of meals at a time of year when cockles were more easily available or attractive than oysters — a single event recorded within a deposit that is otherwise a palimpsest of many collection episodes. A small lens of pure cockle shell was observed within oyster-dominated deposits at the Ertebølle shell mound of Meilgaard (Bailey 1973 pers. obs.), and a thin layer of cockle shells was recorded over a hearth at Hjarnø Sund (Astrup et al., 2020, Fig. 8). A line of cockle shells at the base of Layer 11 (Fig. 6) may indicate a similar example.

3. The differences may be the result of localised or short-lived variations in environmental conditions. Oysters and cockles thrive best on different types of substrates, harder and softer respectively, and are also sensitive to a different range of temperature and salinity conditions. Lewis et al. (2016), for example, attribute the region-wide shift to cockles in the Neolithic period to widespread changes in inshore sediments. Given the variability in sea-bed sediments as demonstrated in the cores and sections of the Hjarnø II investigation, it is possible that there were localised variations and short-term fluctuations in conditions affecting molluscan habitats as well as broader regional trends.

4. Taxonomic representation in the upper shell layer has been biased by the higher degree of shell fragmentation observed in Layer 4 as compared to Layer 11. The umbo of the oyster is generally more robust than that of the cockle, while the mussel umbo is the most fragile. It is therefore possible that significantly fewer umbos of cockle and mussel have remained sufficiently intact to be identifiable in the upper shell deposit because of the higher degree of fragmentation. As shown in Fig. 12, fragmentation indices are higher for all taxa in the upper shell layer (Layer 4), but disproportionately higher for cockle and mussel.

Of these hypotheses, the first is least likely, but it is not possible to choose between the other three without further evidence and all may have contributed to some extent.

4. Discussion

We discuss these results in relation to four issues of wider significance: (1) the differentiation of shell -midden deposits from natural shell accumulations in underwater contexts; (2) the most appropriate methods for the discovery and investigation of underwater shell middens and assessments of their taphonomic history; (3) their usefulness in studies of sea-level change; and (4) the impact of our results on the interpretation of the archaeological record of Mesolithic Denmark and beyond and the prospects for similar discoveries of underwater shell middens elsewhere.

4.1. Natural versus cultural

Identifying cultural shell assemblages in terrestrial settings has been explored extensively in the archaeological literature resulting in the development of numerous criteria (see for example Allely et al., 2020; Attenbrow 1992; Bailey et al., 1994; Gill 1954; Jones and Allen 1978; O'Connor and Sullivan 1994; Stone 1989). Much time has also been devoted to identifying agents which may introduce natural shell into cultural assemblages. These include: wave action and storm surges that create beach ridges containing shell material or wash natural marine specimens onto midden surfaces; the mounding activities of nesting birds; and the practices of non-human predators; compounded by the possibility that deposits may include a mixture of shells from different sources – for example people may choose natural beach ridges on which to camp and process shellfood.

Given the comparatively young nature of the discipline of submerged landscape archaeology, there has been considerably less research conducted on identifying cultural shell assemblages in underwater settings or identifying the agents which may result in disturbances at the site (see Andersen 2009, pp 30–35 and p. 210; Andersen 2013, p. 44; Skaarup and Grøn 2004, pp. 41–44 for discussions on this topic). While it is tempting to assume that we can apply the same criteria and methods to submerged sites as on land, underwater research needs to take account of additional variables such as: the presence of natural death assemblages on the seabed where molluscs have lived and died without human intervention; the re-deposition and displacement of midden shells by wave action; intrusions from burrowing taxa; and the possibility of mixing between these various categories. Typical indicators are species and size of molluscs, with exotic species and small-sized specimens indicating natural deposits, the condition of shell material, particularly the presence of shell grit and water-worn surfaces, and the nature and condition of any cultural material that is present.

The following lines of evidence at Hjarnø Vesterhoved indicate that this assemblage is anthropogenic and was accumulated on dry land:

1. The high concentration of cultural material – flint and bone artefacts, and faunal remains – compared to the surrounding deposits of gyttja, sand and gravel.
2. The sharp and unpatinated condition of the flint artefacts found within the shell layers, demonstrating deposition and burial within the midden matrix, and the abundance of debitage demonstrating *in situ* knapping.
3. The predominance in the marine shells of edible molluscan taxa, edible (large)-sized specimens, evidence of burning, the absence of epizootic infestations on the interior surfaces of the shells, and the presence of land snails that are too small to have been collected as food and must have died *in situ* – all evidence that is typical of food-processed shell remains on Ertebølle middens across Denmark. High levels of fragmentation are also typical of anthropogenic shell middens, but we cannot rely on that indicator in this case because of the increased level of fragmentation caused by the excavation procedures. Comparative analysis of bulk samples removed before application of the suction dredge would be required to control for this variable.
4. The presence of fragmented animal bones, some of which show traces of burning, from a range of different terrestrial and marine taxa such as wild boar, red and roe deer, cod, wildfowl and marine mammals, all of which were frequently exploited during the Ertebølle period.
5. The absence of any traces of wood or uncharred plant material, whether as naturally occurring twigs, broken branches and plants, waste from tool manufacture, or the actual wooden artefacts themselves. This sort of material is abundantly present in the sand and gyttja layers at Hjarnø and in similar deposits excavated at other underwater sites, where it survives because of burial in anaerobic marine sediments soon after deposition. Absence of evidence is necessarily a relatively weak argument, but the absence of such material in the shell-midden deposits when it is so common in the surrounding marine deposits is what would be expected for a shell-midden deposit originally accumulated in subaerial conditions on land, where the organic materials would rapidly decay before the site was permanently submerged by sea-level rise and covered by marine sediment.

While the above evidence indicates that Hjarnø Vesterhoved is an anthropogenic shell assemblage, there is also evidence that this site has undergone some disturbance during the process of inundation and submergence. The higher levels of fragmentation observed in Layer 4 and the presence of more recent marine taxa suggests that this layer has experienced some degree of reworking and mixing with surrounding marine sediments. Additionally, the presence of abundant, small shell fragments in the gyttja of Layer 8, in Trenches 2 and 3, and the steep angle of the boundary between Layer 8 and the shell deposits of Layers 11 and 4 (see Fig. 4) suggests erosion at the edge of the shell midden and re-deposition of some of the shell from the midden. Similarly, the unconformity of the contact between the shell layers and the overlying gyttja suggests truncation of the shell deposits and removal of the uppermost part of the original shell midden.

The disturbance seen at Hjarnø Vesterhoved is unsurprising. Ertebølle shell-midden deposits typically occur on or very close to the immediate shoreline. The thin layer of sand located between the gyttja and the shell deposit at Hjarnø II confirms that the shell was deposited on the immediate shore edge and some of the deposit could easily have spilled over to lie directly on the gyttja surface in places (Figs. 4 and 6). The presence of these sites so close to the front line of wave action means that they would have been susceptible to disturbance and potential mixing with marine sediments and naturally occurring shells or other marine organisms. While the presence of disturbance and reworking at this site is less than ideal, the observations presented here show that substantial parts of the original shell deposit are largely intact and can be distinguished from deposits that have been disturbed or are naturally accumulated materials.

4.2. Site discovery and taphonomic history

This study is based on a combination of geophysical survey, coring and excavation, and all three have contributed to the interpretation. These three methods are complementary, providing different sorts of information of varying scale and resolution. Geophysical survey covers extensive areas relatively quickly, providing first-order information about surface and sub-surface features, but at relatively low resolution. In the present state of the art, we found that sidescan acoustic signals cannot distinguish between shell and gravel. Similarly, sub-bottom profiling using high-frequency signals can provide information on sub-surface deposits, but coring or excavation is necessary to confirm the interpretation of features that show up as reflection layers or boundaries between deposits of different types. Also, the technique has a limited vertical resolution and depth range, depending on the signal frequency of the equipment used and the nature of the deposits, producing imagery that is too 'noisy' to interpret outside that range. From the results obtained in this study, the main value of geophysical survey is to identify target areas for more detailed investigation by coring or diver exploration and to show the distribution of deposits over a larger area or to greater depth than can be reached by these other methods, notably, in the Hjarnø case, the depth and extent of the gyttja deposits. The application of high-resolution geophysics to underwater archaeological deposits has very considerable potential, but its use to identify deposits such as underwater shell middens and subtle differences in types of marine sediments is still at an early experimental stage, and further tests are needed to refine this approach.

Cores provide information of intermediate scale and resolution, stratified sediments that can be used to aid interpretation of geophysical signals, and sediment samples for more detailed laboratory analysis. They can also extend information about the distribution of deposits identified in excavation to areas beyond the excavation trenches.

Excavation provides the most detailed information of all, including macroscopic samples of artefacts and faunal material necessary to provide fuller information about the human activities carried out at a given location. The taphonomic examination of these materials, as demonstrated above, also plays a key role in understanding their depositional history and the agencies involved in the formation and deformation of the overall deposit. Limitations are the logistics of diver operations, which restrict excavation to relatively small trenches and shallow depths.

A fourth method is soil micromorphology, which requires the extraction of samples from the vertical face of an excavation trench and has yet to be applied to the Hjarnø Vesterhoved deposits. An earlier experiment involved the removal of a box core from the Hjarnø Sund excavation and the extraction and micromorphological analysis of sediment samples (Ward and Maksimenko 2019; Ward et al., 2019). The results demonstrated the potential of this technique in an underwater setting and produced details about the source of individual constituent materials such as mineral inclusions and sediment particles and additional detail about anthropogenic and natural influences on the formation and degradation of the deposit. The principal limitation of the method is that it depends on the prior discovery and excavation of deposits by other means.

In this sense, soil micromorphology is complementary to the other methods described and deals with *micro-scale* taphonomic issues – the internal composition of a deposit and the differential survival or transformation of its microscopic constituents during accumulation and after abandonment. We distinguish this from *macro-scale* taphonomic issues that are the main focus of this study – the relationship of shell deposits to their wider geomorphological setting and other (mostly marine) deposits in the vicinity, the extent to which they have been variously damaged or destroyed by subaerial processes and marine submergence, and how they can be discovered and shown to be middens as opposed to natural shells and marine deposits accumulated on the seabed.Where soil micromorphology really comes into its own is in the identification of deposits that are inaccessible to excavation and can only be sampled by minimally invasive methods such as coring. A more recent and more detailed micromorphological analysis of the Hjarnø Sund samples and a comparison with an underwater shell midden in the Gulf of Mexico have demonstrated that midden deposits have a distinctive micromorphological profile contrasting with other types of marine deposits (Cook Hale et al., 2021).

The use of micromorphological techniques does not, of course, preclude the macroscopic analysis of midden contents in relation to surrounding deposits as an important step in differentiating between anthropogenic and natural deposits. Collection of samples is scheduled for future investigations at Hjarnø Vesterhoved and should help to identify the nature of the transition from gyttja to shell deposits at the base of the midden and microscopic evidence of marine influences such as foraminifera and tiny marine molluscs washed into the deposit when it was located so close to the water level (e.g., see Allely et al., 2020; Cook Hale et al., 2021). Further comparisons and tests of all four methods are likely to be rewarding and necessary to advance this type of underwater research.

4.3. Sea-level change and depositional history

Examination of the dates for different types of deposit at Hjarnø Vesterhoved and Hjarnø Sund and the evidence for sea-level change casts some further light on the depositional history of the deposits. Thirty-six radiocarbon dates that are suitable for sea-level studies are available from the two Hjarnø sites (Fig. 15). The dated samples comprise two groups. The first group consists of dates on shell or charcoal recovered from shell midden deposits. These were originally accumulated on the shore edge as subaerial deposits, and we therefore refer to these as 'terrestrial' dates. The second group comprises dates of wooden materials such as remains of dugout boats, paddles, stakes and axe shafts that were abandoned in shallow water on the seaward side of the shore edge and rapidly encased in anaerobic gyttja sediments, all from the gyttja near Hjarnø Sund. We refer to these as 'marine' dates.

Two trends are clearly apparent. First, over the 900-year time span covered by the dates, between *ca.* 5500 and 4600 cal BC, there is a general trend of rising relative sea level, reflecting the combined effects of the final stage of eustatic sea-level rise and isostatic submergence of this part of the Danish coastline (Fig. 15; Astrup 2018). The amount of sea-level rise is small, from −1.7 m MSL to −0.6 m MSL, *ca.* 1 m over this 900-year period. Lateral movement of the shore edge over this period would, therefore, have been minimal and shell-midden deposits on the shoreline would have been vulnerable to prolonged periods of wave action and disturbance at the shore edge. The shell midden at Hjarnø Vesterhoved was accumulating at about the same time as refuse material was being left in adjacent marine sediments only 40 cm lower at the nearby Hjarnø Sund site, confirming the point that the shell layer at Hjarnø Vesterhoved was accumulated on or very close to the contemporaneous shoreline. Secondly, the dates confirm that sea level continued to rise after the accumulation of the shell layers at Hjarnø II, overtopping the shell midden and burying under marine sediment those parts of the shell midden deposit that were not previously eroded or disturbed by wave action. Marine deposits (or at any rate deposits with radiocarbon dates) associated with this final rise, between ca. −0.7 m MSL and the present sea level, are missing, most probably because of continuous reworking and removal of marine sediments on the surface of the seabed in the shallow-water zone.

These indications show that the Hjarnø Vesterhoved deposits would have been vulnerable to damage by water erosion and occasional storm surges even when the site was still in use, before eventually being submerged by subsequent sea-level rise and covered by a protective layer of marine sediments. These sea-level indicators reinforce the stratigraphic evidence for disturbance and erosion and highlight the possibility that the original shell midden was both thicker and more extensive in its original state and has been subjected to episodes of erosion both during and after occupation.

These dates from Hjarnø Vesterhoved also have more general implications about the usefulness of archaeological sites for measuring sea-level change. The use of dated peat/gyttja or dated shell middens as SLIPS (sea-level index points) is subject to a margin of error because generally speaking it is not known how high above MSL (in the case of shell middens) or how deep below MSL (in the case of gyttja) the dated specimens were located. This relationship is assumed to be fairly close and a sufficiently large margin of error added to allow for variation – for peat or gyttja, 0 to −1.5 m MSL, and for terrestrial deposits such as shell middens, 0 to +1.5 m MSL, a total range of 3 m (Astrup 2018). In our case study, we have more precise data on elevation, and comparison of

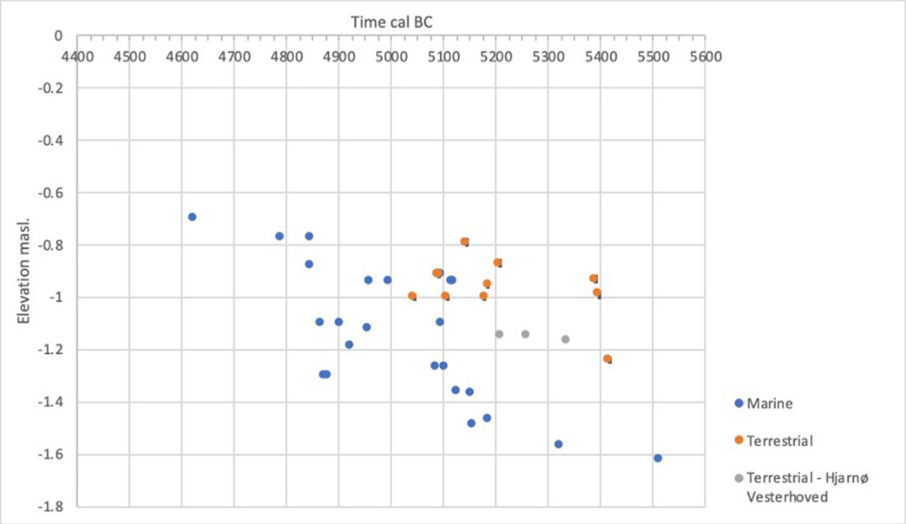

Fig. 15. Sea-level index points from Hjarnø Vesterhoved and Hjarnø Sund, showing the relationship between the calibrated radiocarbon dates of individual samples and their elevation in metres above or below MSL Each circle represent the median of the calibrated range. Marine dates are dates on materials recovered from gyttja deposits; terrestrial dates are on shell or charcoal samples from shell midden deposits. See text for further details. Data from Table 2; Astrup et al., 2020; Skriver et al., (2018).

the elevations of our ‘terrestrial’ and ‘marine’ dates within a given time interval shows that the difference is less than 1 m, and therefore that the plus-minus error term in fixing the sea-level position is not greater than 0.5 m (Fig. 15). This demonstrates the usefulness of shell-midden deposits for giving spatial and chronological precision to the measurement of sea level.

4.4. *Wider archaeological significance*

The Hjarnø results contribute in two ways to improved understanding of the Mesolithic sequence in Denmark, and these in their turn have wider implications for the problem of interpreting the evidence of coastal settlement − or its absence − during earlier periods of low sea level. First, they demonstrate the presence of underwater shell-midden deposits that have survived, at least in part, the potentially destructive effects of sea-level rise. This has particular significance in Denmark because the southern half of the country has undergone isostatic submergence, taking the shorelines of the Mesolithic period below present sea level. Many Mesolithic underwater sites are known in the south but almost all the *in situ* cultural material so far recorded comprises offshore refuse deposits in gyttja sediments or other marine deposits. Although marine shells are present in some of these sites, and shell midden deposits have been claimed or are suspected to have existed at some of them, e.g., at Ronæs Skov and Møllegabet II, their status as anthropogenic deposits remains uncertain, and there is nothing as yet to compare with the concentration of shell mounds in the north of the country. The Hjarnø finds thus extend the geographical distribution of shell middens in Denmark, and there is every reason to suppose that similar sites may have existed on the submerged shorelines further south, and that at least some of them have been preserved and can be found.

The Hjarnø results also contribute new information about the nature of coastal settlement in the early Ertebølle period. Deposits from this period are rare and comprise a handful of sites on uplifted shorelines in northern Jutland, mostly finds in the lowest layers of sites with deposits of later date (Andersen 2007; 2021, pers. comm.). The best-preserved shell midden layer in this group, at Brovst, is slightly older than Hjarnø with flint arrowheads of rhombic type that are typical of the preceding Kongemose culture and with radiocarbon dates in the range of 5663−5374 cal BC (Andersen 1970; Astrup 2018), compared to the Hjarnø range of 5471−5080 cal BC (Table 2). Given the rarity of coastal sites from the late Kongemose and early Ertebølle cultures and the limited information they have yielded on patterns of coastal settlement and subsistence, the Hjarnø deposits are a significant addition to knowledge of this period, showing that a diversified coastal economy combining shell-gathering, fishing and hunting of marine and terrestrial mammals, typical of the later Ertebølle, was already in place at the beginning of this culture period.

The rarity of these early sites and the confirmation of an underwater shell midden at Hjarnø raises the question of whether a whole class of coastal sites is missing from the earlier part of the Mesolithic record because most of the shorelines are underwater and shell-midden deposits have not been preserved or are yet to be discovered. In assessing this issue, we need to take account of three other variables that could have affected time trends in the representation of shell middens. We also look more carefully at the uplifted shorelines in the far north of the Jutland Peninsula, where early sites might more easily be discovered.

The first variable is changes in cultural preferences or demographic pressures that led to avoidance or neglect of marine molluscs in some periods and places despite their availability. However, since such cultural variables are unknowable without independent evidence of the resources available, other variables need to be eliminated before bringing cultural preferences into play.

The second variable, and the one most widely discussed (Andersen 2007; Bailey et al., 2020b; Lewis et al., 2020), is that the distribution and size of shell middens tracks the availability of the marine molluscs, especially oysters, and that this accounts for the rarity of shell middens at the Kongemose/Ertebølle boundary, and their absence before that date. Oysters are close to the limit of their range in Danish waters, especially in the modern environment. The isostatic uplift of the northern Jutland Peninsula has narrowed the inlet from the North Sea, reducing tidal flow and water salinity, and growth conditions for oysters progressively deteriorate as one moves south and east into the brackish waters of the Baltic Sea. During the Mesolithic period, before isostatic uplift took effect in the north, marine inflow into Danish waters was stronger with higher salinities and a larger tidal range. Moreover, although these changes in the marine environment began with the Littorina marine transgression as early as 6500 cal BC, sea level was lower then, and it can be argued that beneficial effects for oyster growth only reached their optimum in the late Ertebølle period as the Littorina transgression reached its peak, coinciding with the accumulation of the largest number of shell middens and the largest mounds.

Although some indirect palaeoenvironmental evidence has been cited in support of this hypothesis (Lewis et al., 2020), there is a risk of circularity of argument – shell mounds were absent in earlier periods because there were no oysters, and the evidence that there were no oysters is the absence of shell mounds. Oysters and other molluscs were certainly present in Danish waters from the beginning of the Littorina transgression (Petersen, 2004). What is not clear is the quantities that were available. What is needed is independent evidence of oyster availability. Natural oyster banks are known to exist on the seabed, and these are a potential target for more detailed investigations relevant to this issue.

A third variable, noted by Fischer (1995, p.382), is the rate of lateral movement of the shoreline during periods of rapid sea-sea level rise, leading to the hypothesis that shell middens were smaller or less visible in earlier periods, not because the oysters were unavailable, but because the shoreline did not stay fixed in one place long enough to allow sufficient accumulation of oyster shells to create archaeologically visible deposits, let alone large shell mounds. A test of this hypothesis is yet to be carried out in Denmark and would require detailed measurements of offshore bathymetry and rates of sea-level rise in different locations, and statistical analysis of multiple radiocarbon dates of shell mounds to refine estimates of accumulation rates. Where multiple radiocarbon dates have been applied in other parts of the world, they have shown that substantial shell mounds can grow surprisingly fast, within a matter of decades or less (Hausmann et al., 2019; Holdaway et al., 2017).

The underlying weakness of the above hypotheses is that while they are based on plausible assumptions, they justify acceptance of the existing archaeological record, rather than providing an incentive to search for new and contradictory evidence. This brings us back to the fourth variable, which is the one we started with, the differential preservation and visibility of shell middens because of sea-level rise. One obvious place to examine this issue further is to look at the uplifted shorelines in the far north of Jutland, where shorelines have reached heights as much as 12 m above modern sea level. The earliest coastal sites in this region are Brovst, noted earlier, and Yderheden, a refuse layer in marine sediments of similar date (Astrup 2018, p. 125). If earlier shell middens existed, we might expect them to have survived on the highest uplifted shorelines, which are known to have been available from at least 7000 cal BC or earlier. Sites of the Maglemosean culture are present at this date within 5 km of the coast but they are not sites on the shoreline. Then there is a gap until the appearance of Ertebølle sites on the coastline from about 5400 cal BC onwards. The difficulty here is that uplift did not take effect until much later. The Maglemosean shorelines are now buried under layers of marine sediment. Moreover, after 7000 cal BC, sea level rose to a highstand at 5200 cal BC before dropping again. Shoreline sites occupied between *ca*. 7000 and 5200 cal BC would therefore have been inundated by sea-level rise and further exposed to erosion as sea level dropped again, processes that are believed to account for the absence of coastal sites in this time interval (Astrup 2018, p. 124). Brovst is instructive here, with evidence of marine sands interleaved with shell layers showing intermittent marine transgression before sea level finally retreated (Andersen 1970, p. 87–88).

Paradoxically, it seems, these uplifted shorelines in the north of Denmark were exposed to risks of site destruction or burial by marine inundation and erosion just as severe as the submerged shorelines in the south – if not more so. This strengthens the case for underwater investigations in search of earlier and deeper shorelines. Artefacts of Maglemose and Kongemose type have been recovered at depths of 6–7 m in Aarhus Bay just north of Horsens Fjord, including remains of wooden fish weirs (Astrup 2018). It is these earlier shorelines where future investigations should be directed, and where new evidence will most likely be found.

5. Conclusion

The Hjarnø Vesterhoved site currently stands as one of only three underwater shell deposits in the world that are demonstrably intact anthropogenic shell middens as opposed to natural deposits, the others being the nearby Hjarnø Sund site (Astrup et al., 2020) and the Econfina Channel Site in the Gulf of Mexico (Cook Hale et al., 2018, 2021). With dates of 5471–5080 cal BC, Hjarnø Vesterhoved is one of the earliest shell middens in Denmark, dating to the early period of the Ertebølle culture with features, including thick layers of oyster shells, typical of the later Ertebølle shell mounds. It also extends the distribution of this type of archaeological deposit to southern Denmark, where shell middens have not previously been reliably recorded and where the shorelines of the Mesolithic period are now under water because of glacio-isostatic submergence. Underwater sites of similar date are known in this region but they mostly lack remains of shellfood and are primarily refuse deposits, that is materials thrown into the shallow water and preserved in anaerobic gyttja sediments alongside settlements on the adjacent shoreline which have been largely destroyed or disturbed by marine erosion.

The Hjarnø midden was accumulated on the edge of the shoreline at the boundary between a natural beach ridge of sand and gravel and a deposit of gyttja. This type of location, often facing a narrow channel as is the case at Hjarnø, is typical of many Ertebølle sites because of its suitability for building fish weirs out from the shore and trapping large quantities of fish (Fischer 1995, 2007). The faunal remains from the midden deposit confirm the importance of fishing alongside the collection of molluscs and the exploitation of other marine resources and hunting of terrestrial mammals. The deposit was exposed to periodic disturbance by minor fluctuations in sea level before it was fully and finally submerged and covered by a protective layer of marine sediment. It probably represents the intact fragment of what was originally a more extensive midden, itself part of a larger settlement area that has largely eroded away and is now mainly represented by artefacts discarded or abandoned in the adjacent gyttja sediments. Beds of eel grass growing on the seabed have helped to stabilise the covering of marine sediments and protect the underlying archaeological deposits until recently, when the disappearance of the eel grass has accelerated erosion.

These results also raise the question of how many other underwater coastal settlements with shell middens may have survived and await discovery, and especially whether they can be found on deeper and earlier submerged shorelines. Artefacts typical of the earlier culture periods in the Danish Mesolithic sequence, the Kongemose and Maglemose cultures, and radiocarbon dated materials extending back to 6500 cal BC, have been found under water at greater depth in several locations, and hold promise for more intensive future investigations. Whether shell middens could have formed on these shorelines is complicated in the Danish case by confounding variables of environmental change and rapid shoreline displacement, which could have affected the availability of oysters in earlier periods and the size of the resulting shell deposits.

Turning to the prospects for the discovery of underwater shell middens more generally, our results demonstrate that, although many deposits are vulnerable to disturbance and destruction by marine erosion, especially those that form on the shoreline, some deposits can survive. Much depends on local conditions of geology, topography and marine sedimentation, conditions that can vary significantly even over short distances, and which do not admit of easy generalisation. There is no substitute for targeted underwater investigations designed to discover such sites if they have survived, and there is every reason to suppose that many more await discovery. In that quest, a variety of techniques will be required across a range of different scales from geophysical survey to coring, underwater excavation and micromorphological analysis.

Finally, our results emphasise the importance of posing and researching questions about the formation and deformation of archaeological deposits in their wider landscape setting, and the various cultural and natural agencies that may be involved. Converting distributions of archaeological sites in space and time into statements about variations in the distribution and density of human populations is bound to produce misleading results without an investigation of all the many processes that affect the differential accumulation, preservation visibility and accessibility of archaeological deposits (see, for example, Dillehay 1989; Holdaway and Wandsnider 2008; Rossignol and Wandsnider 1992; Schiffer 1987). It is doubtful that we fully understand how these processes affect distributions on dry land, a point underlined by the rarity of coastal sites on the uplifted shorelines of northern Denmark, where we might have expected better site preservation. Under water, the situation is further complicated because of the additional effects of marine erosion and accumulation of marine sediments, and the need for research more obvious. Where one underwater example of an intact shell midden has been discovered, it is likely that others will follow. More investigations using the approach and methods described in this study should help to correct the systematic under-representation of shell middens during the periods of low sea level that have dominated world prehistory.

CRediT author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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