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Underwater Shell Middens: Excavation and Remote Sensing of a Submerged Mesolithic site at Hjarnø, Denmark

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ABSTRACT

Shell middens, or shell-matrix deposits, occur in large numbers across the coastlines of the world from the mid-Holocene (ca. 6000–5000 cal BC) onwards, often forming substantial mounds. However, they become smaller, rarer or absent as one goes back into earlier periods, suggesting a world-wide process of economic intensification. Since sea level was generally much lower during these earlier periods, a critical question is the extent to which mounded shell middens could have accumulated on now-submerged palaeoshorelines, and if so, how they were affected by the potentially destructive impact of sea-level rise. Further, and important to modern practice, it is essential that archaeologists consider how such sites can be discovered through underwater investigation. Here we offer a proof of concept that shell middens can survive submergence and can be detected, using systematic investigation of a rare example of a confirmed underwater shell midden at the Mesolithic site of Hjarnø (ca. 5300–4300 cal BC) in Denmark. We

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compare the excavation results with the results of geophysical survey, explore the problems of distinguishing underwater cultural shell middens from natural shell beds and conclude that shell middens can survive inundation by sea-level rise and can be detected by remote sensing, but require at least minimally invasive sampling to establish their cultural status. We suggest the methods developed may be applicable to coastal and marine sites impacted by postglacial sea-level rise worldwide.

Keywords Mesolithic, Ertebølle, underwater archaeology, submerged landscapes, sidescan, sub-bottom profiling

1. INTRODUCTION

Shell middens—shell matrix deposits in which the discarded shells of mollusc food are the dominant physical constituent—occur in their tens of thousands on coastlines across the world. They are a ubiquitous and highly visible signifier of coastal settlements oriented towards intensive use of marine resources of all kinds including fish and sea mammals as well as shellfish. They often form dense clusters of middens of varying size including large mounds hundreds of meters long and many meters in thickness, including famous examples such as the Danish kitchen middens, the shell mounds of San Francisco Bay, Jomon Japan, and northern Australia, the sambaquis of Brazil, and the megamiddens of South Africa (Andersen 2000; Bailey et al. 2013; Balbo et al. 2011; Gutiérrez-Zugasti et al. 2016; Jerardino 2012; Milner et al. 2007). These large mounds and midden clusters date, almost without exception, from the mid-Holocene (ca. 5500 cal BC) onwards, suggesting a worldwide intensification in the exploitation of coastal and marine resources. Earlier and generally smaller shell-matrix deposits are known in smaller numbers from the late Pleistocene and early Holocene, most of which are in coastal caves, but the quantities of shells in these earlier deposits are orders of magnitude less, indicating at best a shallow and episodic gradient of intensifying interest in marine resources (Bailey and Flemming 2008; Cortes-Sánchéz et al. 2011; Erlandson and Fitzpatrick 2006; Jerardino 2016; Marean 2010; Will et al. 2015).

As knowledge of Pleistocene and early Holocene sea-level change has improved, the suspicion has grown that this pattern of intensification may be highly misleading. In fact, it may be largely illusory, reflecting no more than the increased visibility of coastlines and the remains of shellfood during periods of relatively high sea level (Bailey 2011; Bailey and Craighead 2003; Bailey and Flemming 2008; Bailey and Milner 2002; Benjamin et al. 2017; Bicho et al. 2011; Veth et al. 2017; Ward and Veth 2017). At the very least it requires the application of more subtle measures of intensification such as evidence of increased human impact as revealed by changes in the size and age structure of the exploited mollusc populations (Bailey et al. 2008; Gutiérrez-Zugasti 2011; Klein and Bird 2016). However, disentangling the relative influence of differential preservation or visibility versus economic intensification on the long-term archaeological record of coastal settlement is seriously hampered by the fact that most coastlines before stabilization of modern sea level at about 6,000 years are now submerged to a depth that is determined by their age, placement, and site formation prior to abandonment, and the amount of isostatic and tectonic activity at the local and regional scales (see sea-level data and curves as published in Lambeck et al. 2014 and Astrup 2018). What if dense clusters of coastal shell middens and the shallow bays and estuaries with which they are typically associated existed 10,000 years ago, 30,000 years ago, or even earlier, at depths that are now over 40 m below present sea level, but have been destroyed by sea-level rise or buried beneath thick deposits of marine sediment? What are the chances that shell mounds could survive the potentially destructive effect of waves and turbulent shallow-water currents during the earliest stages of inundation by sea-level rise? And what are the chances of detecting such deposits, especially where they are buried beneath later sediment, or occur at depths below sea level, inaccessible to simple methods of underwater survey and excavation by divers? With the recent growth of interest in underwater prehistory and the demonstration of how many prehistoric archaeological finds have survived inundation (Bailey et al. 2017; Benjamin et al. 2011; Evans et al. 2014; Flemming et al. 2017; Harff et al. 2016), these questions are now firmly on research agendas worldwide.

Searches for underwater shell middens have been attempted in several parts of the world, notably in North America, Europe, and the Red Sea, including diver inspection and use of sub-bottom survey for buried deposits, but their discovery has remained elusive, or else their status as cultural deposits has remained uncertain in the absence of more detailed excavation (Andersen 2009, 2013; Bailey et al. 2007, 2015; Easton 1993; Faught 2014; Gusick and Faught 2011; Jazwa and Mather 2014; Nutley 2014; Pearson et al. 1986; Skaarup and Grøn 2004). Confirmed examples are very rare: only some freshwater shell deposits in the lake district of Japan (Hayashida et al. 2014), and a recent discovery in the Gulf of Mexico (Cook Hale et al. 2019). Of the >3,000 underwater finds recorded in Europe, only three are listed as possible shell middens, and of these, two are not certain to be middens (as opposed to natural deposits) and one is a partially eroded midden found low in the intertidal zone.[1] These facts highlight two major challenges: 1) the need to distinguish between cultural and natural accumulations of shell on or beneath the seabed; and 2) how to detect shell middens in circumstances where they are buried beneath marine sediments and/or occur at great depth. Regarding this latter point, where there is no exposure or no erosive feature which uncovers the site, it is critical to consider how such sites can be discovered and studied remotely using acoustic and video technology and, later, through minimally invasive techniques such as core sampling and test-excavation. A proof of concept is required—a known underwater site that is demonstrably a shell midden, where the results of underwater investigation based on conventional excavation techniques and large samples can be compared with evidence recovered from acoustic survey and coring. The data and methods presented herein begin the process by which archaeologists and palaeoecologists will be able to confront these issues.

We address these questions through the investigation of the submerged Mesolithic site of Hjarnø, a midden site in Denmark, chronologically belonging to the late Mesolithic, Ertebølle culture (5400–3900 cal BC) (Skriver et al. 2018). The Hjarnø site represents a rare case of a confirmed underwater shell midden. Because it is in shallow water, it is easily accessible to diver inspection and underwater excavation and therefore offers an opportunity to examine in detail its status as a cultural accumulation of food shells and to compare the results of conventional excavation with a range of remote sensing techniques. Our aim here is to present the results of fieldwork at Hjarnø as part of the Deep History of Sea Country project (Benjamin et al. 2018), with emphasis on field recording, excavation, and geophysical survey. We use the results to explore two hypotheses: 1) that the underwater shell deposit is a midden originally accumulated on dry land and subsequently submerged with minimal modification, as opposed to a reworked midden eroded by wave action and redeposited on the seabed, or a natural shell bank, or a mixture of midden deposits created by cultural deposition in shallow water and natural shells; 2) that it is associated with distinctive acoustic signatures provided by remote sensing using geophysical survey techniques.

2. THE HJARNØ SITE

2.1. Archaeological and Geographical Context

The site is located in shallow water (<2 m) on the southwestern coast of the

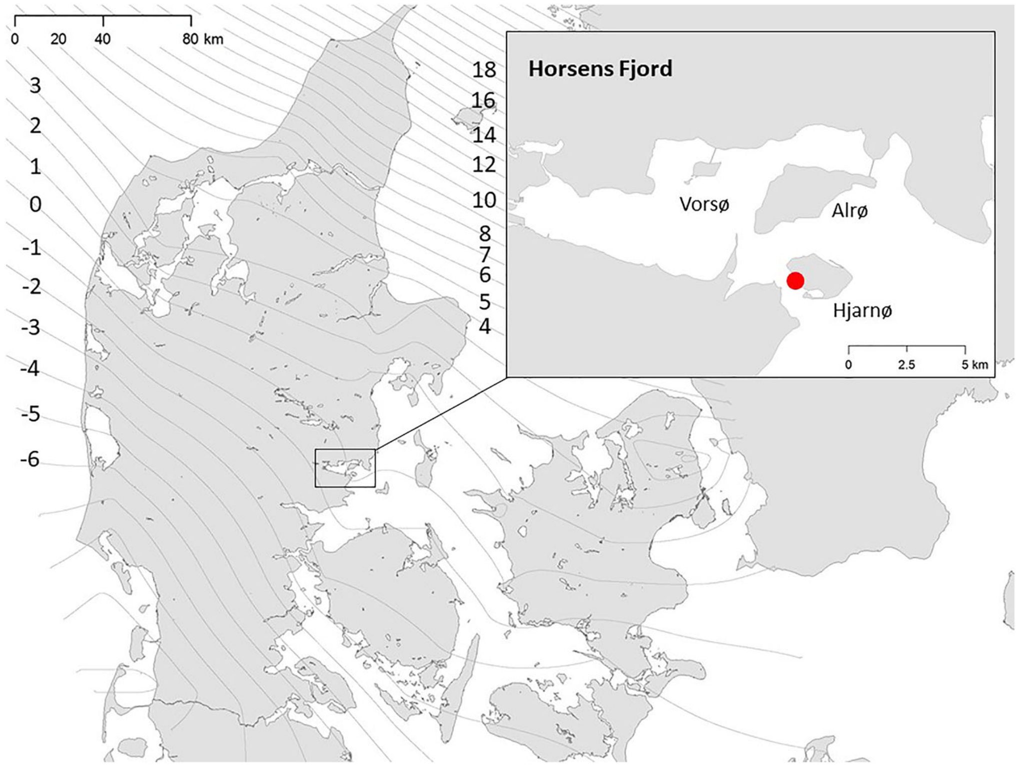

Figure 1. *Map of Denmark on which isostatic uplift that has occurred since ca. 5250 cal is shown in meters above or below present day sea level. Position of the archaeological settlement on the island of Hjarnø in Horsens Fjord is marked with a red dot. (Graphic P. M. Astrup)*

small island of Hjarnø in the outermost part of Horsens Fjord, an 18-km-long sheltered micro-tidal estuary located on the east coast of Jutland, Denmark (Figures 1 and 2). The fjord was formed as a valley by melt-water during the retreat of the Weichselian glaciation. Until the Boreal period (8000–7000 cal BC) it was a river outlet and in the Atlantic period (ca. 7000–3800 cal BC) it was transformed into a saltwater fjord and Hjarnø was cut off from the mainland (Astrup 2018). As elsewhere in Denmark, intensive coastal occupation followed. Subsequently the region underwent submergence in common with other coastlines of southern Denmark, while the shorelines of northern Denmark were slightly uplifted, resulting from glacio-isostatic adjustment following the retreat of the Scandinavian ice sheet (Astrup 2018; Christensen 1995; Christensen and Nielsen 2008) (Figure 1). In consequence, Danish coastal Mesolithic sites form two broad geographical groupings. Those in the north are mostly above present sea level and include over 350 shell mounds, mostly of the Ertebølle period (5400–3900 cal BC) but including some later (Neolithic) and earlier examples, as well as coastal sites without shell remains (Andersen 2000). In the south they are mostly below sea level and include many hundreds of underwater sites including isolated artefacts, culture layers, and organic remains such as fish traps and other wooden artefacts, but no confirmed shell middens (Andersen 2013; Bailey et al. in press; Fischer 2004; Pedersen et al. 1997).[2]

At the time of writing, a total of 37 submerged Mesolithic find spots have been

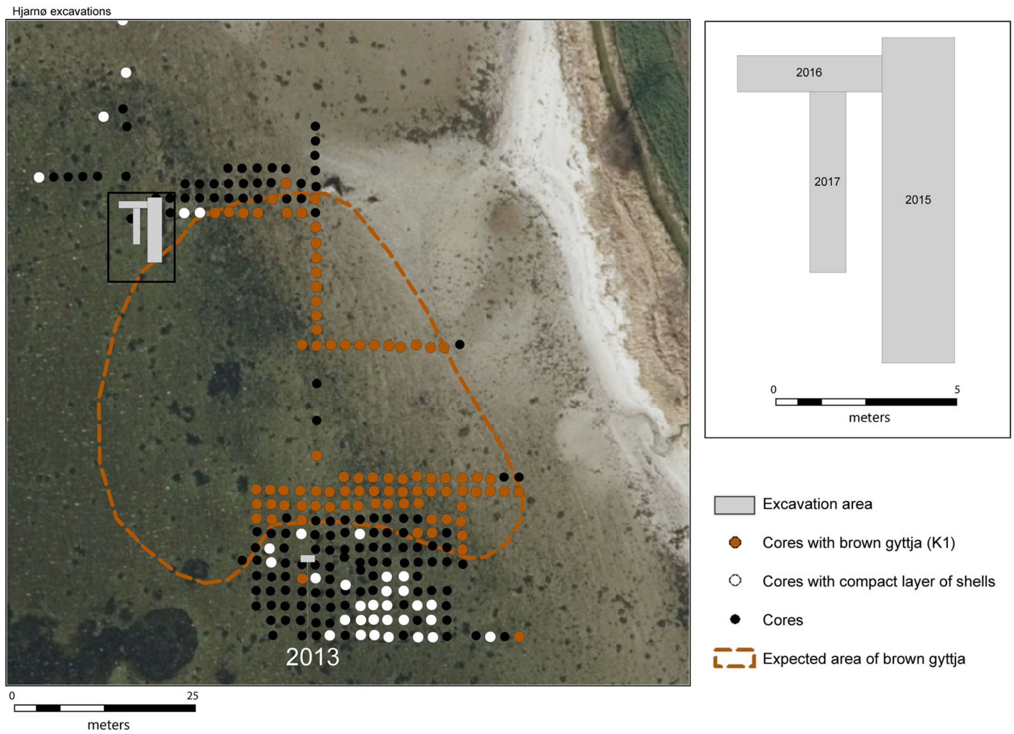

Figure 2. *Location of the excavation trenches (2013, 2015, 2016, and 2017) as well as the distribution of the gyttja layer. White circles = cores in which a compact layer of shells has been demonstrated. Brown circles = cores in which the gyttja/refuse layer has been demonstrated. (Graphic P. M. Astrup)*

recorded in the Horsens Fjord system making this one of the richest concentrations of underwater sites in Denmark. Most of the sites represent single finds or flint-scatters but the record also includes substantial sites with organic remains.[3]

The archaeological deposits at Hjarnø, consisting of gyttja (a dark mud rich in organic material) and concentrated shell material, have been partially exposed by erosion of the overlying sandy sediments since at least 2009, when archaeologists were made aware of the site, and ongoing erosion is constantly exposing new parts of the archaeological deposits. Here, as elsewhere in Denmark in recent decades, erosion has been accelerated by pollution and climate change, which have resulted in progressive removal of eel grass that consolidates a protective layer of sand over the submerged land surface (Rasmussen 1977).

2.2. Previous Investigations

Initial investigations at the site in 2009 focused on the lagoon (gyttja) deposits. A range of well-preserved organic artefacts were recovered including painted paddles, dugout canoes, axes, bows, and fishing implements (Skriver et al. 2017, 2018). Through continued fieldwork, it was possible to define the horizontal and vertical extent of the site through auger survey, which demonstrated that the gyttja deposits served to protect the stratified shell deposits (Figure 2). At least two such shell accumulations have been located: the first

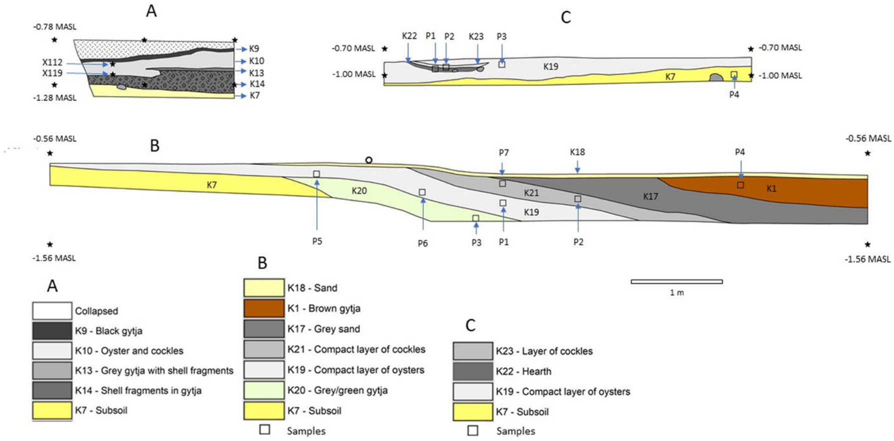

Figure 3. *Section drawings of three trenches excavated in the shell layer at Hjarnø. A) 2013, B) 2015, and C) 2016. Elevations are specified as Meters Above Sea Level (MASL).*

was discovered during sand dredging in the area south of the gyttja layer at a depth of −0.9 m (trench 2013; Figure 2). The other shell accumulation is located at a depth of −0.6 m further north and is partly visible on the seabed (trench 2015, 2016, 2017; Figure 2).

In the southern shell deposit, a small trench measuring 2 m^2 was opened in 2013 (Figure 3A) exposing a 10–20 cm thick shell layer dominated by shells of edible species such as oysters (*Ostrea edulis*), cockles (*Carastoderma edule*), mussels and periwinkles (*Littorina littorea*). The layer also contained large amounts of worked flints (ca. 1,080), charcoal, fish remains (ca. 4,700) and other bones (185), including whale and roe deer (*Capreolus capreolus*). Given the quantity of material culture, and the fact that the shells did not lie in pairs, it was concluded that the shell layer was the product of discarded food remains rather than a natural shell deposit. Excavations in the northern shell deposit in 2015 and 2016 (Figure 3B and 3C) also demonstrated a sequence of stratified shell layers, at least some of which appeared to be anthropogenic. However, given the potential for mixing of natural and cultural shell debris in underwater shell deposits and the difficulties of distinguishing between these two categories of shell material, a new investigation was begun in 2017.

3. METHODS

3.1 Survey and Excavation

Excavation in 2017 was carried out using methods that have been developed as the result of experimentation and development in underwater excavation of Mesolithic settlements over the past 40 years (see Andersen 1985; Dal 2013; Fischer 1995; Uldum et al. 2017). Work focused on the northern shell deposits and a 5 × 1 m trench was opened parallel to the 2015 excavation (Figure 2). Each 1 m^2 square (shown in Figure 4) was excavated in sample units until the coarse sand layer or basal glacial clays below the shell deposits were reached, making use of a simple induction or water dredge (Figure 5). All materials were collected in a 4-mm mesh bag attached to the exhaust. In addition to bivalve shells, collected material included fish bones, hazelnuts, shells of terrestrial molluscs, charcoal, and flint artefacts.

Dating samples were taken from the excavation profile (Figure 4). A 30 × 30 cm × 10 cm box core was used to

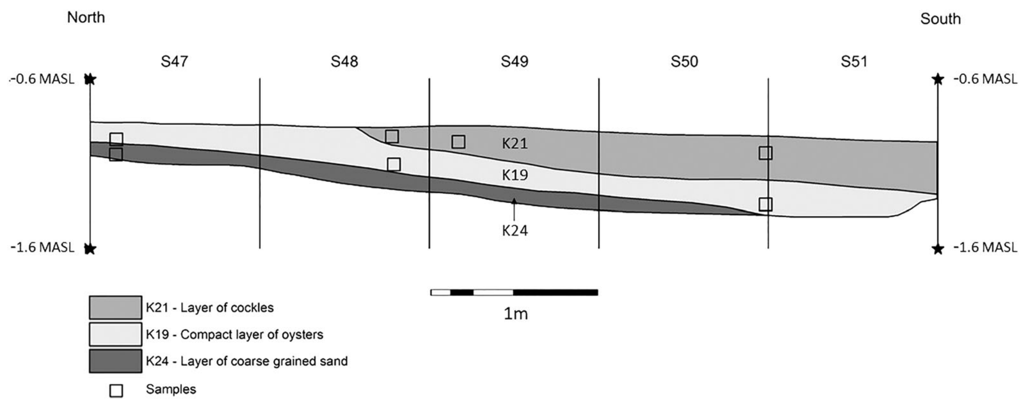

Figure 4. *Section drawing of the 2017 trench with layer and sample information. Elevations are specified as Meters Above Sea Level (MASL). (Drawing P. M. Astrup)*

Figure 5. *Excavation of shell layer at Hjarnø. (Photos J. Benjamin)*

take undisturbed bulk samples of the shell deposit for resin impregnation and subsequent micromorphological analysis (Ward et al. 2019; Ward and Maksimenko 2019). In addition to the excavation, a number of auger surveys were conducted around the wider excavation area in order to further define the extent of shell deposits and to provide ground-truthed reference points for geophysical survey.

Photogrammetric techniques were trialed to record the site in three dimensions through a combination of aerial survey and underwater photography. We recorded images at three scales: landscape, site, and excavation trench (Figure 6). Data acquisition was acquired by low-flying aerial photography (DJI Phantom drone with 12-megapixl camera) for the site location (area landscape). A second aerial dataset was acquired at low tide to map in high resolution the details of the intertidal zone, which were too shallow to record through underwater photogrammetric means. Underwater photogrammetry was then undertaken over an area of ca. 50 × 30 m which encompassed the concentration of organic material, gyttja, and the excavation trench where the midden was excavated. Images of the site area (seabed) were acquired through manual snorkeling techniques with a stereo pair of waterproof cameras fixed to a stability float (GoPro Hero 5, 12 megapixel cameras set to intervalometer/time-lapse function at 0.5 second exposure). Images of the profile visible in the excavation trench were acquired step by step as the trench (and profile) was expanded. Markers were placed at regular intervals under water (at 5 m intervals in three rows) and on the beach to ensure alignment of measurements with the underwater photogrammetry. The three datasets, aerial (landscape), aerial (intertidal), and underwater photogrammetry were then combined in a single georeferenced site map, in high resolution, exportable in both three-dimensional and two-dimensional outputs (Figure 6B). Images were processed in Agisoft Photoscan (v. 1.3.4), using high-resolution alignments, alignment optimization though gradual selection, and optimization steps, including reprojection error, reprojection accuracy, and projection accuracy options, before creating a dense point cloud, mesh and texture (Benjamin et al. 2019).

3.2. Geophysical Data Operations

While a diving team was engaged in excavation, another team carried out geophysical survey, with its primary focus on the western side of the site including the submerged midden area (Figure 7). Two types of survey were carried out: sidescan sonar, using Edgetech 4125 equipment, to characterize variations in the surface texture of the seafloor and identify any visible changes in seabed conditions and surface anomalies; and sub-bottom profiling, using Innomar SES-2000 standard parametric sub-bottom equipment, to identify sub-surface features such as shell layers or other types of buried deposits hidden beneath the overburden of marine sediment. All geophysical instruments were mounted and towed from the RV *Bothilde* (a small boat of just under 5 m in length). Measurements were collected and processed in a WGS84, UTM 32 coordinate system. (Further details on the geophysical work are presented in Supplementary Material).

4. RESULTS

4.1. Midden Stratigraphy and Composition

The Hjarnø shell layers demonstrate a stratigraphy as follows (from bottom to top). A compact layer (K19) ca. 30–40 cm-thick of oysters (*Ostrea edulis*) and cultural material lay directly on top of layers of sand and clay. The oyster layer at the northern end is partially visible on the seabed and consequently exposed to erosion (Figure 4). Further south, the oyster layer is overlain by a ca. 35–45 cm thick layer of cockle (*Cerastoderma edule*) shells (K21). Capping this layer (recorded 3 m east of the profile in trench 2017) is a ca. 45 cm thick layer of sand (K17) (with large amounts of cultural material), and the find-bearing gyttja layer (K1) ca. 40–45 cm thick (see Figure 3B). The oyster shells in layer K19 tend to be oriented slightly inclined to the horizontal and concave-down. In contrast, the overlying cockle shells in layer K21 are either inclined or horizontal concave-up, implying greater bioturbation or human disturbances of these uppermost sediments. A clear boundary between the oyster and cockle layer is visible in trench 2015 and trench 2017 (see Figure 3B and Figure 4).

The two shell layers (K19 and K21), were formed on the contemporaneous shore consisting of sandy deposits, formed over glacial clay and older marine deposits. The shell layers were recorded in section 2015, and are overlain by mobile sands (K17) and then gyttja (K1). The sand layer (K17) indicates deposition on an open

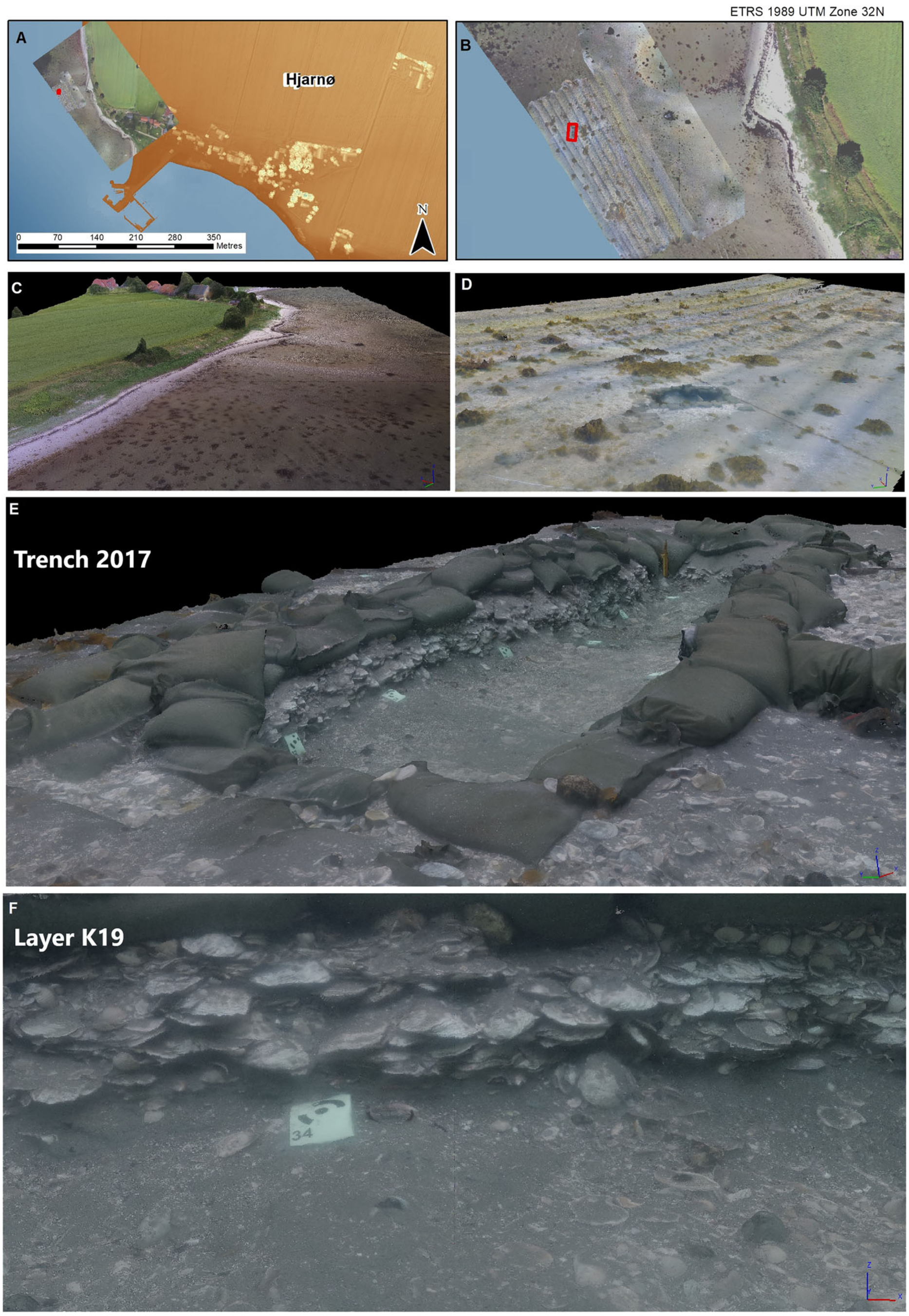

Figure 6. *A) Site and landscape context, including aerial photogrammetric datasets and LiDAR topography; B) locations of the aerial and underwater photogrammetric surveys; C) oblique view of aerial photogrammetry and coastal environment, looking southeast; D) 3D model of the seabed and excavation trench 2017; E) array photogrammetry survey showing excavated trench and context underwater; F) example of stratigraphy in excavation trench.*

Figure 7. *Aerial imagery of the seismic tracklines with highlighted sub-surface shell midden reflectors as interpreted from the sub-bottom data.*

Table 1. **Radiocarbon dating of shell and charcoal samples from the Hjarnø midden site. Results are presented in stratigraphic sequence for each of the excavations. Radiocarbon ages were calibrated using OxCal 4.3 (Bronk Ramsey 2009). Shell samples were calibrated using the Marine13 calibration dataset (Reimer et al. 2013), with a ΔR of −36 ± 54 (after Larsen et al. 2018). Charcoal and bone samples were calibrated with the IntCal13 calibration dataset (Reimer et al. 2013). All calibrated ages are reported at the 95.4% age range.**

Stratum (K)	Trench and sample	Lab No.	Material	Species	^{14}C Age (years BP)	Calibrated Age BC	Median Calibrated Age BC
K1	2015 (P4)	AAR-24753	Charcoal	Hazel	6130 ± 48	5214–4947	5077
K7	2016 (P4)	AAR-26594	Charcoal	Hazel	6285 ± 40	5365–5082	5266
K10	2013 (X119)	AAR-16959	Bone	Roe deer	6426 ± 28	5474–5340	5414
K10	2013 (X112)	AAR-16958	Charcoal	?	6396 ± 27	5468–5320	5379
K19	2016 (P3)	AAR-26591	Shell	Oyster	6637 ± 35	5395–5072	5254
K19	2015 (P5)	AAR-24754	Shell	Oyster	6588 ± 38	5341–5022	5200
K19	2015 (P6)	AAR-24755	Shell	Oyster	6492 ± 48	5270–4910	5090
K19	2015 (P1)	AAR-24750	Shell	Oyster	6617 ± 36	5367–5051	5233
K20	2015 (P3)	AAR-24752	Charcoal	Hazel	6162 ± 34	5215–5011	5122
K21	2015 (P2)	AAR-24751	Shell	Cardium	6538 ± 39	5296–4976	5140
K21	2015 (P7)	AAR-24756	Shell	Cardium	6515 ± 34	5275–4955	5116
K22	2016 (P1)	AAR-26593	Charcoal	Hazel	6390 ± 49	5477–5299	5378
K23	2016 (P2)	AAR-26592	Shell	Cardium	6515 ± 27	5271–4961	5116

coast whereas the gyttja (K1) indicates deposition in a sheltered bay most likely resulting from the formation of a protective sand spit. The shell layers are coherent with clearly defined boundaries, and the stratigraphy is comparable to land-based shell mounds such as the Norsminde shell midden (Andersen 2000). Cultural material (worked flints, animal bone, and charcoal) are present throughout with larger quantities in the lower shell layer (See Table A in Supplementary Material). The greatest thickness (>70 cm) of shell deposits is recorded at the southern end of the midden at a water depth of ca. 0.75 m below sea level and the shell layer becomes thinner towards the north, either because of ongoing erosion or because the deposits slumped downwards over an already inclined base and were dispersed.

4.1.2. Chronology

The main part of the shell midden was deposited around 5200–5100 cal BC, with similar age estimates for the top and basal layers of the midden, indicative of rapid accumulation (Table 1). A sample (AAR-24753) (shown as sample P4 in section 2015; Figure 3B) from the gyttja layer that overlies the shell layers has a similar age (ca. 5214–4947 cal BC), providing a minimum age for cessation of shell deposition in the area. Flint flakes, blades, core, and flake axes typical of the Ertebølle culture are recorded in large numbers across the site and distinctive shaft-hole antler axes date the assemblage to the early part of the Ertebølle culture.

4.1.3. Lithics and Faunal Remains

The flint assemblage from the shell midden appears sharp and unpatinated. Microwear analysis shows that the surfaces are clean and unaltered with no traces of post-depositional transportation. The small pieces of worked flint (<1 cm) found throughout the shell layers indicate that flint knapping activities took place directly on the shell-midden surface.

Almost all layers contain faunal remains, hazelnuts, and charcoal. The marine mollusc remains are almost exclusively typical edible species, such as *Ostrea edulis*, *Cerastoderma edule*, *Littorina littorea*, and *Mytilus edulis* (Larsen et al. 2018). Both marine and terrestrial fauna are represented (see Table B in Supplementary Material), and fish bones are especially numerous, particularly cod and flatfish, occurring in concentrations that suggest the use of specific areas of the midden for fish processing (see also Andersen 1989:26).

Remains of small land snails (*Discus rotundatus*) were also recovered from the shell layer (K19) in all of the excavation trenches. This is a strong indication that the shell layer originally deposited in a terrestrial setting. The discovery of a thin layer (4–6 cm) of cockle shells on top of a hearth with fire-cracked stones and charcoal (Figure 3C) also indicates that the cockle shells were heated, and this is supported by clear traces of heating on the shells in the K21 layer (see Figure 3B). Finally, micromorphological analysis of a sample from the oyster layer K19 in section 2017 also confirms the presence of burnt shell material (Ward et al. 2019).

4.2. Anthropogenic versus Natural Shell Layers

Distinguishing between cultural and natural shell deposits is a perennial problem even on dry land, where large accumulations of shell can be created by natural agencies such as storm surges, beach ridges, or nesting scrub fowl and there are well-known examples of ambiguity in identification and mistaken identity (see, for example, Attenbrow 1992; Bailey et al. 1994; Stone 1989). Even on land, the presence of artefacts and vertebrate food remains in a shell deposit is not sufficient evidence that the mollusc shells are discarded food remains, since people may camp on the surface of natural shell deposits, with a resulting intermixture of natural and cultural materials, something long recognized in the Danish context (Troels-Smith 1995). In underwater deposits, the problems are compounded by the presence of natural death assemblages of shells on the seabed and the possibilities of redeposition and admixture (Jazwa and Mather 2014). Distinguishing criteria usually focus on the taxonomic composition and age-size structure of the mollusc shells, the condition of the shells and the ways in which they are accumulated, and the nature of the surrounding sedimentary matrix, supported in some cases by systematic comparison between known natural shell deposits and known cultural ones.

Evidence in support of a cultural interpretation of the Hjarnø shell deposit is as follows. First, the narrow range of taxa recovered in the midden refers almost exclusively to those that were typically collected by Danish Mesolithic hunter-gatherers, such as *Ostrea edulis*, *Cerastoderma edule*, *Littorina littorea*, and *Mytilus edulis* (Larsen et al. 2018). Larsen et al. (2018) further noted that the shells are almost exclusively of adult specimens, are never paired as is typically the case in natural shell beds, and that epizootic infestations are present only on the outer surfaces of the shells, which is common on living shells, and not post-mortem infestations of the inner surfaces, something which is often observed in natural death assemblages.

Second, the occurrence of sand with little organic matter, flint artefacts, nuts, bone material, and charcoal within the shell deposit also suggests that the shell layers are anthropogenic. This is not definitive because these materials have been observed in a shell deposit at Tybrind Vig, identified as a natural accumulation from the age and size composition of the shells, the presence of intact paired oyster valves, and the sand-and-gravel matrix (Andersen 2013). Nevertheless, the amount of faunal and other cultural material at Hjarnø is suggestive, and the fact that the flint has not got a white-bluish patination further indicates that the material has not been

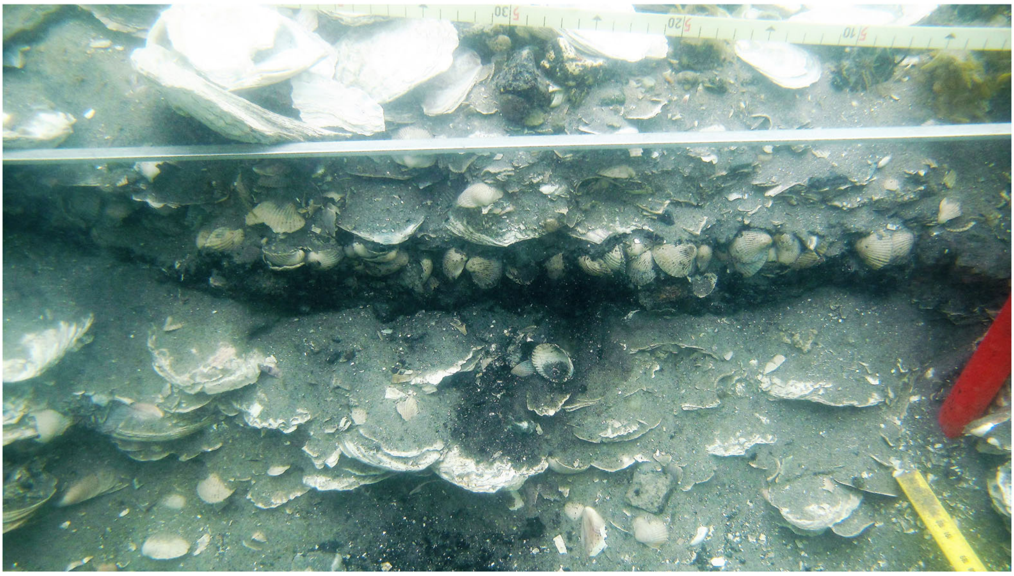

Figure 8. *Hearth in trench 2016. (Photo P. M. Astrup)*

redeposited but is an in situ accumulation. Other indicators that the shell layers were originally deposited on land are the presence of shells of small land snails (*Discus rotundatus*) and the absence of organic material (branches, etc.) in the shell deposits (see also Andersen 1993:68). Final evidence of the anthropogenic origin of the shell deposit is the presence both at the macro- and micro-scale of in situ hearth features (visible in Figure 3C and Figure 8) with fire-cracked stones, charcoal, and burnt shell material. In the Norsminde midden, fish bones are typically found in ash deposits associated with fireplaces (Andersen 1989). This is also the case in the Hjarnø midden.

The shell deposit at Hjarnø resembles the well-studied terrestrial middens from northeastern Denmark with regards to its size, shape, features (such as hearths), and composition of shells, faunal remains, and archaeological material. The abrupt shift from oysters to cockles in the Hjarnø sequence is also replicated on some on-land shell mounds, notably at Norsminde and Krabbesholm (Andersen 1989, 2005). These terrestrial examples occur at the Mesolithic-Neolithic boundary (ca. 4000 cal BC), but the transition most likely represents subtle shifts in local environmental conditions favoring one species over the other and which may occur at different times in different places (Lewis et al. 2016). The different layers documented in 2017 therefore functioned as way to understand the geophysical data/results that were recorded simultaneously. This will be discussed in more detail below.

4.3. Geophysical Survey

4.3.1. Sidescan Sonar

The sidescan survey focused on two sites 1) the submerged shell midden deposit described above; 2) a second submerged site located approximately 400 m north of the midden site (Figure 7). Data were collected over 24 transects and at a 30 m line spacing, sufficient to provided total coverage. Throughout the survey area, moraine deposits and anthropogenic items were observed in the sidescan images. Aquatic vegetation such as macro

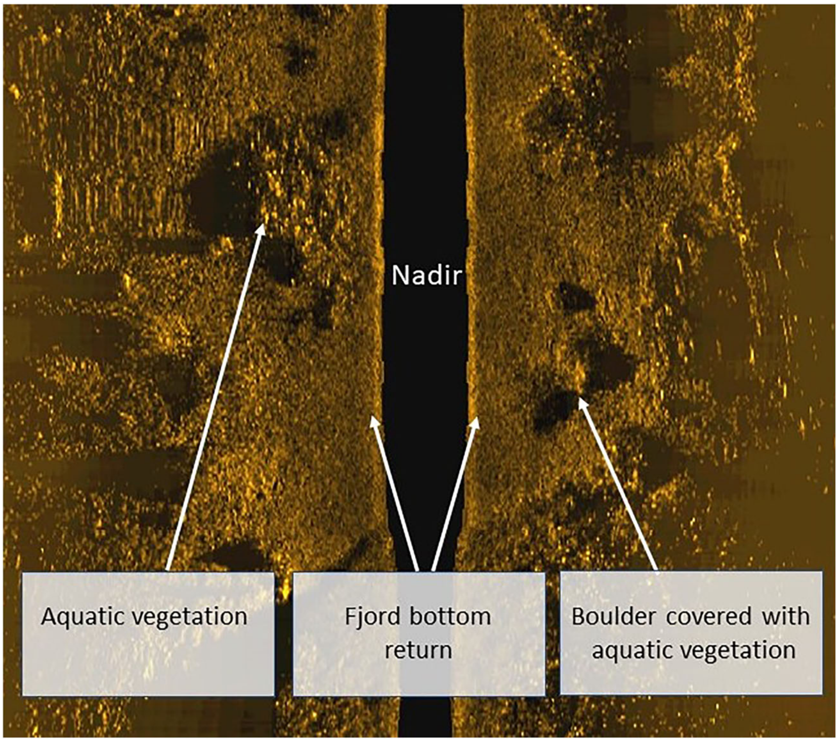

Figure 9. *Sidescan imagery depicting aquatic vegetation delineating underlying natural and potentially anthropogenic material.*

algae and eel grass meadows were present on large portions of the sea bottom. Areas with aquatic vegetation were observed to delineate underlying natural and potentially anthropogenic material (Figure 9). Due to the shallow depths (<1 m in places), beam angles were significantly exaggerated. Shadow distortion was particularly problematic in very shallow depths of less than 0.5 m. For that reason, the exposed eastern portion of the shell midden deposit leading towards the shore could not be recorded easily, though it was well recorded by the intertidal aerial and photogrammetry surveys. Sedimentary characteristics and sedimentary transitions (sands to clayey till) are easy to distinguish in the sidescan imagery. In principle, sidescan operations also have the potential to identify exposed shell deposits, but no such feature was identified within the survey area. There is the added problem that shells and cobbles (≤10 cm) give similar reflective signal returns, and in areas where both types of materials are present on the seabed it will be difficult to distinguish between them using sidescan imagery alone.

4.3.2. Parametric Sub-bottom Profiler

The aim here was to test our ability to identify the size, shape, and depth of the submerged midden using sub-bottom geophysical techniques, as well as to characterize the sub-surface layers and stratigraphy in the adjacent areas. Despite some variation in data quality and some areas partially obscured by environmental features, such as gas pockets and aquatic vegetation cover, the sub-bottom did allow for the identification of the known midden (Figure 10) and also a potential second shell midden 400 m northeast of the main site that

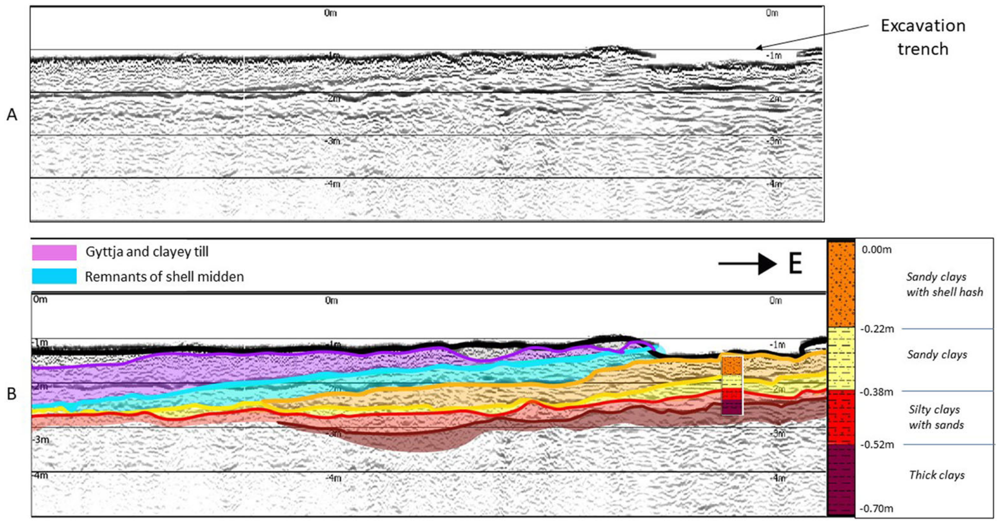

Figure 10. *A) Seismic data depicting sub-surface shell midden; B) seismic data with reflectors, depicting sub-surface shell midden with core collected at the base of the excavated trench. Interpretation by Francis Stankiewicz.*

is buried up to 2 m below the seafloor surface (see Figure 7). Additionally, the sub-bottom survey data revealed stratigraphic layers in the sub-surface deposits of the fjord and produced data that shows the extent of some eroded and semi-exposed deposits.

5. DISCUSSION

5.1. Geophysical Identification of Submerged Shell Deposits

The Hjarnø midden is an example of a well-preserved shell midden that survived transgression and inundation by rising sea level in the middle Holocene. We have presented evidence that this shell deposit is an anthropogenic midden originally deposited in a terrestrial, coastal setting. This site was therefore ideal for a methodological test case to examine the potential for the application of various geophysical methods to identify submerged shell deposits. The application of sidescan and sub-bottom profiling together proved useful to identify submerged environmental features over a large area. Through the sidescan data the team was able to identify a variety of surface features on the seabed, including patches of macro-algae and eel grass and areas of hard materials such as cobbles. In principle, sidescan should be able to identify exposed shell material, but the exposed part of the underwater shell deposit at Hjarnø occurs in a water depth that is too shallow for sidescan to be effective, and its efficacy in distinguishing shell deposits from other hard materials will need to be tested in deeper water. However, the parametric sub-bottom profiler proved effective in shallow water and was able to identify the submerged shell deposit. It also revealed a second and previously unknown shell deposit at a depth of 2 m below the seafloor that was examined the following year. However, it could not be used to distinguish between shell surfaces composed of different taxa, for example, oysters as opposed to cockles. It also identified other reflectors representing stratified layers of different types of sub-surface deposits, most likely of geological rather than cultural significance.

With the results that we have obtained so far, it does not appear that either geophysical technique, whether separately or in combination, can distinguish between naturally accumulated shell beds and cultural midden deposits. It looks as if that differentiation cannot be achieved without the development of more sensitive acoustic measurements (e.g., Hermand et al. 2011) or by intrusive sampling either by coring, at minimum, or by more extensive excavation where feasible.

6. CONCLUSION

This study has shown that the content of the submerged Hjarnø midden and its preservation conditions are comparable to that of the shell middens on the uplifted shorelines of northern Denmark. It demonstrates that the submerged shell layers represent an anthropogenic midden deposit that was formed between ca. 5200 and 5100 cal BC. Key supporting evidence for an anthropogenic origin includes: 1) the large amounts of cultural material in the shell layers; 2) the sharp-edged and unpatinated condition of the flint artefacts (considered as evidence of in situ deposition); 3) the taxonomic composition and size distribution of the shells, which differs from what would appear in a natural shell deposit and is comparable to known records from other terrestrial middens in Denmark; and 4) the absence of signatures for water-deposited layers in the interstices of the shell matrix. Finally, the presence of land snails and a hearth with ash and burnt stones in the oyster layers also provide unambiguous evidence for a deposition at or above contemporaneous sea level, at least for the upper part of the midden,

High-resolution photographic and photogrammetric recording as well as geophysical surveys provide important additional information; sub-bottom seismics in particular can be used to identify submerged shell layers, whereas sidescan is only likely to be helpful where shell deposits are exposed by erosion on the seabed or are known to be associated with other surface features that indicate the presence of underlying cultural material. In both cases, it is likely that intrusive sampling by coring, or more extensive excavation if feasible, will be necessary to determine if shell deposits are anthropogenic or natural in origin.

In terms of our opening hypotheses, we draw two conclusions: first, that the Hjarnø shell deposit is a shell midden and therefore evidence that these deposits can survive the destructive effects of wave action and marine currents during inundation by sea-level rise. Some erosion of the original Hjarnø midden and a degree of water disturbance and mixing of materials cannot be ruled out. However, it is clear that the greater part of the shell deposit so far investigated is a largely intact shell midden. Second, we conclude that geophysical methods provide a useful first step in scanning areas of seabed for potential shell deposits, and especially for the discovery of shell deposits buried beneath marine sediments. However, on this latter point, we maintain a cautious approach and highlight the likely need for further inspection by archaeologists deploying marine coring methods, or by excavation where feasible. This will be required to provide convincing evidence of the cultural status of the deposit and is likely to further assist with the development of more refined acoustic techniques, which remain in a state of technological development and improvement. It is unclear whether large structural shell mound features will be discovered on the seabed, if only because of the likelihood of some degree of erosion, redeposition, and burial by later marine sediments. Nevertheless, our results demonstrate that substantial parts of a shell midden deposit formed on a palaeoshoreline can survive inundation by sea-level rise. This should give encouragement to the search for intact shell-midden deposits on submerged coastlines in other parts of the world and on earlier palaeoeshorelines at greater depths. This in its turn should foster field investigations globally, in order to recover evidence that can provide more effective tests of preconceptions and hypotheses about long-term intensification in coastal palaeoeconomies.

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END NOTES

1. http://splashcos-viewer.eu/.
2. The total number of underwater Stone Age sites for Denmark as a whole is estimated to be at least 2,300 (Fischer 2004) but this includes sites of late Palaeolithic, earlier Mesolithic, and Neolithic periods on all coastlines and the great majority are isolated finds of single artefacts.
3. Ministry of Culture Database http://www.kulturarv.dk/fundogfortidsminder (accessed June 1, 2018).

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