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Submerged landscapes, marine transgression and underwater shell middens: Comparative analysis of site formation and taphonomy in Europe and North America

Jessica Cook Hale [a], Jonathan Benjamin [b, c], Katherine Woo [c], Peter Moe Astrup [d], John McCarthy [b], Nathan Hale [e], Francis Stankiewicz [b], Chelsea Wiseman [b], Claus Skriver [d, 1], Ervan Garrison [a, f], Sean Ulm [c], Geoff Bailey [b, g, *]

[a] Department of Geology, University of Georgia, 210 Field Street, Athens, GA, 30602, USA
[b] College of Humanities, Arts and Social Sciences, Flinders University, GPO Box 2100, Adelaide, SA, 5001, Australia
[c] ARC Centre of Excellence for Australian Biodiversity and Heritage, College of Arts, Society and Education, James Cook University, PO Box 6811, Cairns, QLD, 4870, Australia
[d] Moesgaard Museum, Moesgaard Allé 15, 8270, Højbjerg, Denmark
[e] Aucilla Research Institute, 555 North Jefferson Street, Monticello, FL, 32344, USA
[f] Department of Anthropology, University of Georgia, 355 S Jackson St, Athens, GA, 30602, USA
[g] Department of Archaeology, University of York, Kings Manor, Exhibition Square, York, YO1 7EP, United Kingdom

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A B S T R A C T

Shell middens, sometimes in the form of mounds of great size, are a ubiquitous indicator of coastal settlement and exploitation of marine resources across the world. However, shell middens are relatively rare before the mid-Holocene because most palaeoshorelines before that time are now submerged by sea-level rise since the Last Glacial Maximum (LGM). Previously reported examples of underwater shell middens are almost unknown and of uncertain status, and it has generally been assumed that such deposits would not survive the destructive impact of sea-level rise or would be indistinguishable from natural shell deposits. Recently, two examples of underwater shell deposits have been independently discovered and verified as anthropogenic midden deposits – a Mesolithic shell midden on the island of Hjarnø in the Straits of Denmark, and a Middle to Late Archaic shell midden in the Econfina Channel of the Gulf of Mexico, Florida, USA. We report the comparative geoarchaeological analysis of these deposits, using a sedimentological approach to unravel their formation history and post-depositional transformation. Despite the differences in coastal geomorphology and geology, cultural context, molluscan taxonomy and preservation conditions between these sites, the results demonstrate similar sedimentological profiles that are distinctive of anthropogenic deposits, demonstrate their origin as subaerial deposits at the shore edge before inundation by sea-level rise, and show that these properties can be identified in sediment samples recovered from coring. These findings support arguments that such sites likely exist in greater numbers than previously assumed, that they can be identified from minimally invasive techniques without the need for extensive underwater excavation, and that they should be sought to fill critical gaps in the temporal and geographical record concerning Late Quaternary human use of coastal zones and marine resources.

1. Introduction

Submerged coastal landscapes are critical for addressing key questions identified as grand challenges for archaeology in the 21st century (Kintigh et al., 2014). These include responses to Quaternary climatic and sea-level change, colonisation of new territories and new continents, early developments in seafaring, the

* Corresponding author. Department of Archaeology, University of York, Kings Manor, Exhibition Square, York, YO1 7EP, United Kingdom.
E-mail address: geoff.bailey@york.ac.uk (G. Bailey).
[1] Deceased.

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intensified use of coastal and marine resources and their contribution to the development of complex foraging subsistence systems, agricultural dispersals, and monument building (e.g., Fladmark 1979; Masters and Flemming, 1983; Johnson and Stright 1992; Benjamin et al., 2011; Evans et al., 2014; Flemming et al., 2017; Bailey et al., 2020a).

The potential significance of the archaeology associated with the drowned landscapes of the continental shelves is increasingly acknowledged in recognition of the fact that sea levels were lower than the present for 95% of human history and therefore that most palaeoshorelines are now under water. Research momentum is building, with many hundreds of underwater finds now reported in Europe and North America. However, the discipline of submerged landscape archaeology remains in a pioneer phase of development, posing technological, methodological and theoretical challenges unlike those experienced by terrestrial archaeologists. The costs and risks of failure for underwater site prospection, and scepticism about the usefulness of the results, remain a major deterrent to investigation. This is largely due to uncertainty about how much archaeological material is likely to have survived the destructive impact of marine transgression, how to set about locating such material, and what difference, ultimately, underwater discoveries will make to improved understandings of the past.

Locating more submerged sites will help to move the discipline forward, but how can this best be realised? Archaeological sites under water are less likely to be discovered by accident or reported to local archaeologists than sites on land, though engagement with commercial fishing, offshore industries and the dive community can be productive. ‘Top-down’ approaches involving predictive modelling, remote sensing techniques and palaeolandscape reconstruction have yielded some significant successes (Benjamin 2010; Benjamin et al., 2020; Cook Hale and Garrison 2019; Veth et al., 2020; Peeters and Amkreutz 2020). But these are not without their own potential limitations: extrapolation from known archaeological sites on land where conditions of preservation and visibility may be very different from those under water; applications limited to specific underwater environmental and cultural contexts where sites have already been found; omission of whole classes of sites; or simply failure to lead to any underwater discoveries at all (Grøn 2018)

The discovery of underwater archaeological sites also depends on identifying those locations where the archaeological remains are preserved and are accessible to discovery. The present state of knowledge about why archaeological sites survive in some locations but not others, and more generally the current understanding of the conditions which determine the formation of archaeological deposits and their subsequent transformation during and after inundation by sea-level rise, have made significant advances recently but understanding is still quite limited (Flemming et al., 2017; Bailey et al., 2020a). It is clear that these conditions are sensitive to highly localised variations in human discard behaviour and geomorphological processes; generalisations can lead to misunderstandings.

In addition, all discoveries depend, ultimately, on diver inspection of submerged targets, or coring and grab-sampling from surface boats, survey methods that are necessarily much slower and cover much less ground for a given unit of time and effort than survey on land.

Here, we emphasise a ‘bottom-up’ approach that focuses on known underwater deposits and on the analysis of the depositional and taphonomic conditions under which these sites have been formed and subsequently transformed by post-depositional processes before and after inundation by marine transgression. Specifically, we focus on recently discovered submerged shell middens from two different marine basins and cultural periods: the Mesolithic Ertebølle culture of Denmark in the waters connecting the Baltic Sea and the North Sea, and the Middle to Late Archaic culture along the eastern coast of the Gulf of Mexico, Florida (Figs. 1 and 2). In both cases, analytical results from underwater excavations have already demonstrated that the shell deposits are anthropogenic middens and not natural accumulations of shells (Astrup et al., 2020; Cook et al., 2018).

Shell middens, or shell-matrix deposits, are defined as accumulations of shell refuse discarded by human populations as by-products of food consumption, in which shell remains are the visually dominant physical constituent (Claassen 1998). Artefacts and other food remains are usually present as well as sedimentary particles. In this paper we follow Stein (1992) in taking a sedimentological approach to the analysis of these deposits that includes the sediment fraction as well as the macroscopic remains. Middens composed of freshwater mollusc shells also occur on major riverine systems in Australia and the southeastern United States, and middens dominated by edible terrestrial molluscs also exist (e.g., Balme 1995; Randall 2015; Taylor and Bell 2017), but the great majority of shell middens comprise marine molluscs in coastal environments, and that is our focus in this study. We have chosen to concentrate our study on coastal shell middens, and on these two underwater examples from two different regions and cultural contexts for the following reasons:

1. They are the only two currently known underwater shell middens in the world that have received systematic investigation and evidence of their anthropogenic status.
2. Shell middens are found in large numbers (tens of thousands to hundreds of thousands) in coastal environments worldwide. The largest comprise mounds with impressive dimensions, extending over hundreds of square metres and tens of metres high, though many are much smaller (e.g., Emmitt et al., 2020). They are a visible and unequivocal indicator for the use of aquatic and especially marine resources and are a very common if not universal material correlate of coastal settlement.
3. Shell middens are associated with a wide variety of cultural practices ranging from subsistence to burial ritual, the use of the accumulated shell material for the deliberate construction of features such as causeways, canals, plazas and mounds (terraforming), and with significant shifts in human population structure, increasing political complexity, and elaborations in niche construction (e.g., Thompson and Andrus 2011; Rosendahl et al., 2014; Thomas 2014; Randall and Sassaman 2017).
4. They provide a well-recognized focus for cross-cultural and inter-continental comparative analysis (Bailey and Parkington 1988; Milner et al., 2007; Bailey et al., 2013; Roksandic et al., 2014; Allely et al., 2020).
5. Finally, they are especially significant in the context of underwater exploration. Evidence for the exploitation of marine resources extends far back into the Pleistocene (Erlandson 2001; Marean 2010; Jerardino 2016; Will et al., 2019), but the quantities of mollusc shells or bones of marine vertebrates are very small and shell middens are rare or small in size until the mid-Holocene, when they appear in vastly increased numbers across the world. It remains unclear whether this reflects a world-wide intensification in the use of marine resources associated with new demographic expansion and new socio-cultural developments or is simply the result of differential visibility of palaeoshorelines and loss of underwater sites from the archaeological record. Since most palaeoshorelines before the mid-Holocene are now under water, it is of critical importance to investigate this matter further.

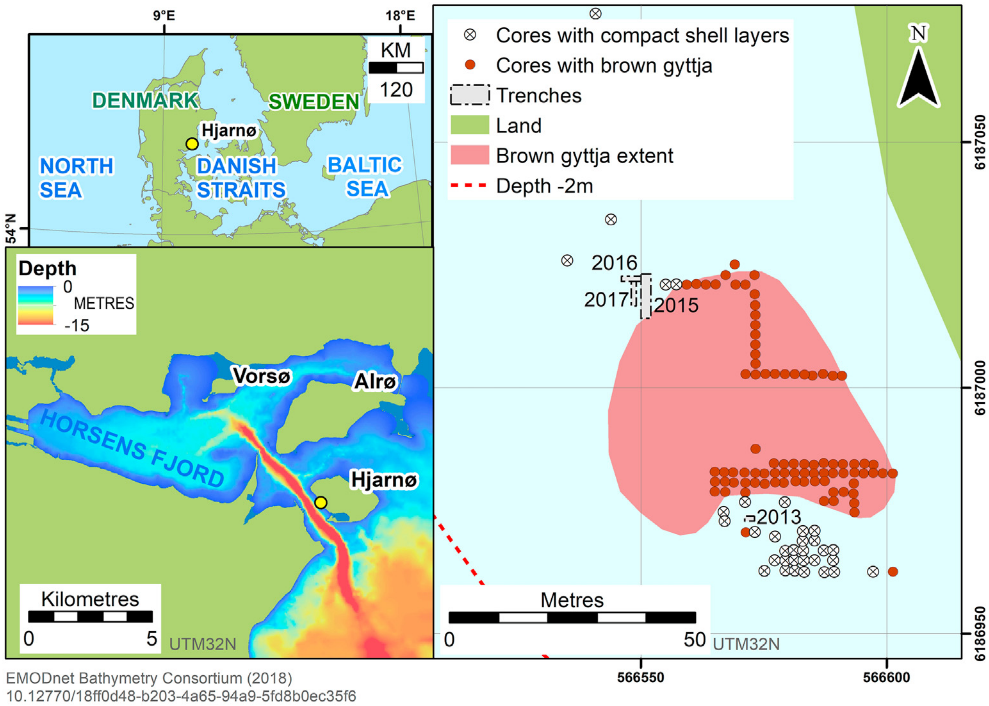

Fig. 1. Overview map showing Hjarnø Sund, including locations of excavation units, cores, trenches and other major features.

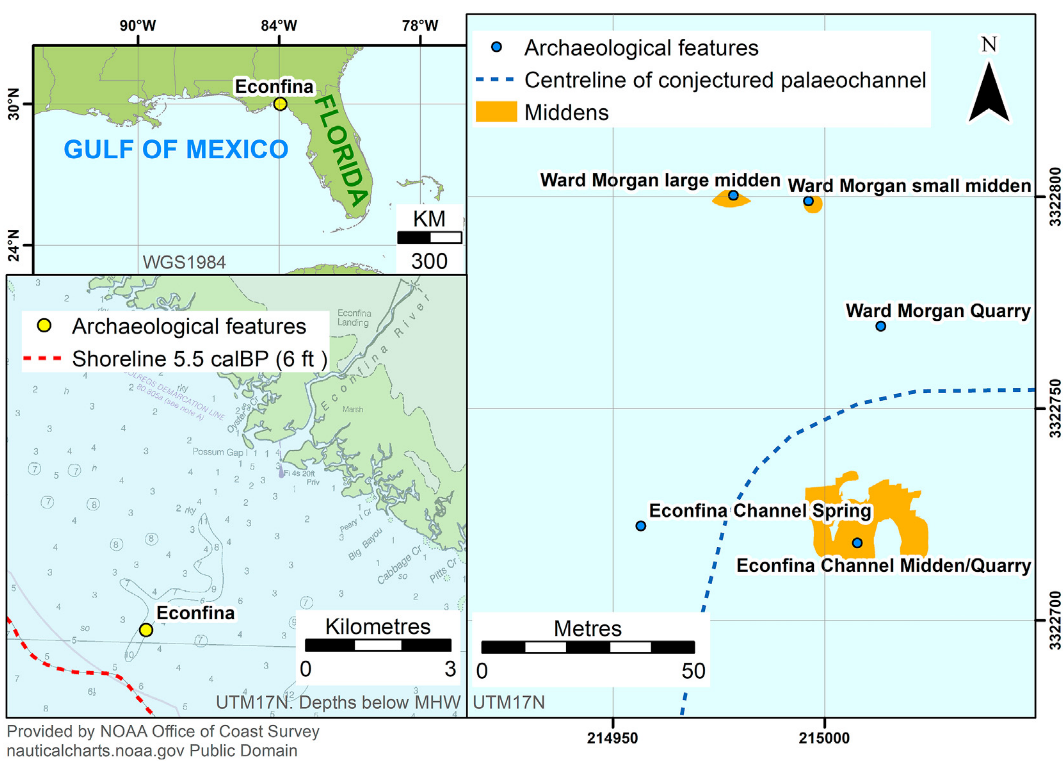

Fig. 2. Overview map showing the location of the Econfina Channel site as well as major features within the site itself.

It has often been assumed that such an underwater investigation would be fruitless because submerged shell middens are assumed to have been destroyed by sea-level rise or reduced to deflated scatters indistinguishable from natural deposits of shells and sediments on the seabed (Andersen 2013; Bailey 2014; Nutley 2014). However, it is now clear from our recent discoveries that some shell middens have survived marine transgression, and it seems likely that many others await discovery if we can establish the conditions conducive to their preservation and how to locate and identify them. There is no *a priori* reason to suppose that shell middens are more vulnerable to destruction or displacement by wave action and water currents than other types of archaeological sites or carbonate shell deposits (e.g. Kidwell and Holland 2002). Moreover, the large volume and relative durability of the shells and their sedimentary matrix, even when subject to disturbance or even partial destruction, mean that they should potentially retain a wealth of macroscopic, microscopic, mineralogical and geochemical data about the original conditions in which the deposits were accumulated, the cultural practices and subsistence activities associated with their formation, and the post-depositional processes of subaerial and submarine degradation or disturbance to which they have been exposed. Given this background, our aims in this article are to:

1. Analyse, within a comparative framework, the two underwater shell deposits that have recently been discovered and established as middens – the Hjarnø Sund site from Denmark in southern Scandinavia (Astrup et al., 2020) and the Econfina Channel site from Florida (Cook Hale and Garrison 2019);
2. Apply the same suite of geoarchaeological methods to unravel their depositional histories and subsequent post-depositional transformations after abandonment and inundation by sea-level rise;
3. Establish how the anthropogenic nature of these deposits might create a distinctive sedimentological profile or profiles, and provide improved methods for the detection and analysis of similar sites in other underwater contexts, especially where depth underwater or difficulties of access prevent full-scale excavation;
4. Explore the implications of the results for the interpretation of geographical and temporal gaps in the coastal archaeological record.

2. Regional context of case studies

2.1. Southern Scandinavia (Hjarnø Sund)

The history of postglacial sea-level change in southern Scandinavia is unusually complex owing to the proximity of the Scandinavian ice sheet, the interaction between eustatic sea-level rise and isostatic land movements associated with deglaciation, and periodic damming of the Baltic by temporary barriers of ice and uplifted land to create a freshwater lake (Astrup 2018; Bailey and Jöns 2020; Bailey et al., 2020b; Jöns et al., 2020; Nilsson et al., 2020). A fully marine connection between the North Sea and the Baltic through the Danish Straits approximating the present-day configuration was established after about 8500 cal BP (the Littorina Transgression). Most shorelines in the early part of this period in Denmark are still submerged at depths of ca. −8 m MSL (8 m below Mean Sea level) or more, depending on local isostatic effects. Occasional traces of underwater archaeological material from this earliest period suggest that people exploiting marine resources colonised this new coastal landscape as soon as it became available (Bailey et al., 2020b). However, most underwater sites in the region are later in date, from locations in shallower water, −5 m MSL or less, so that little is known about the nature of the earliest marine adaptations (Astrup et al., 2020; Bailey et al., 2020b).

In Denmark, most of the underwater finds that can be dated belong to the Ertebølle culture, ca. 7400–6000 cal BP, named after the type site first investigated in the 19th century, which consisted of a large shell mound. This period is also characterised by coastal sites – many are shell mounds, but also many are lacking in shells (Andersen 2000) – coastally adapted societies, specialised marine technologies, and increased evidence of sedentism. The first ceramics appear during the Ertebølle period from about 6700 cal BP onwards, prior to the introduction of the Neolithic FNB culture with agriculture around 5900 cal BP. The coastal sites of the Ertebølle period in the north of Denmark are mostly above the modern shoreline, at up to +12 m MSL, because of isostatic uplift, and the archaeological record includes hundreds of on-land shell middens. Numerous coastal sites of this period also occur in southern Denmark but are mostly under water because of the combined effects of final eustatic sea-level rise and isostatic submergence (Fischer 1995, 2004, 2007; Skaarup and Grøn 2004; Andersen 2013; Astrup 2018; Fischer and Pedersen 2018; Bailey et al., 2020b). Underwater shell middens are almost unknown, either because they have been destroyed by marine erosion, are difficult to distinguish from natural shell beds, have not yet been detected, or because far fewer edible marine molluscs were available along these southern shorelines.

The recently excavated underwater shell midden of Hjarnø Sund is a rare exception. It is located on the west coast of a small island (Hjarnø) in Horsens Fjord, Denmark (Fig. 1) and the midden area was found 50 m from the modern coastline in a water depth of −0.4 to −1.4 m MSL (Astrup et al., 2020). The shell deposit has been dated to just over 7000 cal BP/5000 cal BC (Table 1) placing it at the beginning of the Mesolithic Ertebølle culture.

Excavation and coring in the wider area indicate two discrete areas of shell accumulation about 50 m apart, each about 30 m × 20 m in extent with a maximum thickness of 0.8 m, and an extensive intervening deposit of sand and gyttja (a mud that forms at the lowest levels of peat deposits in anoxic conditions) (Fig. 1; Skriver et al., 2018; Astrup et al., 2020, Fig. 2). The deposit was formerly overgrown by eel grass, but pollution and climate change in recent decades have progressively removed this protective cover, exposing the underlying deposits to erosion. Excavations in the northern area show that the surface of the shell deposits has been partially truncated and disturbed with re-deposited shell material nearby, and is overlain unconformably by sand and gyttja, suggesting that it is the remnant of what was originally a thicker deposit (Astrup et al., 2020, Fig. 4). Beneath the shell-midden are deposits of sand and glacial till.

The gyttja deposits (layer K1), though similar in radiocarbon age and cultural content to the shell deposits, are the youngest in the sequence, partially overlapping with and stratified above the shell deposits in the northern area. With their excellent conditions for preservation of organic materials, the gyttja deposits have yielded a wide range of artefacts eroding out at the surface, including artefacts made of stone, bone and antler, wooden artefacts such as decorated paddles, bows, leister prongs and axe-shafts, and a large number of vertical wooden stakes representing remains of a stationary fish weir built out from the shore, a typical feature of underwater sites in the region. The shell deposits were identified as anthropogenic deposits originally formed on land from the presence of burnt shell, the restricted number of molluscan taxa, principally cockle (*Cerastoderma edule*) and oyster (*Ostrea edulis*), the size of their shells, the presence of unpatinated flint artefacts, vertebrate bone including fish and mammal, charcoal, evidence of burning on the shells and distinct stratigraphic layers (Astrup et al., 2020).

2.2. Gulf of Mexico (Econfina Channel)

The broad, comparatively low gradient and shallow continental shelf of the south-eastern United States presents another ideal environment for addressing questions of submerged shell midden preservation (Fig. 2). The most recent relative sea level (RSL) history has been reconstructed by Joy (2019), following earlier work by Balsillie and Donoghue (2011). At the Last Glacial Maximum (LGM),

Table 1
All radiocarbon dates for Hjarnø and Econfina Channel (Astrup et al., 2020; Cook et al., 2018; Faught and Donoghue, 1997; Skriver et al., 2018) are calibrated using IntCal20 (Reimer and Reimer 2001; Reimer et al., 2020). Dates on shell have been corrected for the local marine reservoir effect: at Hjarnø −44 ± 66; at Econfina Channel −28 ± 133. See text for further detail. Dates are in stratigraphic order (top to base), and depths are given as metres below the surface (mbs) of the deposit in question. Calibrated ages are rounded to the nearest 10 years.

Lab. No	Sample Type	Provenance	Radiocarbon Age ±1σ	Calibrated Age BP 2σ range	Calibrated Age BP Median
Hjarnø Sund					
AAR-24753	Charcoal, hazel	K1, ~0.60 mbs	6130 ± 48	7160–6890	7020
AAR-16958	Charcoal, unident.	K10, ~0.90 mbs	6396 ± 27	7420–7260	7320
AAR-16959	Bone, roe deer	K10, ~0.90 mbs	6426 ± 28	7420–7280	7360
AAR-24751	Shell, cockle	K21–0.80 mbs	6538 ± 39	7120–6640	6870
AAR-24756	Shell, cockle	K21–0.80 mbs	6515 ± 34	7090–6610	6840
AAR-26593	Charcoal, hazel	K22, ~0.85 mbs	6390 ± 49	7420–7170	7320
AAR-26592	Shell, cockle	K23, ~1.00 mbs	6515 ± 27	7080–6620	6840
AAR-26591	Shell, oyster	K19, ~1.00 mbs	6637 ± 35	7200–6750	6980
AAR-24754	Shell, oyster	K19, ~1.00 mbs	6588 ± 38	7160–6690	6920
AAR-24755	Shell, oyster	K19, ~1.00 mbs	6492 ± 48	7070–6570	6810
AAR-24750	Shell, oyster	K19, ~1.00 mbs	6617 ± 36	7180–6720	6960
AAR-24752	Charcoal, hazel	K20, ~1.25 mbs	6162 ± 34	7160–6960	7060
AAR-26594	Charcoal, hazel	K7, ~1.30 mbs	6285 ± 40	7310–7030	7210
Econfina Channel					
UGAMS-27918	Shell, oyster	0 mbs	3010 ± 25	3010–2290	2640
UGAMS-34162	Shell, oyster	0.35 mbs	4320 ± 25	4690–3900	4290
UGAMS-27919	Shell, oyster	0.40 mbs	4490 ± 25	4860–4120	4515
UGAMS-47027	Shell, oyster	0.80 mbs	4580 ± 25	5000–4230	4630

sea levels were approximately −120 to −125 m MSL. The end of the LGM did not initially result in rapid marine transgression and sea level remained at ca. −110 m MSL at 15,000 cal BP. Meltwater Pulse IA during the Bølling-Allerød interstadial caused rapid transgression, however, and by 14,000 cal BP coastlines were positioned ca. −75 m MSL. Rapid transgression recommenced between 12 and 11,000 cal BP, when shorelines retreated from −60 m to −45 m MSL. After the onset of the Holocene, these rates slowed again, and the coastline was around −5 m MSL by 6000 cal BP. The rapid transgression events during the terminal Pleistocene likely coincided with the first entry of human populations into this region (Halligan et al., 2016) but what form coastal occupations may have taken during this period and into the Early Holocene remains unclear because the palaeoshorelines of that period are under water.

It is clear that the coastal zone in what is now the south-eastern United States was occupied by at least 4500 cal BP during the onset of Late Holocene conditions, and perhaps even as early as 6000 cal BP during the Middle Holocene; but evidence for earlier settlement is now submerged (Russo 1994; Thompson and Worth 2011; Turck 2012; Williams 2000). This region had relatively high population densities when compared to other regions of North America as early as the terminal Pleistocene, probably because it was a climate refugium in comparison to other regions across the continent (Anderson and Faught 1998; Russell et al., 2009; Garrison et al., 2012). The archaeological potential of the continental shelves in the Southeast has likewise been verified by multiple successful studies on both the Atlantic and Gulf of Mexico coastlines (Anuskiewicz 1988; Anuskiewicz and Dunbar 1993; Cook et al., 2018; Garrison et al., 2016; Harris et al., 2013; Murphy 1990; Pearson et al., 2014). The Big Bend of Florida, where the peninsula meets the panhandle, contains the highest number of known submerged sites in North America (Faught 2004a, 2004b) and lies within the larger region showing coastal occupations by as early as 6000 cal BP (Russo 1994). These characteristics suggest that the Big Bend is likely to contain multiple sites comprised of shell middens, retaining evidence for coastal occupation before the modern coastline stabilised during the Late Holocene.

The Econfina Channel site is one of the few identified shell midden deposits offshore and under water. It is located approximately 3 km south-west of the mouth of the Econfina River (Fig. 2). The site was first detected by Faught and colleagues during exploratory surveys in the late 1980s and limited excavation was performed (Faught and Donoghue 1997). It was revisited by Cook Hale and colleagues beginning in 2014 and work continues there today (Cook et al., 2018). Econfina Channel is now submerged at −2 to −4 m MSL, and contains multiple features: shell midden concentrations, a quarry, and a freshwater spring (Fig. 2). The midden lies on the south edge of the palaeochannel of the Econfina River and varies in thickness from approximately 0.5 to 1.0 m. Midden materials in proximity to the palaeochannel are thinner and appear more disturbed than those lying within eel grass beds away from the channel. The midden deposits extend in length for ca. 30 m along the axis of the channel, and up to 20 m across from channel margin into eel grass beds. Ongoing mapping activities have detected additional shell midden deposits across the palaeochannel to the north that are up to 27 m in length, again along the axis of the palaeochannel. The exact size and extent of the site remains to be confirmed.

The site was occupied as early as 7000 cal BP, with deposition continuing until submergence. Projectile points of Putnam/Newnan types were recorded during initial excavations in the 1990s (Faught and Donoghue 1997); these were in use from approximately 7000 cal BP to 5000 cal BP. Radiocarbon dates obtained from both the main midden at the site and the midden across the palaeochannel range from approximately 5500 cal BP to 3000 cal BP at the latest (Cook et al., 2018; Faught and Donoghue 1997). The presence of lithic debitage among the midden deposits supports the argument that at least part of the site was subaerial during occupation. Submergence appears to have occurred after 4500 cal BP, but late Holocene RSL curves in this region remain opaque (see Joy 2019). The low gradient of the seabed combined with evidence for isostatic subsidence associated with mantle forebulge relaxation effects detected by Watts and colleagues suggest that submergence may be a result of subsidence of the lithosphere rather than eustatic sea-level change (Watts 2001; Smith and Pun 2006, Fig. 13.14).

The site contains evidence for multiple activities related to subsistence and technological practices. Debitage created at all stages of lithic reduction can be found across various areas of the site; primary reduction remains were found in the quarry area and freshwater spring, while finishing flakes and breakage debitage were recovered from the midden area. Molluscs, specifically *Crassostrea virginica* (oyster) were clearly processed here as well, as demonstrated by the significant quantities of this species in these sites. This location also provided ready access to freshwater, as evidenced by the freshwater spring. These findings support arguments that archaeological inquiries in this region should expect to find Late and Middle Archaic patterns of coastal resource use extending under water into the offshore zone and to earlier periods (McFadden 2016; Sassaman et al., 2017). However, it is important to note that the current body of evidence lacks archaeological sites and data on resource exploitation patterns earlier than 5000 cal BP, when the coastline began to stabilise at roughly the modern position.

3. Methods

Our methods are adapted from Gagliano et al. (1982) and refined through application at multiple submerged sites. These methods are drawn from geological principles that treat sediments from archaeological sites as bioclastic anthropogenic deposits (Gagliano et al., 1982; Murphy 1990; Pearson et al., 2014). This study is also informed by concepts drawn from sequence stratigraphy and palaeobiology. Sequence stratigraphy connects sedimentary deposit sequences to cycles of marine transgression and regression across different chronological orders of magnitude using sedimentary signatures for erosion, deposition, and depositional environment (Catuneanu 2017). Because we are directly concerned with erosional potentials along coastlines that experienced relative sea-level changes, such concepts are highly relevant; archaeological deposits such as these are by definition included within marine transgression erosion and ravinement surfaces that overlie formerly subaerial erosional unconformities recognized as sedimentary sequence boundaries (Catuneanu 2017).

Our methodology is also informed by taphonomic studies in palaeobiology because they examine the preservation potentials for fossil deposits found in sedimentary sequences (Kidwell 1993; Kidwell and Holland 2002). These studies have shown that biomineralizing organisms such as the mollusc taxa found in shell middens have high potential for inclusion in the fossil record, even if only partially intact. Taken together, these concepts allow us to understand submerged shell middens as a specific type of bioclastic deposit with anthropogenic origins subjected to well understood sedimentary processes associated with cycles of marine regression and transgression.

For this study, we used a combination of optical petrography using both transmitted and reflected light, electron microprobe analysis (EMPA), scanning electron microscopy (SEM), and particle size analysis (PSA) modified from Folk and Ward (1957). These techniques provide qualitative data on mineralogical characterizations, microfossil assemblages, and various types of non-geological inclusions, and quantitative date on particle size distributions. For PSA we included non-clastic materials such as shell fragments, bone, and charcoal, because they provide additional information about human activities. However, we acknowledge that inclusion of non-clastic materials skews the results of particle size analysis such that we cannot rely on quantitative analysis alone to infer depositional environments. Therefore, we have reinforced interpretation with qualitative assessments based on mineralogical composition and microfossil inclusions. We have also compared the results of mechanical particle size analysis with digital analysis of grain size applied to micrographs generated by SEM/EMPA performed at millimetre-scale resolution using the software package ImageJ/Fiji and backscattered electron micrographic images taken using SEM.

3.1. Sample recovery

Analyses were performed on sedimentological samples taken at Hjarnø in 2017 and Econfina Channel in 2015–2017 and in 2019. At Hjarnø, the samples from the shell midden were obtained by the removal of two box cores in stratigraphic sequence, each 30 cm × 30 cm x ca. 10–15 cm deep, from the side wall of the 2017 excavated trench (Fig. 1; Ward et al., 2019, Fig. 2). Two push cores 5 cm in diameter were also used to collect samples from the sediments beneath the shell-midden deposit.

The stratigraphy and labelling of the samples from the Hjarnø box cores following Ward et al., (2019), Astrup et al., (2020) are as follows:

Upper Box Core (A)

BC101: 0.01–0.09 mbs (metres below surface), Layer K21, layer dominated by cockle shells including a hearth.

BC102: 0.09–0.10 mbs, Layer K21, cockle-shell layer.

BC103: 0.10–0.19 mbs, Layer K19, layer dominated by oyster shells.

Lower Box Core (B)

BC201: 0.21–0.29 mbs, base of Layer K19, and top part of Layer K24, described as ‘coarse sand’ (Astrup et al., 2020, Fig. 4) or ‘well sorted grey … medium silty sand’ (Ward et al., 2019, Fig. 2)

BC202: 0.29–0.34 mbs, continuation of Layer K24.

The Econfina samples from 2015 to 2017 were taken using bulk sampling methods (see Cook et al., 2018) across the site and include materials from the surface sediments within the midden, the lithic quarry zone, the palaeochannel, and the eel grass beds beyond the midden zone itself. The sample from 2019 was taken using a hand-driven 3-inch aluminium core that specifically targeted the lower level of the midden after it was exposed by hand excavation to remove the top 40 cm of surface materials. The area of the midden chosen for coring was within the southern and eastern section of the site where eel grass beds have preserved finer sediments and where past sampling indicated that the midden is thickest, and likely best preserved. The northern and western edges of the midden grade into the Econfina palaeochannel and are more poorly preserved, with depth to bedrock often less than −0.4 m. Bulk sampling in 2015–2017 has shown that the only area of the midden suitable for coring is within these eel grass beds (Cook et al., 2018; Garrison and Cook Hale 2019). The lower-lying material was expressly targeted because prior studies from 2015–2017 had already examined the upper levels to characterise the degree of disturbance caused by marine transgression (Cook et al., 2018; Garrison and Cook Hale 2019). The lower levels, however, were considered to have a higher probability of being undisturbed, offering better insight into the original depositional context and site formation processes.

3.2. Sample preparation

Samples from the Hjarnø box cores were previously examined by Ward et al. (2019). Materials from the box cores arrived for analysis at the University of Georgia (UGA) Geoarchaeology laboratory in the form of thin-section slides, previously prepared thick-section epoxy mounts, loose materials, together with sediments from within the two cores from beneath the midden. The thin sections included slides from the full midden sequence represented by both box cores (BC101–103, BC 201 and BC 202), the epoxy mounts represented only the sediments in the lower box core (BC 201 and 202). Both the thin sections and the epoxy mounts required further preparation since they were unpolished and thus not suitable for examination by electron microprobe analysis (EMPA) or scanning electron microscope (SEM) and this polishing was subsequently undertaken at the UGA EMPA lab. Thin section slides were polished to a mirror finish, down to 1-μm sized grit. All samples used for SEM and EMPA analysis were then carbon-coated before analysis.

Bulk sediment samples from across the Econfina Channel site were dried in the UGA Geoarchaeology laboratory after recovery. The core from Econfina Channel was also split at the UGA Geoarchaeology lab immediately after recovery, photographed and assigned Munsell colours (Fig. 3). It was then oven-dried at 60 °C at UGA Crop and Soil Sciences before being impregnated with epoxy and cut into individual sections. These were also polished to 1-μm sized grit and carbon coated.

3.3. Optical petrography

Images of the box core slides were taken using transmitted light using a petrographic microscope equipped with Nikon image capture capabilities at the UGA Department of Geology. Images of the epoxy mounts from both Hjarnø and Econfina were taken using reflected light instead due to the thickness of the specimens. These datasets were useful for qualitative characterisation of micro-stratigraphy, microfossils, and the presence or absence of inclusions such as charcoal, burnt shell, and micro-debitage.

3.4. Electron microprobe analysis (EMPA)

The Hjarnø box core slides were analysed with the UGA Department of Geology JEOL 8600 electron microprobe using a 15 KV accelerating voltage and 15 nA beam current. Mineral grains were qualitatively identified using a Bruker 5010 Silicon Drift Detector (SDD) energy dispersive X-ray (EDS) detector controlled by a Bruker Quantax energy dispersive analysis (EDS) system. Analyses were calculated using the Phi-Rho-Z matrix correction model (Armstrong, 1988). Backscattered electron images (BEI) and secondary electron images and X-ray maps were acquired using imaging software of the Quantax analysis system.

X-ray maps were generated for individual study areas within each slide using a dwell time of 5 min for each area mapped. At least 5 areas were examined in the box core slides from Hjarnø at 75× magnification. This covered a roughly 3.5 mm by 3 mm area at each location on the sample. Areas of specific mineralogical interest were identified at higher magnification as needed.

Epoxy mounts from Econfina Channel were not suitable for EMPA given the small size of the vacuum chamber and configuration of the sample mounts, but they were suitable for SEM analysis.

3.5. Scanning electron microscopy (SEM)

Epoxy mounts from both Hjarnø and Econfina Channel were examined in Hitachi FlexSEM 1000II at the Georgia Electron Microscopy Laboratory at the University of Georgia. We used variable pressure and performed backscatter imaging, though we included some limited EDS reconnaissance for qualitative characterisation of mineralogy in the samples from Econfina Channel. Samples were carbon-coated and mounted to the stage with copper tape to minimise charging effects. Operating voltage was 20 keV and magnification was either 50× or 80x. Micrographs were taken along spacings designed to limit inclusion of shell materials (although they could not be completely eliminated due to their prevalence in both sample sets), focusing on clastic materials instead.

For the Hjarnø material, the total estimated area of epoxy mounts was approximately 6000 mm^2, the total area imaged (all samples combined) was 1000 mm^2, and a total of 216 micrographs were taken. For Econfina Channel, the total estimated area of epoxy mounts was approximately 6250 mm^2, the total area imaged from all samples combined was 915 mm^2, and a total of 182 micrographs were taken.

3.6. Particle size analysis (PSA)

Because of the variable nature of the material available for analysis, it was only possible to conduct mechanical PSA on the bulk samples from the Econfina Channel midden and from other features in the vicinity of the site, and from the cores taken from sediments beneath the midden at Hjarnø. However, we were able to obtain digital PSA results from the epoxy mounts of the lower box core from the Hjarnø midden and from the epoxy mounts from the core into the lower part of the midden at Econfina Channel. Thus, we have both digital and mechanical data for the Econfina midden, digital data for the Hjarnø midden, and mechanical data for non-midden features/sediments from both Hjarnø and Econfina. For statistical methods, we first calculated distributions and first order statistical measures for all samples, classifying them into discrete groups by site, feature, and method. We then used both a parametric two-sample *t*-test and a nonparametric Wilcoxon/Kruskal-Wallis rank sums test to compare results for all particle sizes. We also ran Gradistat statistics (Blott and Pye 2001) to obtain basic statistical measures and distributions showing modality, skewness and kurtosis for PSA data, and linear discriminant function analysis (DFA) to examine differences between groups.

Fig. 3. Core from Econfina channel.

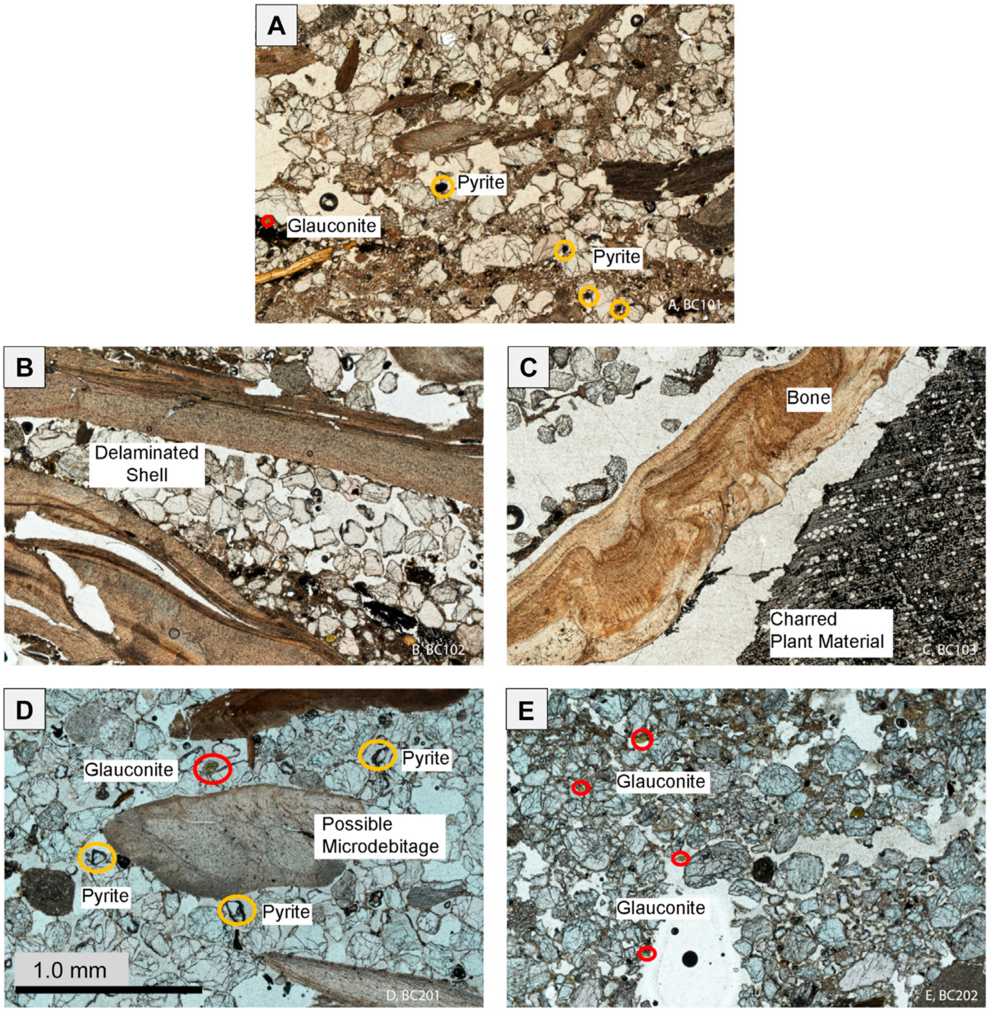

Fig. 4. Micrographs from each box core slide from Hjarnø, in transmitted, plane polarized light, showing glauconite grains, circled in red, pyrite grains in gold. A): BC101, showing the highly heterogenous nature of the midden; B): BC102, showing shell undergoing delamination; C): BC103, showing bone and charred plant material; D): BC201, showing a rock fragment, likely a piece of micro-debitage; E): BC202, showing the increase in glauconite. The BC numbers are in stratigraphic sequence. BC101–103 are from the upper box core (box core A) and refer to the shell-matrix deposits at the top of the sequence (Layers K21 and K19). BC201–202 are from the lower box core and refer to the base of the sequence (base of Layer K19 and Layer K24).

3.6.1. Mechanical particle size analysis

The bulk samples from Econfina Channel were assigned to site features based on visual inspection during recovery by divers. Push cores taken from beneath the shell-midden deposit at Hjarnø had specific provenance recorded. Once materials from both sites were sufficiently dried, they were separated into grain sizes using a mechanical shaker and sieve sizes for 63, 125, 250, 500, 1000, 2000, and 4000 μm. Each sample was weighed, then shaken for 30 min, which was sufficient time to separate grain sizes. After grain size separation was complete, material from each sieve was weighed and recorded.

3.6.2. Digital particle size analysis

Digital analysis offers an opportunity to analyse particle size distributions where mechanical methods are not applicable, as was the case with the Hjarno samples from the lower box core, where only resin-impregnated epoxy mounts were available for analysis. We were also interested in comparing digital and mechanical methods to test for consistency between the two methods. First, we processed the images in the software package ImageJ 1.52K (Schneider et al., 2012) using a macro written for this analysis by JWCH.[2] We then batch processed all the BEI images using the “Analyse Particles” tool, compiled the results in a.csv table that summarised mean particle size by filename, and plotted these in Excel. Final statistical analysis was done using the software package JMP 15.

3.7. Radiocarbon dating

We obtained one additional radiocarbon date from shell material sampled from the bottom of the core from Econfina Channel to improve chronological controls; by comparison, Hjarnø is better constrained. Other dates reported by Cook Hale and colleagues were taken from a shallow profile near the midden surface; one sample was taken at the surface of the midden/seabed, another was

[2] Macro is as follows: run(“8-bit”); setOption(“BlackBackground”, true); run(“-Make Binary”); run(“Invert LUT”); run(“Set Scale ... ”, “distance = 1 known = 0.575 pixel = 1 unit = micron”);

recovered from approximately 0.35 m below the surface of the midden/seabed, and a third was recovered approximately 0.40 m below the surface. The surface sample and the sample taken from 0.40 m below the seabed were previously reported in Cook et al. (2018). The new sample was dated at the University of Georgia Center for Applied Isotope Studies (UGA CAIS) using accelerator mass spectrometry (AMS).

The shell was subsampled at the hinge and the outer surface was dissolved using dilute HCl. The sample was then rinsed and was dried in an oven at 105 °C. The pre-treated subsample was then reacted with 100% phosphoric acid to produce CO_2. This CO_2 sample was cryogenically purified and catalytically converted to graphite. It was then measured using the 0.5 MeV accelerator mass spectrometer. The radiocarbon date was finally calibrated using the Marine20 calibration curve (Reimer et al., 2020) in OxCal version 4.4 (Bronk , 2009) using a ΔR estimate of -28 ± 133 ^{14}C years calculated using weighted averages for marine reservoir corrections for the Apalachicola Bay area (Hadden and Cherkinsky 2015, 2017). Dates for materials from Hjarnø were also recalibrated using Intcal20 (Reimer et al., 2020). Samples of shell were calibrated using a ΔR of -44 ± 66 calculated for marine reservoir corrections from Horsens Fjord region (Heier-Nielsen et al., 1995).

The oldest recalibrated date from Hjarnø is 7360 cal BP and the youngest date is 6810 cal BP. Dates at Econfina range from 4550 cal BP to 4210, with a date of 2570 cal BP at the surface of the midden (Table 1).

4. Results

4.1. Optical petrography

4.1.1. Hjarnø box core slides

Examination of the box core slides in transmitted light revealed that the Hjarnø midden materials were highly heterogenous, with ample charcoal, shell, sands of various sizes, and clay all well represented. Sands consisted of a mix of feldspars and quartz. Trace minerals included amphiboles. Two authigenic minerals were also observed: pyrite was detected within all of the slides, and some glauconite was also seen, increasing towards the bottom of the profile. Quartz and feldspar grains were sub-angular to angular, and sorting varied from poorly sorted to well sorted depending on depth within the box core. Charcoal in some cases retained internal structures of burned plant materials but not to the degree that taxonomic identification could be made. Some bone fragments were observed (Fig. 4). Ward et al. (2019, Fig. 9e) report one foraminifera in the uppermost unit of the box core (BC 101) near the midden surface, but we saw no other examples in our slides, and it remains unclear whether this single find is an integral feature resulting from overwash of the deposit as it was forming, or a later intrusion resulting from submergence by marine transgression.

4.1.2. Econfina Channel epoxy mounts

Examination of the Econfina Channel core epoxy mounts showed more homogeneity than the Hjarnø materials. Mineralogy was dominated by sub-rounded to well-rounded sand grains composed of quartz; sorting was varied. No feldspars were observed anywhere in the profile. Clay clasts were observed in the bottom of the profile. Charcoal was evident throughout the profile, but in smaller fragments, while shell materials appeared blackened and burned. Foraminifera were observed throughout the profile (Fig. 5).

4.2. EMPA of Hjarnø box core slides

Qualitative mineralogical analysis demonstrates that clear differences exist within the layers of the midden (Fig. 6). Some of these are likely associated with depositional context, but others reflect human activities. Authigenic minerals such as pyrite were observed that demonstrate diagenetic changes experienced by the midden materials since they were deposited.

BC101, a hearth feature in the cockle layer near the top of the upper box core (Layer K21), showed angular to rounded grains, with angularity that decreased down profile. Grains were overall poorly sorted. Sand sized feldspars and quartz grains were both common. Feldspars were common enough (>25%) to characterise these sands as arkosic. Feldspars included potassium feldspar and alkali feldspars. No true end member feldspars were seen, as would be expected for these minerals. The process by which feldspars crystallise from a magma is controlled by the chemistry of the original melt; calcium rich plagioclase forms at higher temperatures than sodium rich plagioclase, for example, and as the chemistry evolves and temperatures drop, feldspars show zones enriched in these elements that reflect this thermodynamic and geochemical history (Bowen 1956). A few heavy minerals were observed, including an ilmenite grain and an amphibole. X-ray mapping also showed varying degrees of pyritization within BC101, with an increase moving down the profile.

BC102, the upper layer of the shell midden dominated by cockle shells (Layer K21), showed angular to sub-angular grains, with no apparent change in angularity within the profile. Sand sized feldspars and quartz grains were both common, and sorting was poorer than in BC101. Feldspars were slightly less common in BC102 (~20%, approximately), making these sands less arkosic than BC101. Feldspars again included potassium alkali feldspars, and again no true end member feldspars were seen. Amphibole was again observed in BC102. X-ray mapping showed increasing degrees of pyritization within BC102 compared with BC101; this increase was observed moving down profile, suggesting that redox conditions in this portion of the midden were more anoxic (Fig. 6).

BC103, the oyster-dominated midden unit (Layer K19), was similar to BC101 and BC102, again showing poorly sorted angular to sub-angular grains. Sand sized feldspars and quartz grains were both common. BC103 also showed a greater abundance of clay and rock fragments, though the mineralogy is again consistent with the local glacial till deposits. Feldspars, as before, included potassium alkali feldspar, and again no true end member feldspars were seen. Amphibole was also again observed in BC103. X-ray mapping showed increasing degrees of pyritization compared with BC102; this increase was observed moving down profile, suggesting that redox conditions in this portion of the midden were increasingly anoxic compared to BC101 and BC102.

BC201, the deposit at the base of the shell midden (the boundary between Layers K19 and K24), showed minimal to no identifiable shell fragments. Feldspars and quartz grains were dominant, once again, with no apparent change in ratio of feldspar types, which again showed no true end members. Pyritization increased again in BC201. Additionally, BC201 was poorly sorted, with the most heterogenous sorting evident mid-profile. The presence of pyrite but the lack of shell suggests that this sample may represent the bottom of the midden deposit because the formation of authigenic pyrite is enhanced by anoxic environments where sulphur is available, such as that found in marine sulphates.

BC202, the lowest unit in the sequence (Layer K24), showed minimal to no identifiable shell fragments. Mineralogical

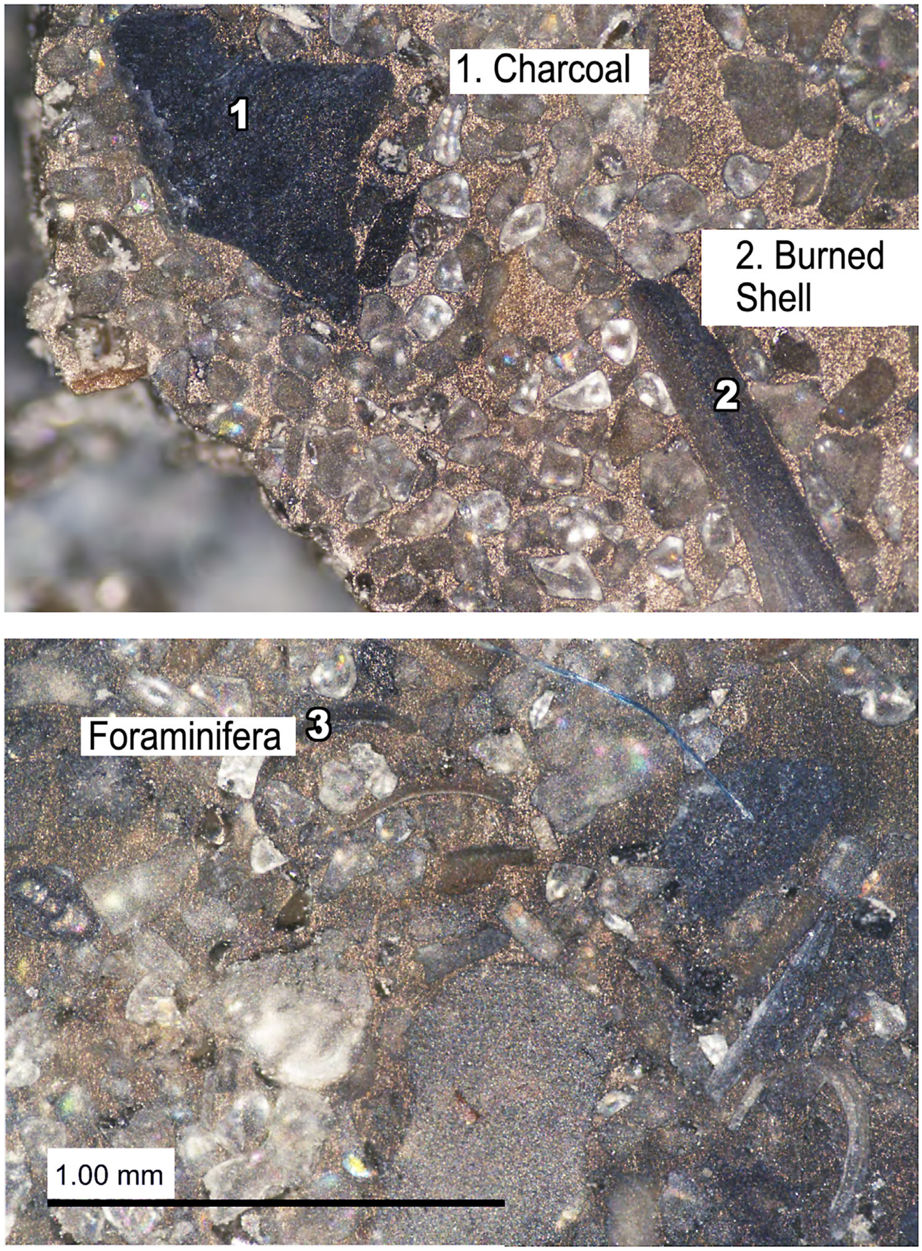

Fig. 5. Micrographs taken in reflected light of the area at the bottom of the core sample from Econfina Channel. 1: charcoal fragment; 2: burnt shell; 3: foraminifera test.

composition was much the same as the four samples above, but clay was greatly increased, along with what appear to be rip-up clasts, which are large clasts eroded during high energy events such as floods. Grains were very poorly sorted and more rounded than above. Pyritization was greatest in this sample. Large clasts were separated by layers of much finer materials, including clay and very fine quartz-dominated sands.

4.3. SEM of epoxy mounts

4.3.1. Hjarnø

These were primarily studied for imagery suitable for PSA analysis in ImageJ (see section 4.4), since mineralogy had already been confirmed qualitatively by EMPA analysis on the box core slides. Pyrite was again visible in framboidal form. Inclusions such as bone were confirmed, while no foraminifera were observed. These findings were all consistent with petrographic investigations and EMPA results.

4.3.2. Econfina

Econfina samples were assessed for mineralogy on a qualitative basis using electron dispersive spectroscopy (EDS). Clastics were all quartz, and no feldspars were observed. Average grain sizes trended towards fine and very fine sands. Clay clasts were evident in the bottom of the profile and showed strong evidence for pyritization; iron and sulphur were both detected in amounts greater than 1%. Sediments and general geochemistry are consistent with a brackish tidal marsh environment rich in organic materials subject to influx of marine sulphates during tidal cycles. No organic materials such as woody stems or leaves were observed, but this is not surprising in a sample from subtropical tidal marsh where humid conditions and warm temperatures support decomposition. The modern

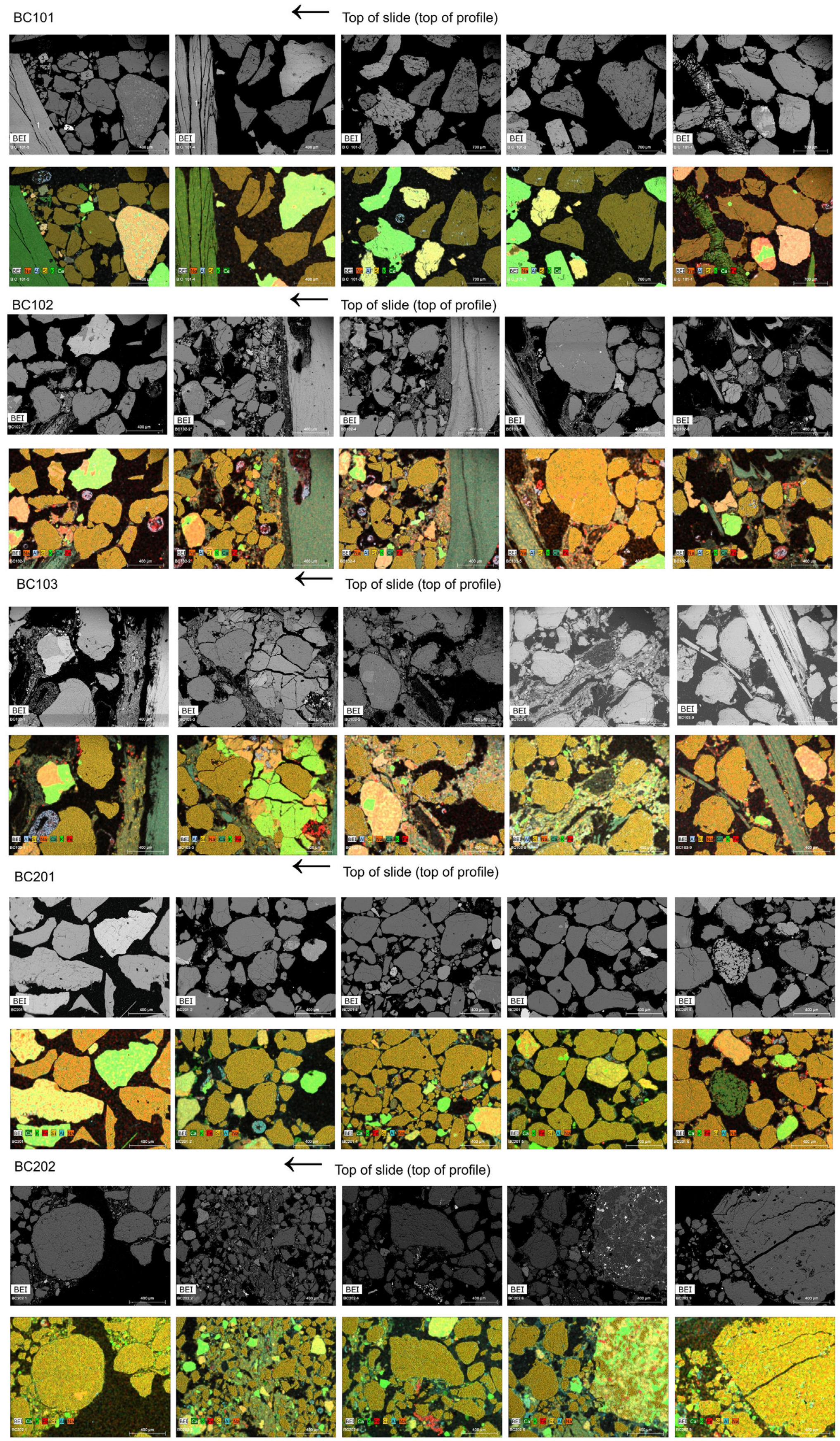

Fig. 6. EMPA x-ray maps of thin sections from the Hjarnø box cores. Backscatter electron images (BEI) within each layer are numbered in sequence from the top of the layer to the base (left to right in the illustration), and the images for each layer are shown in stratigraphic order, with BC101 at the top of the illustration and BC202 at the bottom. For explanation of BC numbers, see Fig. 4 caption and text. Further details are as follows: BC101: 1) Shell; 2) Ilmenite; 3) Amphibole; BC102 shows increased pyrite occurrence, finer grained matrix with rock fragments, apatite (bone) and shell; BC103 shows similar features to BC102; BC201 shows a reduction in pyrite and shell materials; BC202 shows an increase in clay and other fine particles along with intermittent coarse grained materials.

environment along the banks of tidal creeks in Apalachee Bay consists of sediments of much the same nature.

The material from Econfina Channel also contained ample shell materials in varying states of preservation. Many shells showed deterioration along their edges in SEM and microscopy, with discernible blackening along the outer edges as well. This blackening may be associated with burning, since EDS reconnaissance did not detect pyritization along the edges of shell fragments. This blackening could also result from discolouration from the surrounding sediments. We also observed abundant foraminifera throughout the profile, including in close proximity to the clay clasts observed at the very bottom of the profile. Most of these appeared to be *Globigerinoides* sp.; they consisted of tests with trochospiral morphology (chambers are arranged in a spiral coil).

Finally, it is noteworthy that opaline chert, a form of cryptocrystalline quartz material is present in pore spaces in the lower levels of the profile (Fig. 7). Small bright dots are pyrite in framboidal form, which appears to have formed within pore spaces. The opaline chert is visible in the form of concentric layers and circles forming in pore spaces. One foraminifera test can be observed in the lower right-hand portion of the composite micrograph and it shows no evidence for dissolution. However, other ovoid shapes within the centre and to the left side of the image are not consistent with foraminifera and show much greater evidence for dissolution.

4.4. Particle size analysis

Particle size analysis offers insight into depositional context because particle size movement is controlled by the strength of a force acting on these sediments. Generally speaking, larger particles require stronger forces to mobilise them, though mobilisation of clay and silt is also affected by their electro-static characteristics. Deposition is likewise a result of the strength of forces acting on sediments; larger sized particles generally come to rest in higher energy conditions, but smaller particles do not settle until forces subside (Folk and Ward 1957; Hjulstrom 1935).

We emphasise that mechanical particle size analysis in this study was carried out without removing the non-clastic materials. Particle size analysis results are not therefore conclusive by themselves and must be assessed alongside mineralogical characteristics and microfossil inclusions to infer depositional context. In the case of Hjarnø, samples suitable for mechanical PSA were only available from the cores taken from deposits beneath the midden, not from the midden itself. For the latter we have relied on digital PSA of the epoxy mounts from the lower part of the sequence (box core B). However, we emphasise that digital PSA did not include particle sizes finer than 63 μm (silts and clays) for two reasons. First, the method used in ImageJ could not reliably differentiate between remaining speckles in the micrographs and actual particles. Second, clay clasts were read as solid particles by the software during processing. Therefore, only sand size analysis is presented for these samples.

4.4.1. Vertical midden profiles: digital PSA results

4.4.1.1. Hjarnø. Materials from the Hjarnø epoxy mounts in box core B were dominated by very fine and fine sands (<250 μm), with slightly fewer very fine sands (63-μm size fraction) than Econfina and a slight decrease in very fine sands moving down profile. Medium to very fine gravels made up less than 25% of the samples tested, though to varying degrees (Fig. 8, S1, see also S5, S6, S10). The coarsest materials (2000–4000-μm size fractions, very fine gravels) were found midway down the profile, below which was an increase in very fine sands again. The very fine gravels are most likely representative of increased shell in this section of the box core. The lower third of the profile (from −0.295 to −0.34 mbs) shows a clear pattern of intermittent spikes of coarser versus finer materials, consistent with the findings from BC201 and BC202 during EMPA analysis. Minimal to no shell was evident during visual examination, suggesting that these coarser materials are in fact clastic and not carbonate materials. The Gradistat statistics provide additional confirmation of these characteristics, typically showing mean values for particle sizes in the fine sand to medium sand categories but with a skew towards the coarser end of the range. Kurtosis is varied and the distributions are typically polymodal, both features reflecting the poorly sorted nature of the sediments.

The almost complete lack of foraminifera in the Hjarnø deposits argues against storm overwash. We cannot rule out intermittent high energy events associated with aeolian forces but given the sedimentology of the region we consider it most likely that these larger particles towards the bottom of the profile represent poorly sorted glacial or glacio-fluvial till sediments that represent the original land surface upon which the midden was deposited, instead of midden materials themselves (Astrup et al., 2020).

4.4.1.2. Econfina. The Econfina samples contained slightly more coarse materials than those from Hjarnø. Towards the top of the profile, spikes of very fine gravels appear, interspersed with medium and fine to very fine sands (Fig. 8). These larger particles appear to represent shell, given the dominance of these materials in this part of the profile and past results from bulk sediment sampling showing that very fine gravels correlated with shell within the midden (Cook et al., 2018). This pattern shifts at around −0.425 m to less extreme variation but reappears around −0.555 m to −0.565 m and may represent impacts on shell materials such as de-calcification, trampling impacts, or other taphonomic changes. From −0.565 m to the bottom of the core, visual inspection showed that clay clasts were present within the sediments. PSA results actually show a decrease in finer sediments suggesting that the increase in the very fine gravel fraction may include these clasts.

This observation suggests two possibilities: either forces acted on this midden deposit that were sufficient to erode clays in the form of clasts, or, alternatively, these clasts formed during flocculation of clay particles in a brackish estuarine context. Either scenario is possible given the location of this midden. The microfossil assemblage of foraminifera indicates that the Econfina palaeochannel was, at the time the midden was deposited, a tidally influenced estuarine feature. This may indicate that a higher energy environment was present at Econfina Channel in comparison to Hjarnø, but additional study of clastic materials will be necessary to fully support this conclusion.

Gradistat statistics are consistent with these observations, showing that samples were generally trimodal to polymodal and poorly sorted. Texturally, they were generally slightly gravelly to gravelly sands and kurtosis was again varied, likely reflecting the poorly sorted nature of the deposit. Mean particle size was generally medium sand and skewness ranged from very fine through symmetrical to coarse. A few locations that overlapped with the eel grass beds to the south were bimodal and moderately sorted, with texture ranging from sandy gravel to gravelly sand and distributions showing variable skewness (S2, see also S5, S6, S10).

4.4.2. Non-midden samples: Mechanical PSA results

4.4.2.1. Hjarnø. Gradistat results from samples subjected to mechanical PSA from below the Hjarnø midden were also trimodal to polymodal like those from the midden profile but showed both

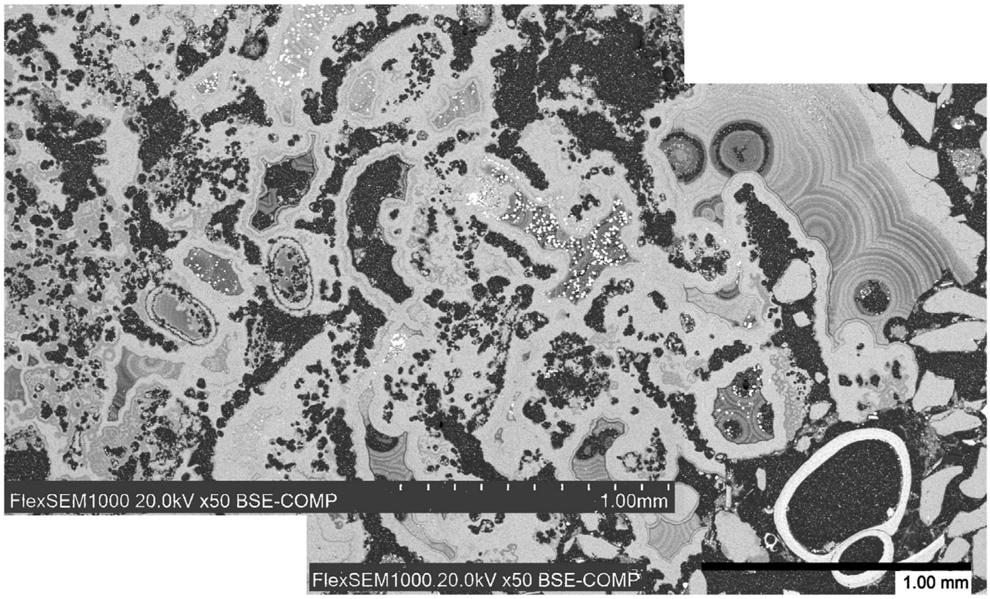

Fig. 7. Composite micrograph taken by SEM of opaline chert formation within pore spaces in the lower levels of the core from Econfina Channel. Opaline chert is defined by its concentric patterning within the spaces that it infills.

poor and moderate sorting. Texturally they were slightly gravelly sand though one sample was gravelly sand. Mean particle size was medium sand. Skewness ranged from fine to symmetrical to very coarse, and kurtosis was predominantly leptokurtic (S3, see also S5, S6, S10).

4.4.2.2. Econfina. Gradistat results from samples subjected to mechanical PSA across the Econfina Channel site varied by location. Samples from the surface of the eel grass beds at Econfina were polymodal, trimodal or bimodal, and ranged from poorly sorted to moderately well sorted. Texturally, these sediments were gravelly sand to slightly gravelly sand, skewed towards very coarse materials, and were mesokurtic to leptokurtic. Mean particle sizes were fine, medium, and coarse sands, with finer particle sizes further south of the midden. Sediments from the quarry zone taken at the surface were polymodal with a few trimodal samples and ranged from poorly sorted to very poorly sorted. Texturally, they resembled the midden and were composed of sandy gravel or gravelly sand. They skewed from fine to symmetrical to coarse or very coarse materials. Kurtosis ranged from mesokurtic to very platykurtic, while mean particle sizes ranged from medium to coarse or very coarse sands. One sample was recovered in 2015 from the paleochannel itself. It was polymodal and poorly sorted gravelly sand. It skewed towards coarse materials and its kurtosis was mesokurtic. Mean particle size was medium sand (S4, see also S5, S6, S10).

4.4.2.3. Comparison of Econfina and Hjarnø mechanical PSA. Samples subjected to mechanical PSA from Econfina showed greater variability than those from Hjarnø, including some overlap between midden and non-midden quarry zone and eel-grass zone samples at Econfina. Sorting was also more variable at Econfina and included samples that were moderately well sorted. The only samples from Hjarnø that were similar were the moderately sorted samples from beneath the midden.

These differences likely result from differences in parent geology and sedimentary conditions between these two marine basins. Analyses included samples from across multiple site features at Econfina, while the non-midden samples at Hjarnø were confined to eight samples recovered from two push cores that expressly targeted sediments from below the midden itself. Interestingly, these findings suggest that non-midden deposits such as the samples from below the midden at Hjarnø and the eel-grass zone at Econfina may be generally better sorted than the midden samples from both sites.

4.4.3. Digital versus Mechanical PSA results

Parametric statistical comparison of mean particle size by method (One way, student's t-test) indicates that there are differences between the mean values for each particle size derived from each method. Non-parametric statistical comparison of mean particle size by method (Wilcoxon/Kruskal-Wallis, ranked sums) also shows that there are differences between the mean values for each particle size, with the exception of the 500-μm size fraction (S7, see also S5, S6, S10). These differences between the two methods could be because the materials tested using mechanical separation were surface materials from Econfina and from below the midden at Hjarnø, whereas the materials tested using digital methods were taken from vertical profiles within each midden that clearly demonstrate change with depth. It could also be the case that digital PSA methods over- or under-counted various size fractions due to digital "noise" in the micrographs.

5. Discussion

5.1. Site depositional contexts

5.1.1. Hjarnø

Prior studies suggest the midden was deposited on a subaerial beach terrace composed of glacial or glacio-fluvial till deposits (Skriver et al., 2018; Astrup et al., 2020). Our findings support this interpretation and amplify the results of the earlier micromorphological study (Ward et al., 2019; Ward and Maksimenko 2019) through more detailed correlation of the mineralogy with the parent geology and comparative analysis of midden and non-midden sediments at Hjarnø and Econfina channel. EMPA analysis indicates that these sediments are generally arkosic in mineralogy and include minor heavy minerals such as ilmenite and amphibole. This suggests that their source was likely granitic.

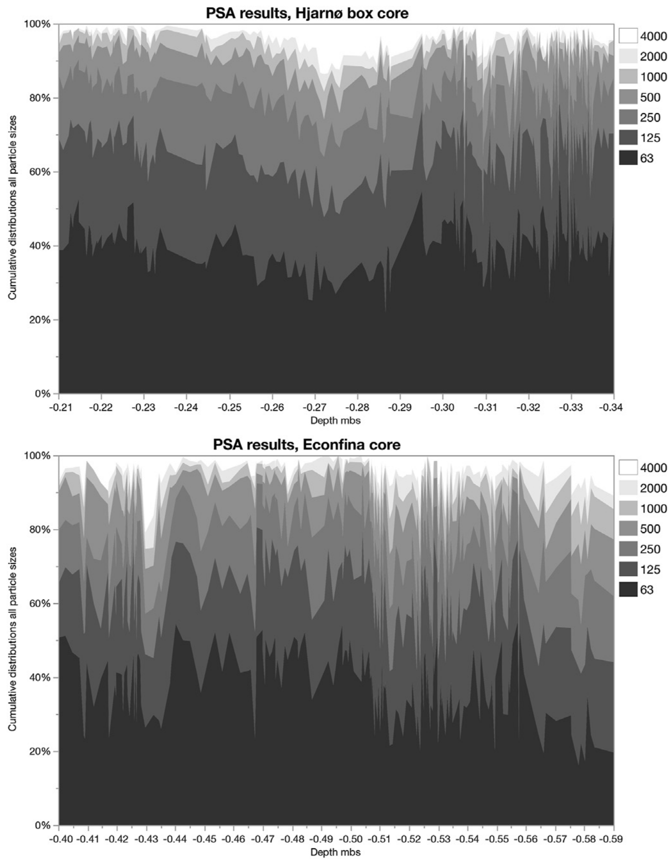

Fig. 8. Digital PSA results from Hjarnø and Econfina Channel materials showing microstratigraphic variation in the proportions of coarse to finer grained material through the two sequences. Samples were measured at approximately 1-mm intervals and are shown in stratigraphic order, reading from left to right, with depths given in metres below midden surface (mbs). The Hjarnø data refers to the lower part of the midden sequence in box core B. The slightly higher proportion of coarse materials can be seen in the profile from Econfina. The profile from Hjarnø shows where coarser fractions intermittently dominate the sediments in the lower levels of the profile and these most likely correlate with the contact between the midden and the land surface, which was composed of poorly sorted glacial or glacio-fluvial till. Details of provenance and depth relationships are given in the text and in Supplementary files S1, S2 and S10, which also give full details of particle size statistics.

Transport to this area of Jutland probably occurred during the LGM when the expansion of the Scandinavian ice sheet eroded bedrock of this type in Norway; once the ice sheet collapsed these sediments were deposited as glacial till. Thus, sediments within and below this midden are local and reflect the regional geology and geomorphological history.

Other characteristics of the midden also support interpretation of deposition in a terrestrial context. The poorly sorted materials are consistent with both glacial till and anthropogenic origins but are inconsistent with particle size distribution patterns found in non-anthropogenic geomorphological contexts such as shoreface deposits or tidally influenced channels. For example, shoreface deposits tend to show consistent grain size sorting; upper shoreface deposits are usually comprised of coarser grains while finer grain sizes usually only settle in lower energy contexts further offshore. Likewise, tidal deposits usually, though not always, show features such as mud drapes and/or herringbone patterns associated with ebb and flow (Nichols 2009). These features can be ephemeral, however. A better indicator of terrestrial deposition is the almost total lack of foraminifera or any other inclusions suggestive of marine or brackish water contexts. The glauconite and pyrite are both authigenic minerals that form in anoxic conditions during and after submergence and cannot be used to infer original depositional context. Finally, zooarchaeological results are consistent with terrestrial midden deposits; while the oyster and cockle are marine taxa, the condition of the shell is consistent with processing for food, and land snails were also found within the midden materials (Astrup et al., 2020).

The two slides from the lower box core examined by EMPA, and the PSA analysis from the epoxy mounts from the lower box core, appear to represent the bottom of the midden and contact with the former land surface upon which it was deposited. This is based on the lack of shell and charcoal and increase in sand stringers with rip up clasts that are interspersed with fine grained materials. The lack of foraminifera argues against a tidally influenced marine context, but the coarse versus finer materials observed within the sediments below the midden are consistent with poorly sorted glacial till deposits possibly subjected to intermittent glacial outwash events. Again, this is not consistent with shoreface or fully fluvial deposits. The re-calcification observed throughout the box core slides during EMPA also indicates that the midden materials came into contact with freshwater, not saltwater. This freshwater could simply have percolated through the midden as rainwater or groundwater and does not necessarily imply a fluvial source. In sum, all the evidence points to deposition of the Hjarnø shell deposit as a midden on land exposed to freshwater inputs, prior to submergence.

5.1.2. *Econfina Channel*

Like the Hjarnø sediments, the materials examined in the Econfina Channel core originated locally. Again, we infer depositional context based on mineralogy and inclusions such as microfossils as well as some aspects of the particle size analysis, with all of the above caveats concerning the manner in which non-clastic materials could skew these results. The sediments are more mature with no feldspars and are comparatively well rounded, unlike the glacial till at Hjarnø. This is to be expected; these are sands eroded from the Appalachian Mountains and transported hundreds of kilometres before deposition on the continental shelf. Any metastable minerals the original sediments may have contained, such as feldspars, decomposed into clays long before these sands reached the Gulf of Mexico.

Unlike Hjarnø, inclusions within this midden material suggest that it was deposited in an intertidal context. There are abundant foraminifera throughout the entire profile; the top of this core was 0.4 m below the seabed surface, and the taxa represented are not epifaunal. Most of these appeared to be *Globigerinoides* sp. These taxa are abundant in the Gulf of Mexico and their presence could be explained in several ways. This deposit could have been exposed to marine waters such as tidal cycles during deposition. Alternatively, these foraminifera could have entered terrestrial deposits via storm surges, which are not uncommon in this region. They could also have been accidentally harvested along with the shellfish targeted for human consumption (Lane et al., 2011; Nagel et al., 2016; Rosendahl et al., 2007). However, this location was not wholly saltwater when the midden was deposited. There is evidence of decalcification in the shell materials, and the dissolution of what appear to be diatoms along with redeposition of opaline chert within pore spaces of the clays at the bottom of the core, which appears to represent the contact between the base of the midden and the former ground surface. Both of these phenomena are most likely to occur in a freshwater context, rather than saltwater. This suggests that the midden at Econfina Channel was deposited on the edge of an intertidal zone along the bank of a tidal creek where the water table intersected the surface.

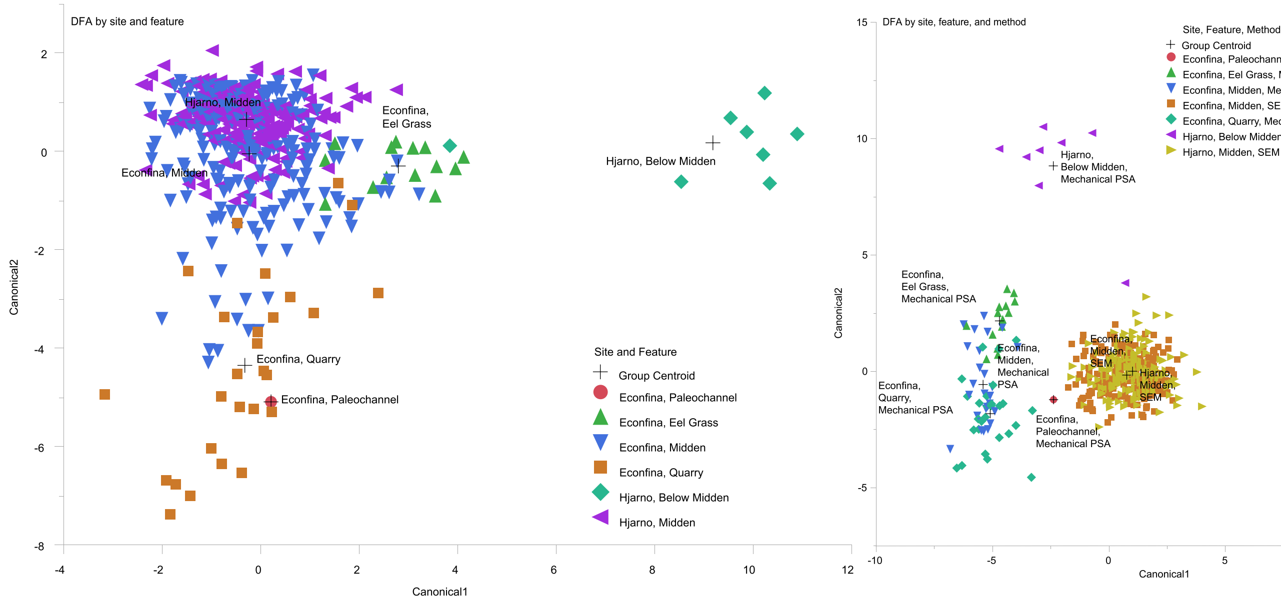

Fig. 9. Discriminant function analysis (DFA) results by site, feature, and PSA method. Left panel shows all results regardless of PSA method, showing significant overlap of the midden deposits at Econfina Channel and Hjarnø, and quite good separation from the off-site sediments. In the right panel, results are further subdivided according to PSA method (mechanical or SEM). The SEM results confirm a significant overlap between the midden deposits at Econfina Channel and Hjarnø. However, the mechanical PSA results show more overlap between the Econfina Channel midden and other deposits in the vicinity, though offsite sediments from Hjarnø continue to differentiate well from all other groups. This likely reflects the fact that SEM PSA was done on sub-surface materials from both middens, while mechanical PSA at Econfina Channel was carried out on surficial deposits. Higher proportions of very fine sands can be seen in the group means for SEM PSA from both middens, and lower proportions of larger particles (2000 and 4000 micron size fractions [2-4 mm and greater]), in contrast to materials analyzed with mechanical PSA from surficial samples (Table 2, S10). Note that the fine fractions are preserved downcore within the Econfina Channel midden but stripped out from the other Econfina Channel samples. This is to be expected from surficial sediments exposed to tidal, wave, and storm energies and is consistent with other findings. For a discussion of this method of DFA within JMP, see https://www.jmp.com/support/help/en/15.2/index.shtml#page/jmp/disciminant-analysis.shtml.

5.2. Midden sediment characteristics

One of the most important outcomes of this analysis is to show that the midden deposits from Econfina Channel and Hjarnø, despite their differences in cultural, ecological and geological context, share similar characteristics that reflect their anthropogenic origin. Both contain sediments that are generally poorly sorted and intermingled with materials indicating human activities. Additional multivariate analysis, specifically discriminant function analysis (DFA), sheds some further light on this question.

DFA (linear, assuming common covariances) shows that midden sediments sampled at Econfina Channel and Hjarnø overlap substantially in terms of grain size characteristics when compared to one another and other features/areas within both sites. Given that we carried out particle size analysis on sediments that include non-clastic materials in this study, however, it is especially important to ask how midden sediments compare to non-midden sediments. Earlier studies at the Econfina Channel that examined bulk sediments across the site found that multiple different intrasite areas could be distinguished from one another; over 80% of samples from different features across the site were classified correctly by DFA (Cook et al., 2018, table 7). To extend this assessment, we ran DFA on all samples at Econfina Channel and Hjarnø, including both midden and off-midden samples. The entropy r^2 score is very low, and 168, or just over 35%, of the samples tested from the two sites were misclassified; these were primarily from midden materials at Econfina and Hjarnø, which show a large degree of overlap. The non-midden sediments from Hjarnø stand out particularly well and there is only limited overlap between the midden samples as a group and the Econfina off-midden samples (Table 2; Fig. 9; S8 and S9).

Inclusion of non-clastic materials in our methods also raises other important questions. Clearly, humans modify their environments, as multiple studies in niche construction demonstrate (see Laland and O'Brien 2010). Our results here raise questions about how such modifications might affect the course of interdigitating sedimentary processes. For example, it is unknown if the presence of a shell midden might act to trap different size classes of sediments relative to offsite locations that are not shell middens. Our results suggest that separate analysis of clastic and non-clastic materials would be a highly productive avenue for future research into such issues.

5.3. Mechanical versus digital particle size analysis

Discriminant function analysis results suggest that midden samples tested at Econfina Channel are more like midden samples from Hjarnø despite their differences in mineralogy and inclusions of anthropogenic origin, than they are to non-midden samples at Econfina or Hjarnø. However, comparison of the digital results with mechanical results indicates differences between the two methods, and these may reflect the fact that they were applied to different types of sediments, and perhaps to imperfections or inaccuracies in the digital micrographs. Mechanical PSA was applied to surficial deposits, which are liable to stripping out of finer sediment fractions by wave energy, whereas the midden deposits analysed by digital PSA have higher proportions of finer sediment (see S10). We were, therefore, unable to conduct a rigorous comparative test of the digital PSA method; additional future testing with larger sample sizes from both sites, particularly from Hjarnø, will be needed to clarify this issue.

Nevertheless, and given the above caveat, it is still significant that the midden samples from Econfina Channel were more like one another, and more like the midden samples from Hjarnø, than

Table 2
Discriminant function analysis results for all sediments. Entropy R^2 indicates the goodness of fit for the modelled group classifications; scores closer to 1.0 indicate better fit. Values of -2LogLikelihood likewise indicate goodness of fit; larger values indicate better fit. The sum total for each column in the comparison matrix gives the number of samples predicted for the column category, while the sum total for each row gives the actual group membership, given in each row category. Samples from the Econfina and Hjarnø middens are highlighted to demonstrate the high degree of similarity between predicted and actual classifications. The upper table confirms a strong similarity between the results from the Hjarnø and Econfina midden sediments for all samples and a separation from non-midden sediments. The SEM results in the lower table confirm the strong relationship between the two middens but a weaker relationship when mechanical PSA is included. For further discussion see the caption for Fig. 9 and the text.

DFA analysis by Site and Feature

Score Summaries

Source	**Count**	**Number Misclassified**	**Percent Misclassified**	**Entropy R2**	**-2LogLikelihood**
Training set	474	169	35.65	0.11	903.58

Actual classification	**Predicted classification**					
	Econfina, paleochannel	Econfina, quarry	Econfina, eel grass beds non-midden	Econfina, midden	Hjarnø, midden	Hjarnø, below midden
Econfina, paleochannel	1	0	0	0	0	0
Econfina, eel grass beds non-midden	0	0	14	0	0	0
Econfina, midden	0	11	9	**94**	**94**	0
Hjarno, midden	0	0	0	**46**	**170**	0
Hjarno, below midden	0	0	0	0	0	7
Econfina, quarry	3	21	2	1	0	0

DFA analysis by Site, Feature, and PSA Method

Score Summaries

Source	**Count**	**Number Misclassified**	**Percent Misclassified**	**Entropy R2**	**-2LogLikelihood**
Training set	474	174	36.71	0.32	798.37

Actual classification	**Predicted classification**						
	Econfina, Paleochannel, Mechanical PSA	Econfina, Eel Grass, Mechanical PSA	Econfina, Midden, Mechanical PSA	Econfina, Midden, SEM	Econfina, Quarry, Mechanical PSA	Hjarno, Below Midden, Mechanical PSA	Hjarno, Midden, SEM
Econfina, Paleochannel, Mechanical PSA	1	0	0	0	0	0	0
Econfina, Eel Grass, Mechanical PSA	0	12	2	0	0	0	0
Econfina, Midden, Mechanical PSA	0	6	14	0	6	0	0
Econfina, Midden, SEM	0	0	0	**101**	0	0	**81**
Econfina, Quarry, Mechanical PSA	3	0	7	0	17	0	0
Hjarno, Below Midden, Mechanical PSA	0	0	0	1	0	7	0
Hjarno, Midden, SEM	0	0	0	**68**	0	0	**148**

samples taken from other, non-midden site features in the wider Econfina area and from below the midden at Hjarnø. Given the evidence for different depositional contexts at Econfina Channel and Hjarnø, we interpret our discriminant function analyses to indicate that middens share specifically quantifiable sedimentological commonalities.

The data are consistent with earlier studies by Gagliano and colleagues (Gagliano et al., 1982: 90–95) and show that the cumulative grain size distributions for both datasets are not consistent with any natural landform sampled during their 1982 study. Instead, the Econfina and Hjarnø midden materials are generally more consistent with the Site Type II identified by Gagliano et al. These were primarily shell midden sites sampled along the northern Gulf of Mexico coastline. Non-anthropogenic landforms in general are described by Gagliano et al. as relatively well-sorted in comparison to anthropogenic ones, though this term is used in a comparative instead of a strictly quantitative sense. Despite this, it is useful to note that distribution analyses for all materials from Hjarnø and Econfina Channel show a variety of non-normal distributions inconsistent with well sorted sediments (see S5, S6, S10).

5.4. Implications for the survival and discovery of submerged shell midden sites

The two case studies discussed here represent different cultures on different continents and they are far from identical. They are located in two different marine basins, have different parent geologies, different histories of coastal geomorphological change and different marine ecologies and molluscan fauna. Nevertheless, although the results of a comparative approach point to certain differences, they also highlight similarities with important implications for the survival, discovery and analysis of submerged shell midden sites.

The differences refer primarily to the different environmental contexts of the two middens. The midden at Hjarnø was likely deposited on a terrestrial surface that lacked detectable marine influence, whereas Econfina Channel was likely deposited on the edge of an intertidal zone. The Econfina Channel site experienced more damage to the midden materials from boring marine organisms and, possibly, higher energy fluid dynamics. However, it is critical to note that both deposits survived submergence with sufficient materials intact to differentiate them from non-anthropogenic shell deposits. This suggests that favourable conditions for shell midden survival exist in other marine basins, from temperate regions to the sub-tropics, and likely beyond, even in regions such as the Gulf of Mexico that experience tropical cyclone impacts.

Both middens contain evidence for diagenetic processes common to deposits that were initially at least partially subaerial, and which later became engulfed by anoxic sediments before open marine conditions were established (Lowery and Wagner 2012). Both contain abundant evidence for pyritization, which occurs when marine sulphates are reduced by bacteria that metabolise oxygen and organic materials within the sediments. The lower levels of the Hjarnø midden also contained some glauconite, which is typical for anoxic sediments, but it is less abundant than the pyrite. This glauconite formed after full submergence of the Hjarnø site while the materials were still overlain by gyttja. Its absence at Econfina may be a result of the nature of the sediments. Glauconite as a mineral contains varying proportions of potassium, sodium, iron, aluminium, and magnesium. At Econfina, quartz and carbonate dominate the mineralogy and the only iron sources come from clays, whereas at Hjarnø, feldspars are common, providing a source for sodium, potassium, aluminium, and magnesium. Thus, the difference in authigenic mineral assemblage is linked to the initial mineralogical assemblage present during deposition. Despite the mineralogical differences, both middens were buried in anoxic conditions that both preserved organic materials and also promoted formation of these authigenic minerals.

Regarding similarities, the sediments from the two middens cannot be differentiated from one another based on multivariate analysis of PSA results, especially the results derived from digital SEM measurements. This is especially significant given that the two shell middens were deposited in different geomorphological contexts and that the Econfina midden is not as well preserved as the Hjarnø midden. These results further support the sedimentological model for shell midden sediments as uniquely anthropogenic bioclastic deposits that can be quantitatively and qualitatively characterised. It is important to note that our interpretations of anthropogenic influence also rest on additional lines of evidence, including artefact and ecofact inclusions. Nevertheless, our results strongly suggest that shell middens can be identified from sedimentological analysis of small samples despite differences in climate regime, environmental context and culture, using a methodology that includes particle size and inclusion analyses. These observations have supported our decision to include non-clastic materials in the grain size analysis, although this is not a typical approach in sedimentology. They strongly support future studies of submerged landscapes where logistical challenges and budgetary constraints may well restrict investigators to coring methods or limited sediment grab samples only, instead of full excavation.

Some past studies have concluded that open-air sites such as these are not productive targets for offshore survey because they do not preserve well during and after submergence (see Faught and Donoghue 1997). Other studies have proposed that human populations did not use coastal resources or create visible accumulations of shell deposits during marine transgression events because the shoreline was moving too fast to allow the stabilisation of shorelines and sufficient accumulation of archaeological materials in any one location (Fischer 1995, p 382; Bailey 2011, p 322). Our results argue against both assertions, at least for the areas we have studied, demonstrating that shell deposits can survive inundation, and that molluscan resources continued to be available and were exploited with sufficient intensity to create shell-midden deposits even during periods when marine transgression was in progress. Coastal locations and marine molluscan resources continued to be available and attractive to human populations despite the dynamically changing nature of the coastal zone.

5.5. Interpretation of geographical and temporal gaps in shell midden distributions

Our results also suggest that geographical and temporal gaps in the occurrence of shell middens may have as much to do with the differential visibility and discovery of such deposits as to regional variations or time trends in the availability of marine molluscs or subsistence practices. In both the Gulf of Mexico and Denmark, our underwater shell middens occur on stretches of coastline – the Big Bend in Florida and the southern coastlines of the Danish Straits – where on-land coastal shell middens are absent, although substantial on-land shell middens of a similar date are present in neighbouring regions. In both cases the coastlines lacking on-land shell middens have been differentially impacted by relative sea-level rise in the early to mid-Holocene compared to the neighbouring regions (Astrup 2018; Russo 2006). Shell middens are absent anywhere in either region before about 7000 cal BP because earlier shorelines nearly everywhere are now under water.

Such gaps in the record could result from the differential availability of marine molluscs on different palaeoshorelines, or differences in the interest taken in marine resources by different human populations and cultures at different times and places. Many such theories have been proposed to account for the absence of shell middens in the archaeological record, especially their rarity or absence in late Pleistocene and early-to-mid-Holocene periods, and especially for their apparently late appearance in large numbers from c. 7000 years ago onwards. These theories assume that human populations neglected marine resources because of their supposedly increased labour demands or technological requirements in comparison with hunting and gathering on land, until forced to change by mid-Holocene population growth, reduction of land and terrestrial resources by sea-level rise or other climatic changes, or because of the inferred or assumed absence of marine molluscs (Binford 1968; Osborn 1977; Beaton 1985; Waddington et al., 2007; Lewis et al., 2020).

The assumptions supporting the above theories have been repeatedly challenged as being based on faulty data or faulty logic and on a failure to recognise let alone to address the possibility that earlier coastal site are missing because of submergence by sea-level rise (Erlandson 2001; Bailey and Milner 2002; Erlandson and Fitzpatrick 2006; Hausmann et al., 2021). Our results provide empirical support for these challenges, indicating that gaps in the coastal archaeological record may be more apparent than real, that shell midden deposits can survive submergence, and most importantly that they can be investigated with minimally invasive techniques such as coring and identified as middens from sedimentological and micromorphological analysis of core contents. This is of particular relevance to the investigation of underwater shell middens on earlier shorelines at greater depth, where the deposits may be beyond reach of diver investigation and further obscured by overlying layers of marine sediment. Since we know that buried shell layers can be identified from geophysical remote sensing (Astrup et al., 2020), the prospect of being able to discriminate between anthropogenic and natural shell deposits from the analysis of samples recovered by coring offers an extremely promising avenue for future underwater investigation. Our results indicate that shell middens represent ideal targets for underwater prospection, suggest that many more may await discovery on submerged palaeoshorelines, and argue in favour of continued and intensified exploration of the continental shelves in the search for more such sites.

6. Conclusions

In this study we have employed a methodology drawing on nearly 40 years of geoarchaeological experience in characterisation of archaeological sediments to examine two different underwater shell-midden sites with respect to depositional context and post-depositional, taphonomic, and diagenetic changes. Our findings demonstrate that shell-midden deposits can survive inundation by sea-level rise with sufficient stratigraphic integrity to provide detailed and varied information about cultural and subsistence practices and geochronology.

Our results also show that shell midden sites represent ideal targets for offshore archaeological site prospection. They appear to possess a specific sedimentological profile that can be identified from analysis of core samples or with minimal excavation, despite differing degrees of preservation and differences in cultural, geological and palaeoclimatic context. They also contain valuable archaeological data that is essential to better understand long-term changes in patterns of coastal settlement and economy associated with late Pleistocene and early Holocene coastlines that are now mostly submerged.

Finally, our results emphasise the growing need to take greater care of the underwater cultural heritage and its management. Sites created by foraging populations may seem to be more ephemeral and less obvious than the underwater cultural heritage of later periods such as historic vessels and maritime infrastructure, but they are no less informative. Our results indicate that they may be far more common than previously assumed. This is particularly important as shallow-water and coastal sites are now at increased risk around the world and in different marine basins from both anthropogenic and natural threats (Anderson et al., 2017). Our results can assist modern cultural heritage managers in identifying which modern coastal locations are most vulnerable to damage from modern climate change and marine transgression, and those which are more likely to survive. This in turn should help to optimise modern cultural heritage management practices at a time when accelerating climate change makes such a goal most urgent.

In memoriam

We acknowledge our friend and co-author Claus Skriver, who tragically passed away during the production of this article. We honour his work and friendship. The archaeological community will miss him dearly.

Credit author statement (parenthesis indicates location of primary contribution in the field)

JWCH: Conceptualization; Formal analysis; Investigation; Methodology; Project administration; Funding acquisition; Resources; Software; Supervision; Validation; Visualization; Writing – original draft, review and editing (Econfina). JB: Conceptualization; Formal analysis; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Writing – original draft, review and editing (Hjarnø and Econfina). KW: Formal analysis; Investigation; Methodology; Data curation; Writing – review and editing (Hjarnø and Econfina). PMA: Conceptualization; Formal analysis; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Writing – original draft, review and editing (Hjarnø). JM: Formal analysis; Investigation; Software; Visualization (Hjarnø). NH: Formal analysis; Investigation; Validation; Data curation; Writing – review and editing (Econfina). FS: Formal analysis; Investigation (Hjarnø and Econfina). CW: Formal analysis; Investigation; Writing – review and editing (Hjarnø); CS: Investigation (Hjarnø). EG: Conceptualization; Formal analysis; Investigation; Methodology; Project administration; Resources; Supervision; Validation; Writing – original draft, review and editing (Econfina). SU: Formal Analysis; Methodology; Conceptualization; Writing – review and editing. GB: Conceptualization; Investigation; Supervision; Writing – original draft, review, editing, final draft (Hjarnø).

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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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.quascirev.2021.106867.

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