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Geophysical and Geotechnical Assessments of a Submerged Ertebølle settlement in Horsens Fjord, Denmark

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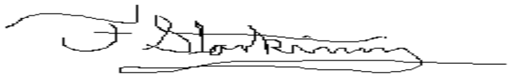
Abstract

Archaeological research within Horsens Fjord, Denmark, located on the eastern portion of the Jutland, has allowed for further knowledge and a better understanding of the Ertebølle culture (ca. 7400–6000 cal BP). Well-preserved subsurface and surface artifacts have been and continue to be identified within the fjord's waters. The settlement's original location along the shoreline has allowed for rising waters and marine sediments to submerge or bury any remnant anthropogenic material. Despite the rising sea-level, modern day waters and sediments within Horsens Fjord provide favorable conditions for artifact preservation. This has occurred as a consequence of a nutrient rich and eutrophic environment. To study this environment both in a broad and detailed scale, a multidisciplinary approach was used employing a suite of methodological applications with a focus on high resolution Innomar ISE 2000 subbottom profiler and Edgetech 4125 sidescan sonar, an auger corer and the use of a high accuracy Trimble R8 RTK GPS. Such well-preserved sites, with the use of high resolution geophysical and geotechnical data, offer a rare glimpse into the extents and correlations among paleolandscapes and prehistoric cultures. The use of geophysical and geotechnical methods advances the knowledge of past cultures and the techniques in which they are identified.

Declaration of a Candidate

I certify that this thesis does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.



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Prelude

This thesis was formatted in accordance to the Archaeology Flinders University Semester 1 & 2 Handbook. All language throughout the thesis is written as US English. The dating convention is referenced to present day, Before Present (BP). The primary research focus of this thesis is the Mesolithic era, dating to 5900-1100 cal BP in accordance with the chronology set forth by Andersen, 2004; Andersen, 2013; Bailey, 2017; Skriver, 2017 and Astrup, 2019.

Abbreviations

BOEM: Bureau of Ocean Energy Management

BC: Before Christ

BP: Before the Present

Ca: Circa-approximately

Cal: Calibrated

Cal BP: Calibrated Years Before the Present or Calendar Years Before the Present

CM: Centimeters

DHSC: Deep History of Sea Country

DSAS: Digital Shoreline Analysis System

EGN: Empirical Gain Normalization

EH: English Heritage

FT: Feet

GEUS: Geological Survey of Denmark and Greenland

GIA: Glacial Isostatic Adjustment

ICOMOS: International Council on Monuments and Sites

KM: Kilometers

M: Meters

MSL: Mean Sea-level

MOMU: Moesgaard Museum

NOAA: National Oceanic and Atmospheric Administration

RCP: Representative Concentration Pathways

RCYBP: Radiocarbon Years Before the Present

RSL: Relative Sea-level

RTK: Real Time Kinematic

RV: Research Vessel

SB: Single Beam

SBP: Subbottom Profiler

SCUBA: Self-Contained Underwater Breathing Apparatus

SS: Sidescan Sonar

TVG: Time Varying Gain

UCH: Underwater Cultural Heritage

UNESCO: United Nations Education, Scientific and Cultural Organization

US: United States of America

USGS: United States Geological Survey

V: Volume

VRS: Virtual Reference Station

1.0 Introduction

The exploration of the marine environments, both on the sea surface and subsurface, is important to understanding past cultures, particularly hunter gatherers from the Mesolithic (Andersen, 1981; Price, 1985; Sala, 2012). Archaeological geophysics, a scientific discipline (Sala, 2012), can provide important information on the once exposed environments of prehistoric cultures, their settlements and marine adaptation (Astrup, 2019). During the Mesolithic Period, sea-level was considerably lower than today's current water levels (Astrup, 2019). Lower sea-levels and the absence of glacial ice exposed more lands for hunter gathers to expand their hunting areas and techniques, not only on land, but also along the coastal regions (Evan et al, 2014; Astrup, 2019). The use of marine geophysical sonars in the site research depths of 2m and less, is difficult due to land-sea interferences and shallow water hazards such as erratic boulders. However, the importance of these coastal groups outweighs the difficulties in obtaining data due to the potential to further understand societal development of the Mesolithic Period from land to sea (Astrup, 2019). The techniques used in this thesis allowed for a much broader investigation of the submerged environment in which the Mesolithic inhabitants covered.

This thesis research was conducted as part of the Deep History of Sea Country (DHSC) project, led by Flinders University, Australia, and the Moesgaard Museum (MOMU), Denmark. A team of archaeologists and geoscientists collaborated to examine the Ertebølle culture in Horsens Fjord, Denmark. As part of this multidisciplinary research project, a high resolution sidescan sonar and a high resolution parametric subbottom profiler were used to map the submerged prehistoric environments between and around Snaptun and Hjarnø Island in Horsens Fjord, Denmark (Figure 1). The operations occurred during two field seasons in 2017 and 2018, in which submerged anthropogenic and environmental features were analyzed and interpreted. The two field seasons concentrated on two study sites on the western end of Hjarnø Island, within 600 m from one another. An additional, broader region was studied for reconnaissance purposes to obtain a better understanding of the submerged paleoenvironments.

Figure 1: Satellite imagery of the primary and secondary study areas (sites A and B) located on the western end of Hjarnø Island, eastern end of Jutland, Denmark (ESRI GIS).

To further study these sites, marine geophysical and geotechnical applications were used to examine the seafloor and subsurface environmental features, exploring broader questions pertaining to the locations of prehistoric settlements. More specifically, this study, as a sub-project to the DHSC project, examined the distribution and extent of submerged shell middens "Køkkenmødding" and subsurface paleochannels. The absence of marine geophysical techniques in the prehistoric archaeological studies should be rectified according to research needs and be more widely used to broaden the understanding of past cultures. Additionally, these techniques expand the total search area in an effort to understand and interpret submerged—subsurface environments on a broader scale. Results from the submerged prehistoric site studies and interpretations from geophysical data inform further unanswered questions and hypotheses pertaining to the prehistoric cultures and settlements.

Land based archaeological investigations are well established in Denmark. The first research to investigate prehistoric shell middens on land in Denmark occurred in 1837 (Andersen, 2004). It wasn't until the end of WWII that investigations in submerged prehistoric archaeology began to gain attention, sometime in the late 1950s (Andersen, 2013; Skaarup and Grøn, 2003). However, before 1990, Danish archaeologists had no clear experience or knowledge with submerged prehistoric sites underwater (Andersen, 2013). Prehistoric settlements and cultural resources, such as the Mesolithic sites analyzed by this research, are difficult to identify due to years of reworking and erosion by natural and anthropogenic processes. In addition, the geologic make of the subsurface sediments sometimes add a layer of protection and preserve any settlements and artifacts for millennia (Andersen, 2013, Skriver, 2018; Astrup, 2019)

In the past, to assist in the identification of submerged prehistoric settlements, such as those in Horsens Fjord, Denmark (Figure 1), marine archaeologists conducted underwater surveys and excavations using self-contained underwater breathing apparatus (SCUBA) and geotechnical methods to identify and confirm cultural resources and the environments in which they lay (Andersen, 2013; Astrup, 2018, Skriver, 2017). While such techniques have proven beneficial; underwater Stone Age settlements in Denmark and elsewhere in the world are difficult to research, time-consuming, technically challenging, and expensive (Andersen, 2013). More recently, marine geophysical methods have been more widely used in both in the academic and commercial sectors to identify cultural sites (Fugro and BOEM, 2017; EH, 2015; Watts, 1995; Faught, 2003; Grøn, 2018). These methods, as use throughout this research project, cover a much wider area, potentially identifying more areas of interest and in a timely and cost effective manner.

The Mesolithic Ertebølle culture of Denmark, such as this site and the one at Tybrind Vig (Andersen, 2013), some 7,400 to 5,900 years ago (Table 1), are typically located along shallow and sheltered fjords around the northern and eastern Jutland Peninsula (Andersen, 2004; Andersen, 2013; Astrup, 2019; Bailey, 2017; Skriver, 2017). The culture heavily dependent on coastal environments and use numerous marine resources (Astrup, et al., 2019). Discarded materials obtained from prehistoric sites are typically made from natural substances (bone and wood) that either provided food or were made into tools (Bailey, 2007).

Table 1: Chronological chart of archaeological periods and changes in paleogeography.

Cal BP	Archaeological period	Archaeological subdivision	Palaeogeographical stage	Cal BC
5900–5300	Early Neolithic	Funnel Beaker	Littorina Sea	3950–3300
6300–5900	Late Mesolithic	Late Ertebølle		4300–3950
6800–6300		Middle Ertebølle		4800–4300
7400–6800		Early Ertebølle		5400–4800
7700–7400	Middle Mesolithic	Late Kongemose		5700–5400
8000–7700		Middle Kongemose		6000–5700
8400–8000		Early Kongemose		6400–6000
9,800–8400	Early Mesolithic	Maglemosian	Initial Littorina Sea	7800–6400
10,700–9,800			Ancylus Lake	8700–7800
11,000–10,700			Yoldia Sea	9000–8700
11,700–11,000	Late Paleolithic	Ahrensburgian		9700–9000
12,500–11,700			Baltic Ice Lake	10,500–9700
14,000–12,500		Bromme/ Federmesser		12,000–10,500
14,700–14,000		Hamburgian		12,700–12,000

Since the de-glaciation, 14,000 BP, Denmark's coastline has undergone significant changes (Andersen, 2013; Astrup, 2019; Bailey and Larson, 2017). Eustatic and isostatic movements, due to the melting of the glacial ice, have caused a slight uplift on the northern Jutland peninsula, triggering waters to recede where they were once plentiful, and exposing prehistoric coastlines (Petersen, et al., 2005). The progressive uplift since the last glaciation is 13 m Mean Sea-level (MSL) (Astrup, et al., 2019). On the central and southern Jutland peninsula, the Mesolithic coastline is located at -8 m, along with any archaeological remains (Andersen, 1995).

Thus, due to isostatic uplift or post glacial rebound, some 350 Ertebølle sites were documented on land, in the northern region of the Jutland peninsula (Andersen, 2000; Flemming and Bailey, 2017). Although many of the excavated Mesolithic sites in Denmark were identified in the northern terrestrial Jutland, not all excavated sites contained shell middens (Astrup, 2019). In the south Jutland, 2,300 underwater artifacts have been documented that account for the Paleolithic, early Mesolithic and Neolithic periods (Fisher, 2004). Prior to 2017, few Mesolithic underwater sites had been excavated, with no submerged midden sites discovered (Astrup, 2019).

Submerged prehistoric artifacts, from the Ertebølle Mesolithic culture, were discovered just offshore Hjarnø Island, located at the mouth of Horsens Fjord, Denmark. Within Horsens Fjord, there have been 37 discovered submerged sites, one of which includes this thesis research site conducted at Hjarnø Sund which is observed at a depth of 0.5–2.0 m (Borup 2003; Skriver et al. 2017; and Larsen, 2018). Kitchen middens, such as the one at Hjarnø, are typically observed along prehistoric shorelines, close to natural shell banks and fishing-localities (Anderson, 2013b). Within this region, well preserved archaeological artifacts, including organic material such as wooden dugout canoes, wooden paddles, axes, and bows were discovered along the seafloor (Skriver et al., 2017). With artifact discoveries of increasing numbers, the question arises whether the exposed materials have resulted from a recent increase in erosional processes.

To investigate the environment and coastal processes, geophysical and geotechnical techniques were used as main the tools. These techniques used in confirming and expanding on findings and theories by archaeologist, have allowed for the identification of surface and subsurface prehistoric sites and paleoenvironments (Anderson, 2013b and Astrup, 2019). This allows scientists to view and interpret the submerged and subsurface environments, highlighting regions of high probability for preservation of prehistoric sites. The geophysical methods do not necessarily allow scientists to discover and make a determination of the data in real-time, the data still needs to be processed and interpreted (Sala et al, 2012). From the data, subsurface environmental layers may be traced and followed to potentially identify paleoenvironments that may have been favorable for Ertebølle settlements. In addition, while interpreting these paleoenvironments, any abrupt and irregular shifts in the data may be further researched to investigation the potential for anthropogenic disturbances. Based on the data interpretations, further concentrated excavations and geotechnical operations may persist to truth the interpreted data. As a result of the interpreted and truthed underwater data, further data analysis maybe applied from infield truthed results. The results of this study provide a rare opportunity to improve the methods used to determine and map underwater prehistoric sites such as middens and environmental patterns that can then be more efficiently surveyed in detail using SCUBA, Automated Underwater Vehicles (AUVs) and geotechnical methods, such as auger and vibracores, as well as ground samples.

Figure 2: Aerial imagery of the western portion of Horsens Fjord, Denmark.

Throughout both field seasons, research efforts were concentrated on the eastern end of the Horsens Fjord, Denmark. Due to the vessel size and weather conditions, the western portion of Horsens Fjord was not surveyed in the reconnaissance phase of the study. Throughout the eastern end of Horsens Fjord, the geophysical operations focused on four study areas which were studied in four separate phases. Phase one (1) consisted of an existing data review in and around the region of Horsens Fjord by the Geological Survey of Denmark and Greenland (GEUS), Moesgaard Museum and the DHSC teams. Phase two (2) consisted of a reconnaissance geophysical investigation of the eastern portion of Horsens Fjord spanning from the northern end of Alrø Island (Figure 2), to the eastern end of Hjarnø Island, around to the southern tip and to Snaptun; here on referred to as site C. Phase three (3) consisted of a detailed geophysical and geotechnical survey, with underwater excavations on the southwestern end of Hjarnø Island, here on referred to as site A; and Phase four (4) consisted of a detailed subbottom and sidescan survey on the northwestern end of Hjarnø island, here on referred to as site B. The primary sites, were located on the western end of Hjarnø (sites A and B) within 600 m from one another, making them ideal focus sites in the 2017 and 2018 field seasons.

Prior to any field operations, sidescan and subbottom datasets were obtained from GEUS, the Submerged Prehistoric Archaeology and Landscapes of the Continental Shelf (SPLASHCOS), and MOMU. Data obtained from GEUS contained sidescan and subbottom data within the vicinity of Horsens Fjord. The preliminary sidescan and subbottom data were obtained by GEUS to assist in the planning and management stages for the geophysical operations in Horsens Fjord. GPS and core data were obtained from the MOMU and SPLASHCOS viewer which consolidates the Danish national inventory. The core dataset was used as a reference for the geophysical, geotechnical and underwater excavation operations. MOMU, an official state curator for submerged environments, record, preserve and archive data and artifacts from prehistoric sites throughout their region of Denmark. Previously, MOMU archaeologists and researchers conducted geotechnical and excavations of the primary research site (site A) at Hjarnø

(Skriver, 2017; Astrup, 2019). Unlike the research previously conducted, this research focused on geophysical techniques which not only benefit the thesis research aims, but further benefit the outcomes from previous research ventures.

1.1 Research Question, Aims and Objectives

The primary aim of this project is to develop a greater understanding of the Ertebølle culture and the regions they encompassed through the identification of prehistoric settlements or anthropogenic disturbances and subsurface paleoenvironments. To achieve this aim through technical means, the following question was asked:

> To what extent can marine geophysical methods be used to delineate and map prehistoric settlements or disturbances, such as shell middens in an extreme shallow water setting (2 m and less)?

To further satisfy and support the main research question, two objectives were pursued:

1) If the extent of the shell middens in subsurface environments around Hjarnø Island can be identified using sidescan and subbottom profilers, what is the prehistoric site's area and volume?
2) What, if any, correlation can be made among naturally formed paleolandscapes and prehistoric sites from the Ertebølle culture? Therefore, what are the subsurface features that correlate most to the identified prehistoric sites?

1.2 Underwater Prehistoric Archaeology

Submerged prehistoric archaeology is an interdisciplinary field which been greatly contributed to by geological, biological, anthropological and many other techniques. In recent years, technological advances have allowed for exploratory strategies in support of underwater archaeological research, providing discoveries that could not be accomplished using physical surveys solely (Flemming, 2014). The combination of geophysical and modeling techniques, along with finds from amateur and professional archaeologists, have led to the discovery of some 2,500 prehistoric finds within European waters, dating as far back as 20,000 years ago (Fischer, 2001; Skriver, 2017; Astrup, 2019).

In archaeology, the search for prehistoric sites range from local-regional scales to a global scale. Researchers in countries such as Denmark and elsewhere in Europe, Australia, and the Americas have made large leaps in the research and analysis of prehistoric sites and early human migration patterns. Large data based models were and currently are being expanded upon to highlight migration routes by prehistoric inhabitants along African and European coastal regions, the Atlantic and Pacific coasts of North America, as well as to Australia via ocean crossings (Astrup, 2017, Faught, 2003; and Faught and Gusick, 2011). Some motives to further the research in prehistoric underwater archaeology include questions concerning coastal adaptations and settlement patterns (Andersen, 2018; Faught, 2003; and Faught and Gusick, 2011). For example, when, where and why did past inhabitants establish settlements along coastal zones? Further, what was the function of prehistoric structures, such as shell middens, in settlement patterns? The support of Cultural Resource Management (CRM) projects by government agencies such as the Agency for Culture and Palaces under the Ministry of Culture in Denmark and the Bureau of Ocean Energy Management (BOEM) in the USA, have led to significant discoveries of prehistoric submerged sites in those countries. The protection of prehistoric submerged archaeological sites is recognized by most countries, although the methods by which these sites were identified have not been fully developed (Flemming, 2014).

Methods to identify prehistoric sites vary considerably among countries and environments. Although some methods have proven more reliable than others, there is criticism towards most, such as geophysical techniques. However, academic and commercial sectors, including various universities, BOEM and UNESCO, continuously review and revise these techniques for the betterment of research and site identification. Not only does this include field research methods, it also included desktop based research methods, including models

Some examples of studies at the forefront of prehistoric archaeological research include those completed by Faught (2003), Fischer et al. (2004), and Kenady et al. (2016). Faught (2003) used marine geophysical techniques to explore submerged prehistoric sites in the Apalachee Bay. Kenady et al. (2016) used ground penetrating radar (GPR) and electrical resistivity under varying soil conditions in terrestrial sites in the Gulf of Carpenteria to create volume estimates for buried shell deposits. Both of these studies include geographical, geological, environmental and cultural characteristics for the region of interest, to highlight culturally significant features including rock shelters, rock outcrops and paleochannels. After identifying geological, environmental and cultural features in geophysical data sets, further investigative ground truthing and processing methods were applied. The research conducted at Horsens Fjord seeks to utilize and expand similar methods and hypotheses to study the submerged Mesolithic sites.

2.0 Literature Review

2.1 Overview of Sea-Level Rise and Global Prehistory

Glacial icecaps began to subside at the end of the Last Glacial Maximum, 21,000 years BP, exposing land and increasing routes for animal migrations (Bailey, 2017; Chiocci et al, 2017). Anatomically modern humans began to disperse and migrate north to regions of the world not previously accessible (Bailey, 2017). This was an important time in human development as exchange of knowledge spread technological advances. As the glaciers receded from terrestrial surfaces, sea-levels rose around the globe (Lambeck, 1990, Issar, 2010). An exception was the areas that had been covered by glacial ice sheets, which rose in height due to Glacial Isostatic Rebound (GIR). Over the past 20,000 years, sea-levels rose by 130 m to modern-day positions (Bailey, 2017). Previous settlements by human inhabitants became inundated, submerging records of prehistoric civilizations such as the Ertebølle culture in Horsens Fjord, Denmark (Astrup, 2019). Despite the importance in human history, archaeology applied to submerged prehistory is a relatively new field when compared with other archaeological fields.

2.2 Challenges and Progress in World Archaeology

World archaeology involves a range of techniques from infield excavations to remote sensing surveys. Despite this, numerous complications arise when attempting to locate and study a site. One major issue pertains to archaeological looting, both locally and globally (Prioux, 2013). The clandestine acts, usually occur with the exposure of illicit artefacts and selling them on the black market, in most cases destroying the site in the process (Prioux, 2013). This omits any potential contribution, via research and documentation, a site could offer for past human inhabitants and modern day society. To prevent this, citizens and museums in Denmark are working closely to take a stand in protecting their heritage.

In some regions, “legal permitting” for commercial exploitation of archaeological items, such as commercial treasure hunting entities, are no less problematic than illegal looting (UNESCO, 2016). For example, a permit for excavating a wreck off the coast of Mozambique was legally obtained from a commercial treasure hunting company. However, the methods at which they obtained the artifacts for resale, left the site exposed to the marine environment, warranting further destruction and loss any valuable scientific data (UNESCO, 2016). A more enforced universal set of laws and regulations are needed to further implement and to assist with the protection of cultural resources. Additionally, training, public outreach and management are actions that continuously need to be expanded to enforce existing rules and regulations. Although a single standard across the globe maybe unattainable, government and non-government entities such as UNESCO and the international council on monuments and sites (ICOMOS) have set out to push the boundaries to increase scientific techniques and theory pertaining to archaeological heritage. Since 1945, archaeological scientific techniques and theory have strengthened with the founding of the United Nations Educational, Scientific and Cultural Organization (UNESCO), some 74 years ago. Since then, the World’s Cultural and Natural Heritage was established in 1972, and the Convention on the Protection of Underwater Cultural Heritage Treaty was adopted by UNESCO in 2001. The latter convention established several recommendations for the protection of underwater cultural heritage and set out rules and regulations for the research and preservation of underwater cultural heritage items.

Since the creation of UNESCO's UCH division, reference material has been created for the protection of submerged cultural resources, such as the *Manual of Activities Directed at Underwater Heritage* and the *Training Manual on UCH Management in Asia and the Pacific* were created and made accessible to governing parties and their citizens. These and numerous other referenced materials provided recommendations as to the best preservation and research methods to protect submerged heritage sites. Within Denmark, the Agency for Culture and Palaces, under the Ministry of Culture, play a key role in the protection and preservation of cultural heritage material. The Agency for Culture and Palaces acts on the recommendations by UNESCO to make them reality. Additionally, museums around Denmark, have played a major role cultural heritage preservation. With roughly 300 museums nationwide, citizens are able to access the cultural and natural history material through exhibitions, research and science documentation. The addition of geophysical techniques to an already vast and growing Danish cultural heritage would allow researchers to grow broaden their knowledge of submerged and subsurface archaeological sites, including the environment in which they lay.

2.3 Background to Danish Archaeology

Denmark's terrestrial and marine environment has produced a plethora of rich archaeological finds which not only benefit the archaeological field from a national standpoint, but also a global standpoint. Although, very little marine geophysical research has been completed in support of submerged landscapes for prehistoric archaeology in Denmark. Contributions to prehistoric archaeology, such as Mesolithic sites in Horsens Fjord, are informative and benefit substantially from marine archaeology (Benjamin, 2010). Nearly two thirds of Denmark's land area was submerged by the early Mesolithic, thereby submerging a large portion of archaeological sites. As such, the “Danish Model” was created to assist in the study of submerged sites (Fischer, 1997).

The “Danish Model” provides an investigative method for submerged archaeological sites that has proven effective (Benjamin, 2010). The Mesolithic, from Denmark to Sweden, provide some of the most studied sites throughout the globe (Fisher, 1995). This is impart due to the environment in which they are located, where habitation regions contain coastal and estuarine evidence of prehistory and a high potential for organic remains (Fisher, 1995). In addition, the “fishing site model” was created under the assumption that the Mesolithic culture was based on inhabitants, clustering their sites along easily accessible food and water sources, suitable with permanent structures (Fisher, 1997). This model was further expanded to create survey models to map and identify potential sites for further investigations (Benjamin, 2010). The Danish model was used as a basis for the entirety of this thesis research. The use of the Danish model, as well as a strong community engagement in Horsens Fjord, has led to the construction of a large dataset of identified archaeological locations and information pertaining to submerged sites. According to the Danish model, it is recommended to be familiarized with the region through multidisciplinary approaches, including historical research (Fisher, 1997). In addition, information regarding previously collected data from academic, commercial and military institutions, construction of plans for potential survey site recordings, and the presentation of research findings should also become familiarized (Benjamin, 2010). To further follow the Danish model through the thesis research, historical documentation and previously collected data was obtained.

Within the realm of Danish archaeology, there have been numerous successful excavations in aquatic environments over the years (Skriver, 2017; Astrup, 2018, Astrup, 2019). Just as in Tybrind Vig, the Hjarnø sites, represent an unusually good state of preservation, particularly organic remains (Andersen, 2013). Well preserved and calm environments, such as the ones within Horsens Fjord, provide excellent opportunities to practice and fine tune marine geophysical research methods. However, they add more questions regarding site stability and research methods in high energy environments. Thus, issues may arise when exploring more challenging marine environments such as those in Australia and the United States which generally contain deeper waters, strong currents, or exposure to wave activity. Benjamin (2010) alluded to this in a paper titled *Submerged prehistoric landscapes and underwater site discovery: Reevaluating the 'Danish Model' for International practices*.

2.4 Mesolithic Ertebølle Culture

The Ertebølle culture (7200–6000 BP) describes prehistoric hunter-gatherer-fishers from the Late Mesolithic period (Grøn, 2003). Typically, evidence for this culture are identified in southern Scandinavian countries such as Denmark, Germany and Poland (Price, 1991; Philippsen, 2014). Large shell middens (Figure 3) are commonly observed in Mesolithic settlements, which are predominantly located along coastlines or have been submerged by sea-level rise (Price, 1991; Benjamin, 2010). In addition to coastal sites, settlements and artifacts have also been identified in terrestrial and freshwater sites. In addition to shell middens, evidence of the Mesolithic culture are indicated by discarded material or remains such as fishing fences and paddles (Philippsen, 2014).

In modern day Denmark, waters at depth and submerged sediments within Horsens Fjord and elsewhere are hypoxic to anoxic, providing favorable conditions for site preservation (Markager, 2011). Thus, there is significant potential for discovering submerged prehistoric settlements and artifacts. Throughout Denmark, 2000 prehistoric sites, including the Bronze Age, Neolithic and Iron Age, have been recorded, mostly dating to the Late Mesolithic Ertebølle culture (ca. 7400-6000 cal BP) (Astrup, et al., 2017). Hjarnø, located within Horsens fjord, revealed a plethora of submerged prehistoric artifacts and shell middens dating from the late Kongemosen to the Middle Ertebølle (Skriver, et al., 2017).

Figure 3: Depiction of prehistoric woman with baby on reconstructed shell midden at Moesgaard Museum.

The archaeological material discovered around Horsens Fjord includes shell middens, tools, fish traps and paddles painted with decorative material from the Mesolithic Ertebølle culture (Andersen, 2013). Typically, shell middens, otherwise known as "køkkenmøddinger" in Denmark, are depicted with stratified shell deposits with cultural material observed in the surface and subsurface soils (Astrup, 2017) (Figure 3). Within the stratified layers of the shell middens, charred bone remains, food crusts, food remains and other anthropogenic placed items may remain. The concentration of artifacts observed at a site typically attests to the culture size and duration of stay.

Additionally, radiocarbon dating has been used on artifacts to obtain dates. Not only can radiocarbon dating be used with artifact remains, it can also be used with geological and environmental remains, identifying the time frame of a site with each geological layer.

2.5 Geology and Physical Environment

Denmark, officially known as the Kingdom of Denmark, is located in northern Europe (Dewey, 1926) (Figure 4). The eastern, western and northern regions of Denmark are surrounded by the North Sea and Baltic Sea. It consists of a Jutland Peninsula in the western portion of Denmark and numerous large and small islands on the eastern end, between the Jutland and Sweden (Dewey, 1926). Surface geology of Denmark is largely sedimentary, and includes chalks, sands, glacial sands, and moraine clays (Dewey, 1926) (Figures 4 and 5). Cretaceous chalks are predominantly located in the northern and southeastern part of Denmark and are most notable in steep white cliffs. Moraine deposits cover roughly two-thirds of terrestrial Denmark, which provides productive agricultural lands. The research site at Horsens Fjord is characterized by moraine clays and sandy deposits.

Figure 4: Drafted map of Denmark's 1926 surface geology (Dewey, 1926).

Moraine glacial deposits, including clays, sands and erratic boulders were left behind on the terrestrial portions of Denmark as the Baltic Ice-sheet retreated (Dewey, 1926). The glacial ice sheet weight created subsidence of the northern part of Denmark to depths of 45.7 m. As the glacial ice reversed, the northern subsidence reversed, enabling isostatic rebound and forming terrestrial habitats (Dewey, 1926). A majority of the coastline around Denmark reveals a smooth topography, without any drastic vertical changes in the environment. Numerous bays and coves were filled in with more modern sediments over time. Promontories that once jutted out are eroded down to the smooth coastline that we see today (Andersen, 2013).

Similar to the terrestrial lands of Denmark, the surrounding seafloor deposits include muds, sands, lag deposits and sedimentary bedrock (Figure 5). More specifically, Horsens Fjord contains sands with coarse materials and muds. Ward (2019) indicated that the micromorphology evidence indicates that the 2017 site represents a conglomerate of various sediments, which appear to remain stable and largely undisturbed by inundation and submergence. Although the material observed along the water's edge and the artifacts located depict a well preserved and stable environment; the number of artifacts emerging at sea surface indicate otherwise. Typically, swash run-up along coastlines influence the engineering design, leading to the erosion of coastal environments (Elfrink, 2002).

Hjarnø is a protected environment; however, the Global Wind Atlas reports the mean wind speed at 6.78 m/s (GWA, 2018). Wind forces generate wave action resulting in various levels of coastal erosion (Yanalagaran, 2018), a potential cause of the artifact exposure in Hjarnø Sund. Furthermore, seasonal episodes of may prompt further erosional patterns via wind and weather (Andersen, 2013). In addition to wind and wave caused erosion, the so-called 'eelgrass death' [Eelgrass (*Zostera marina*)] in the 1930s in which an epidemic caused a large eel grass die off, resulting in creased erosion of the Mesolithic site (Skriver, 2017). Eelgrass favors muddy sediments for its root structure to form a blanket-like mass encapsulating sediments to prevent erosion. The loss of eelgrass exposed some of the Mesolithic site and artifacts at Hjarnø (Rasmussen 1977; Fischer 2011; Skriver et al., 2017).

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Figure 5: Surface sediments along the seafloor surrounding Denmark (Astrup, 2018, and GEUS http:data.geus.dk/geusmap).

2.6 Horsens Fjord Geology

Hjarnø Island is situated in Horsens Fjord at the eastern end of the Jutland peninsula (Figure 4 and 6). Glacial deposits make up the fjord's and island's landscape (Henriksen, 2011). The open funnel shaped fjord is a protected body from three sides. The fjord surrounding Hjarnø is predominantly fed by two main creaks Bygholm å and Hansted å, numerous other small streams also feed fresh water into the fjord (Henriksen, 2011). GEUS reports the mean depths within Horsens Fjord as 2.9 m, with its deepest regions located within the shipping channel, reaching depths up to 22 m. Horsens Fjord and its surrounding depressions are thought to be remnants of old glacial beds (Hansen, 1971). At the northern and southern mouth of Horsens Fjord, seismic and borehole investigations identified two major fault zones in which graben structures were created (Lykke-Andersen, 1995).

Figure 6: Aerial Imagery of Hjarnø, Hjarnø Sund and Snaptun from 1954 (https://map.krak.dk, Obtained 2018).

At the mouth of Horsens Fjord is Hjarnø Island, created during glacial retreat. The resulting soils provides rich agricultural production. The island primarily consists of moraine deposits with some fresh and saltwater deposits (GEUS, 2018). Large glacial till and moraine deposits were observed within the subsurface environments surrounding Snaptun and Hjarnø, particularly on the eastern ends of Hjarnø Island. The seabed sediment, as depicted in Figure 7, primarily consists of muds, sandy muds, muddy sand and glacial till (Steffen, et al., 2011).

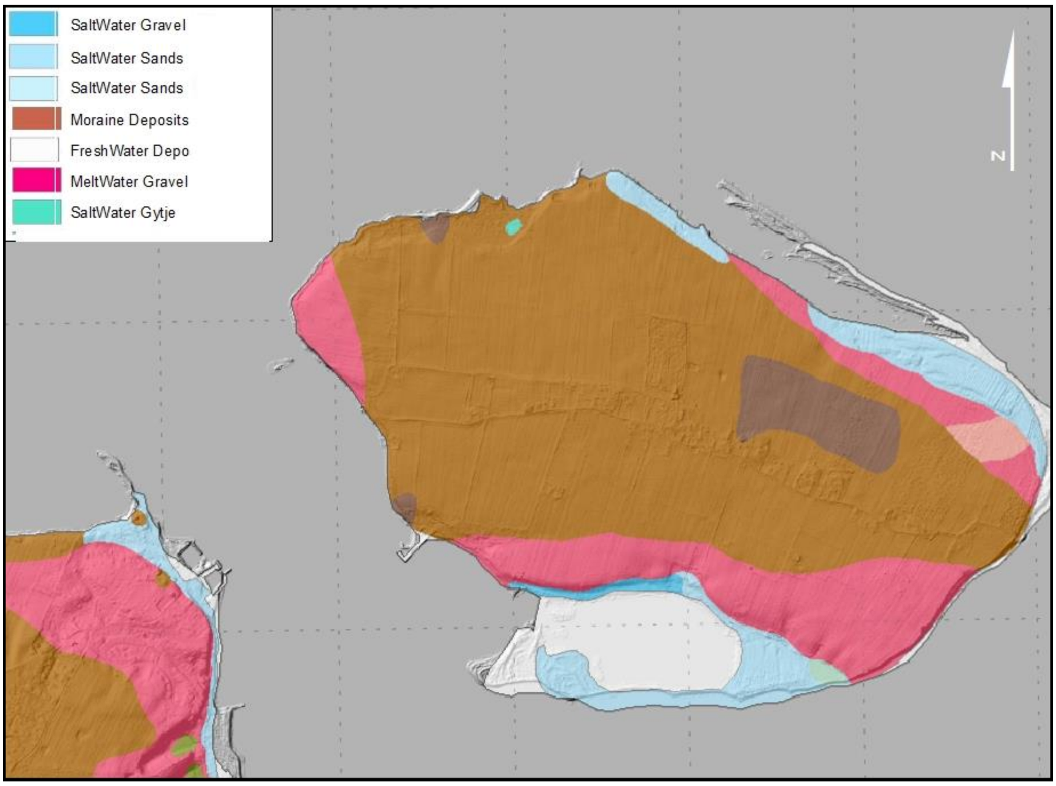

Figure 7: Surface geological and elevation map based on remote sensing and ground truthed data of Hjarnø Island and Snaptun (GEUS GIS Group, 2018).

2.7 Sea-level Rise

A substantial challenge to marine archaeologists, particularly those studying prehistoric sites such as Hjarnø, is an understanding of the marine environment. Items within the marine environment, such as cultural resources, are constantly reworked, exposed and protected (Gayes, 2013). Recent climatic warming has increased rates of sea-level rise through thermal expansion of the oceans and melting of ice caps (Figure 8) (AMAP, 2017). More specifically, large influencers to sea-level rise include glaciers from Greenland, Canada, Russia, and Alaska in addition to thermal expansion and land ice from Antarctica (Whitehouse, 2009). To monitor these fluctuations in sea-levels, tide gauges and satellites were used throughout the world.

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Figure 8: Sea-level historical and projected influences, as expressed relative to 2006, influencing global mean sea-level according to RCP4.5 AND RCP8.5 sea-level scenarios (SWIPA, 2017).

Tide gauges have been used for centuries to measure relative sea-level (RSL) to a vertical datum or reference such as a measured fixed point on land (Emery and Aubrey, 1991). Since 1992, sea-level measurements have been recorded via satellites by scientific establishments such as the National Oceanic and Atmospheric Administration (NOAA) and made available to scientists and the public globally. The tide gauges measure the average water levels with regular seasonal fluctuations due to coastal ocean temperatures, salinities, winds, atmospheric pressures and ocean currents over the course of a year. As a result, a linear trend are determined as observed on to an RSL website, such as NOAA's. Two of closest observed tide gauges to Horsens Fjord are located to the north in Aarhus and to the south in Fredericia (Figure 9). The two tide gauges depict an increased linear trend averaging an increase RSL from 0.61 to 1.1 mm/year from 1888 to 2012.

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Figure 9: Relative sea-level trends of Aarhus and Fredericia, Denmark as indicted by the direction of change (NOAA, 2018).

Although tide gauges are accurate for modern day sea-level measurements, such as the one in Figure 9, they are of little use for studying past sea-levels. To account for sea-level changes and the land-sea configuration in the Mesolithic, Glacial Isostatic Adjustment (GIA), and the release of land from overburdened glacial ice were calculated (Astrup, 2018). GIA models are used to account for past sea-level changes around Scandinavia (Påsse, 2015; Whitehouse, 2009). Through the observable GIA models, the initial phase of deglaciation depicted the highest rate of uplift (Påsse 2001; Steffen and Wu 2011). Some regions of Scandinavia are measured up to 33 m above mean sea-level, such as the Great Belt and the southern Baltic, as noted in Table 2 (Astrup, 2018). The rise in sea-level leads to inundation of terrestrial and freshwater environments, becoming brackish and eventually becoming inundated with salt water (Whitehouse, 2009).

Table 2: Southern Scandinavian sea-level rise (Astrup, 2018).

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The inundation of Scandinavian terrestrial and freshwater features via sea-level rise and GIA transformed the environments (Figure 10) (Whitehouse, 2009, Astrup, 2018). These estimates for inundation are based on sea-level curves and specifications in the GIA models, as indicated in Figure 11. Southern Scandinavia underwent radical changes from 4000 to 8000 BC in which numerous animal species died out due to rapid infilling of seawater as portions of Denmark became an archipelago (Astrup, 2018; Andersen 2013, and Petersen 1976, 1981). Sea level rise was especially rapid through the Wiechsel glaciation, between 7000 and 6000 BC when sea level rose some 30 m (Andersen, 2013 and Petersen 1976, 1981). These transformations required a change in overall hunting and fishing practices, further affecting the Ertebølle culture (Astrup, 2018).

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Figure 10: Regions of potential seawater influx into freshwater basins caused by eustatic and isostatic sea-levels, map created from elevation data (Astrup, 2018).

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Figure 11: Sea-level curve based on specifications from GIA models (Astrup, 2018).

In addition to the eustatic effects (changes in sea-level) on the Ertebølle culture, southern Scandenavia was and is currently influenced by two additional main environmental processes, coastal processes and isostacy (vertical changes in the Earth's crust) (Astrup, 2018). Figure 12 depicts an eustatic sea-level curve based on radiocarbon dates. The sea-level curve is considered a good approximation for global sea-level due to its distance from any glacial influences (Whitehouse, 2009). Eustatic curves, may serve as a more accurate for a given area by accounting for isostatic rebound, thereby reflecting Denmark's glaciation during the Mesolithic period (Whitehouse, 2009; Påsse, 2015; Astrup, 2018).

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Figure 12: Eustatic sea-level curve based on radiocarbon dates and areas away from glaciation (Astrup, 2018 and Lambeck, 2014).

With increased concerns for climate change, it is expected for temperatures and environmental features, such as rain to increase (Henriksen, 2011). The increase rain, increases the water runoff, which increases the nutrient input into the fjord. These may result in potential increased storm events about the fjord, resulting in increased winds and temperatures, causing higher coastal processes and erosional effects about archaeological sites (Henriksen, 2011 and Ward, 2019).

To analyse and study prehistoric sites in the marine environment that were affected millennia's ago and are continuously affected by sea-level change today (Figure 13), a variety of field experiments need to be employed. For this project, field research methods included underwater excavations, geotechnical sediment sampling and remote sensing analysis, both aerial and submerged. These methods are employed to observe and interpret the marine environment on the seafloor and below the subsurface to answer questions concerning the hypotheses.

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Figure 13: Depiction of the archaeological site in Denmark as represented by isostatic uplift, meters above and below present day sea-level, since ca. 5250 cal (Astrup et. al., 2019).

3.0 Methods

A multidisciplinary approach to studying paleoenvironments is important to identify prehistoric cultures and sites, and understand how landscapes were formed, changed and used in the Mesolithic period. In Denmark and throughout the globe, submerged landscapes are an understudied field which is gradually gaining attention (Bailey et al, 2017). In order to understand submerged paleoenvironments and underwater settlements, a number of methodological approaches are needed to interpret and understand their environment. These methodological approaches were conducted in the following manner to satisfy the aims and overall research question for this thesis.

In order to answer the research question, mapping the extents of prehistoric settlements with geophysical methods the following tasks were conducted 1) a review of previously conducted historical and archival studies, both archaeological and geological, concerning shell middens and their surrounding environments; 2) a literature review on the Ertebølle culture and Horsens Fjord, Denmark; 3) a review of previously collected geophysical data obtained by GEUS; 4) an analysis of historical geotechnical data logs from Moesgaard Museum to assist with the interpretation phase of the geophysical survey; 5) collection of geophysical data with the use of an Innomar subbottom and Edgetech sidescan data throughout the eastern regions of Horsens Fjord, with the primary focus on the western end of Hjarnø Island; 6) processing all geophysical data sets for seafloor and subsurface interpretations; and 7) a compiled and discussed report of the findings to provide

The second research question focused on the extent of the shell middens in subsurface environments around Hjarnø Island that were identified through the use of geophysical and geotechnical methods. Once these extents were identified, areas and volumes of the prehistoric sites were sought after through the following tasks; 1) identify and digitize surface and subsurface anthropogenic and natural reflectors within the geophysical datasets; 2) create isopach maps of subsurface features, including shell middens and gyttja layers in sediment rich with organic material that were deposited and have remained in place on the seafloor beneath eutrophic waters; and 3) calculate and illustrate the total area and volume of the gyttja and shell midden regions.

The final question, sought to identify a correlation among naturally formed paleolandscapes and prehistoric sites. In order to do this, the following tasks were conducted; 1) obtain previously gathered information on submerged archaeological sites from the Danish Ministry of Culture and SPLASHOS, pertaining specifically to prehistoric settlements; 2) process and digitize previously collected geophysical data using two separate software programs to compare and analyze subsurface paleolandforms; and 3) import all digitized features into ESRI GIS for geospatial analysis to identify any correlations among submerged archaeological sites and subsurface paleoenvironments.

3.1 Desktop Based Study and Planning

In preparation for the 2017 and 2018 field seasons, previously collected field research data were thoroughly examined in a desktop study. The desktop study consisted of a review of previously conducted historical, archaeological and geological studies including geophysical data near to and within Horsens Fjord. Datasets were obtained by the Geological Survey of Denmark and Greenland (GEUS). The GEUS data files included reconnaissance level sidescan and subbottom data, as seen in Figure 14. The data were processed in a widely used ellipsoid, WGS84, and UTM 32 coordinate system. Sonarwiz processing software was used to process the datasets to view any potentially useful submerged features that may require further investigations. The data were then imported into GIS for further analysis and review. Based on the historical datasets and regular meetings with the DHSC team, areas of interest were established and plotted into a navigation software in preparation for the 2017 and 2018 field seasons.

Figure 14: Historical sidescan and subbottom GPS tracklines from GEUS database (http://data.geus.dk/geusmap, Obtained 2017).

Based on the historical data and research goals of the DHSC team, geophysical survey lines were created and plotted in Hypack navigation software to further investigate the submerged environments within Horsens Fjord. To further assist with the planning stages of the geophysical survey, 176 cultural resource sites in Horsens Fjord were identified and obtained using SPLASHCOS' (2017 and 2018) national inventory, both historic and prehistoric. Any relevant sites were researched and matched to the nearest; survey lines to locate any potential submerged or subsurface midden sites and environments favorable for prehistoric inhabitants. After the reconnaissance lines were plotted or as weather permitted, the densely spaced survey lines were plotted. Each survey line was spaced at 5 meter increments. The survey tracklines were plot in a north-south direction and were planned in a manner that moved from deep to shallow waters, until no further operations could safely be conducted. Tie-lines were then placed sporadically throughout the sites A, B and C, with an increased number of tie-lines within sites A and B.

3.2 Geophysical Survey Equipment

To achieve full coverage of the research sites, specific geophysical equipment was selected based on resolution and survey efficiencies (Table 3). To cover the site at the seafloor surface and subsurface, a sidescan sonar and subbottom profiler were used. To assist with location accuracies and motion effects on the equipment, a global position system (GPS) and motion reference unit (MRU) were also used. For the highest location accuracies with the highest time efficiencies, the GPS was used in real time kinematics (RTK) with a virtual reference station (VRS).

Table 3: Geophysical data collection and data analysis techniques.

Geophysical System	**Type**
Navigation/Positioning	Hypack 2017 Trimble R8
Sidescan Sonar	EdgeTech: 600 kHz/1600 kHz
High-Resolution Seismic Reflection Motion Reference Unit	Innomar SES 2000: 4 kHz/15 kHz Seatex MRU
Ground Truth Method	**Type**
Core Samples	Auger Corer: 1 m Depths
Processing Methods	**Type**
Sidescan and Subbottom Data	Cheasapeake Technology-Sonarwiz 7 Subbottom Processing Interpreted Environmental Reflectors 3D Modeling
Subbottom Data	Innomar ISE2 Subbottom Processing Comparative analysis with Sonarwiz 7 Interpreted Environmental Reflectors
Data Modeling and Analysis	Golden Software, Inc Surfer 13 Area Approximations Volume Estimates Thickness Profile Views
Site Mapping and Spatial Analysis	ESRI ArcGIS 10.1 Charting of Collected Processing Data Spatial Analysis

3.2.1 Navigation

Positioning for all surveying applications were acquired with the use of a Trimble R8 RTK GPS interfaced with VRS. VRS provided instant cellular access to RTK corrections using a fixed continuously operating reference station in Denmark. The GPS receiver collects corrected signals from GLONASS satellites, precisely measuring code phase and doppler phase shifts, enabling it to calculate position and velocity of the vessel or location points to <2 cm accuracy both on land and marine environments (Trimble, 2015). Once the signals were received by the GPS receiver, the signals were then extended to Hypack 2017's navigation software for accurate survey planning and charting. Positional data were recorded in WGS-84, UTM 32 in Easting and Northing. Once the GPS string was set in Hypack's navigation software, the GPS strings were then output through the NMEA Output extension to the sidescan and subbottom topside computers for sonar location accuracies.

In addition to the marine surveys, foreshore and upland surveys were conducted with a fixed height rover rod and an RTK R8 secure on top of the rover rod (Figure 15). GPS location points acquired were recorded in the same coordinate system as the marine geophysical survey. The location points were recorded with in the nearshore zone via land surveying techniques (fixed height rover rod method) due to the shallow depths within the upper shoreface which was otherwise unattainable by boat. The location points were collected for site data representation concerning natural and anthropogenic applications where the vessel could not reach. High location accuracies are important in the exploration of culturally significant prehistoric sites and environmental conditions due the ability to correct for survey instrument offsets, including the sidescan sonar, subbottom profiler and MRU, as well as location point accuracies for all excavations and auger core site. Each location recorded was documented according to its easting, northing and elevations.

Figure 15: Collection of site locations at low tide with a Trimble R8 RTK (Photo: J. Benjamin).

3.2.2 Sidescan Sonar

Figure 16: Image of EdgeTech 4125 mobilization (Photo: J. Benjamin).

Throughout the marine geophysical research operations, both in 2017 and 2018, an EdgeTech 4125 sidescan sonar system with a frequency of 600 kHz (Low) and 1600 kHz (High) was used. The towfish was deployed (Figure 16) in coordination with Hypack's acquisition and navigation software. Position offsets were set in Hypack Hardware's setup for the survey operations and output to Edgetech's Discover software for the acquisition phase of the survey. Positional data for the sidescan were recorded in WGS-84, UTM 32 in Easting and Northing.

The Edgetech 4125 sidescan sonar employs full spectrum chirp technology, wideband and high energy pulses (It is coupled with high resolution and signal to noise ratio echo data) (Edgetech, 2016). A recorded high frequency range of 25 m was used throughout the entirety of the survey. In addition, a low frequency range of 55 m was recorded together with the high frequency data.

The survey covered the length of the channel stretching from the eastern end of Snaptun to the western portions of Hjarnø Island, within Horsens Fjord. In addition, reconnaissance survey lines were collected north of Alrø Island, around the eastern end of Hjarnø and around the southern tip of Hjarnø. The sites were then narrowed even further to marked areas of interest and the excavated sites A and B, located on the western end of Hjarnø. These sites were located in shallow waters with a maximum depth of 2 m.

3.2.3 Subbottom Profiler

The second phase of the geophysical research operations consisted of an Innomar SES-2000 standard parametric subbottom profiler (Figure 17). Reconnaissance and densely spaced survey lines were collected with the parametric subbottom throughout the eastern portion of the fjord. This included subbottom data collection from the northeastern end of Snaptun to the northern end of Alrø Island and around the southern end of Hjarnø Island. This system mapped and assisted in the characterization of the environmental conditions and geological formations to depths of 10 m below the subsurface (Figure 18). The SES-2000 operated at a range of 4 kHz to 15

Figure 17: Image of Innomar SES-2000 subbottom mounted on the bow of the vessel with Seatex MRU (Photo: J. Benjamin).

kHz, emitting up to 60 pings/second with a pulse width up to 1.3 ms (Innomar, 2009). Depending on sediment type throughout the survey, a resolution of 5 cm was achieved. The SES-2000 sonar head was mounted on the bow of the vessel using a pole mount and mounted 0.30 m below the water's surface. Throughout the survey, data were corrected for any vessel motion using a motion reference unit (MRU) installed on a pole mount and integrated directly into Innomar's SESWIN hardware collection software.

A Seatex MRU was employed throughout the subbottom data collection phase of the survey. Since the subbottom transducer was fixed to the vessel, all heave, pitch and role data were recorded with high accuracies to account for the vessels motion (Kongsberg, 2008). The Seatex MRU was interfaced with Innomar's SESWIN acquisition software in an EM-3000 format. Throughout the processing phase of the subbottom data, the MRU data were used to process out any motion caused by wave action or vessel m-aneuvering. To further assist omit motion data and prevent any offset error to the system, the MRU was positioned directly over the Innomar SES 2000 subbottom, attached to the subbottom down pole.

Unlike the sidescan position outputs, the position of the subbottom came directly from the Trimble R8 RTK. The measured offsets and position for the subbottom were set and recorded in Innomar's acquisition software (SESWIN) for the survey operations. Positional data for the subbottom were recorded in WGS-84, UTM 32 in Easting and Northing. Once survey operations were completed, the data were exported for processing in Innomar's ISE2 and Sonarwiz software.

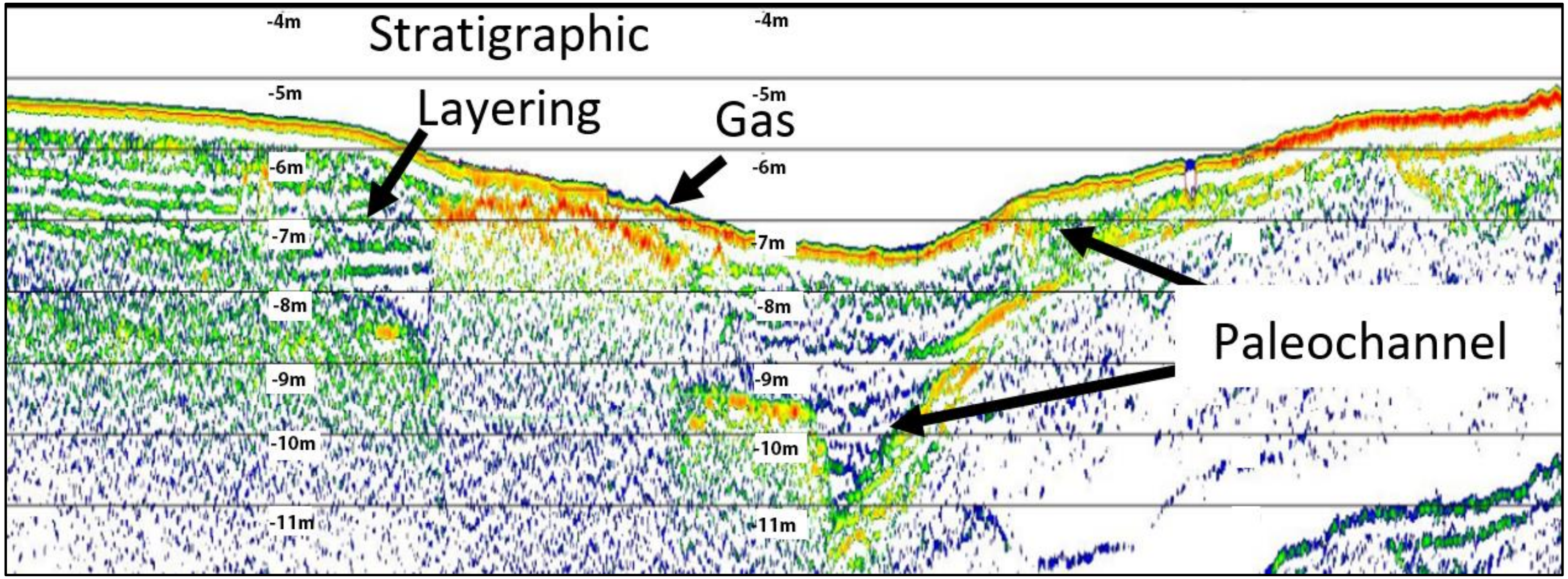

Figure 18: Innomar subbottom data example of stratified layers with paleochannel and gas pocket from a reconnaissance line at the southern end of Hjarnø.

3.3 Geophysical Data Acquisition

Horsens Fjord's eastern waterways, such as those near Hjarnø Island, were investigated using a high resolution sidescan sonar (Edgetech 4125) and a parametric subbottom system (Innomar SES 2000). The survey data was collected and processed in WGS84, UTM 32 coordinate system. In the first stage of the 2017 and 2018 field seasons, reconnaissance survey lines were collected. The reconnaissance survey lines were collected throughout the eastern portion of Horsens Fjord, through Alrø and Hjarnø Sund and throughout the northern end of Alrø Island. Densely-spaced tracklines were concentrated around Hjarnø Island and Snaptun. The sidescan and seismic survey focused on two primary sites located on the western end of Hjarnø Island, approximately 600 m north-south of each other.

Throughout the two field seasons, 2017 and 2018, all geophysical instruments were mounted on and towed from the Research Vessel (R/V) Botetca. The sidescan sonar towfish was deployed with a 1 m layback off the central starboard tow-point of the vessel. The subbottom sonar was mounted on the bow of the vessel with a forward offset of 3.3 m below the water's surface. The GPS was set as the center of reference, 1.42 m above the water line.

Vessel mobilization for field season 1, on the R/V Botetca, began on June 8th, 2017 at the Hjarnø Lystbådehavn (marina). All research personnel mobilized the equipment at sunrise to begin survey operations and demobilized the equipment just before sunset or when weather worsened. At the completion of the day, data would then be reviewed and backed up daily. Geophysical data collection was completed on June 16th, 2017 and the survey equipment was returned to Moesgaard Museum in Denmark and Innomar's facility in Germany on June 17th, 2017.

Vessel mobilization for field season 2 was conduction on the R/V Botetca and began on June 14th, 2018 at the Hjarnø Lystbådehavn (marina). All research personnel and survey equipment were mobilized at sunrise to begin survey operations and demobilized just before sunset or when weather worsened. Weather and sea conditions remained favorable for a majority of the 2018 field season, with only a few weather days. Geophysical data collection was completed on June 28th, 2018 and the survey equipment was returned back to Moesgaard Museum in Denmark and Innomar in Germany.

Planned tracklines for the sidescan and subbottom survey were based on historical datasets acquired by Moesgaard museum and GEUS, as well as DHSC site priority areas. For geophysical survey operations, the English Heritage Guidance Notes on Marine Geophysics for Archaeology (EH) (English Heritage, 2013) were used as a reference for archaeological requirements. The EH Guidance Notes recommends line spacing with a maximum of 30 m with alternate lines running in the opposite direction (Dix, 2008). The recommendation was created to increase the quality and consistency in underwater archaeology surveys (Dix, 2008).

The sidescan operations were planned to cover the entire region between Snaptun and Hjarnø. The parallel line pattern allowed for the sidescan range to overlap on any nadir and vessel gaps from adjacent lines, acquiring well over 100% coverage. The tight line spacing and overlapped data allowed for increased accuracies and interpretations. Additionally, investigatory reconnaissance lines were completed with the sidescan and subbottom profiler. The reconnaissance survey was conducted to identify areas of interest for further seismic operations.

Due to depth constraints, all areas of interest, as selected via the desktop study, were not reached during the geophysical studies. Although the submerged archaeological excavation sites (sites A and B) were mapped to the best of the team's ability, avoidance procedures were necessary due to hazardous conditions. These surface and submerged hazards included boulders, shallow water regions, survey stakes, and a dive platform (Figure

Figure 19: Marine geophysical survey operations utilizing the Innomar subbottom, SES2000, mounted on the bow of the survey vessel (Photo: J. Benjamin).

19).

3.4 Geophysical Data Processing

Historical data processing and interpretation of past studies at Horsens Fjord was conducted prior to any field collection methods for environmental research. Although, the historical data gave insight to the submerged environments of Horsens Fjord, it did not cover the extents of the excavation sites. Soon after review of the historical data, the data acquisition stage was conducted, this left the post processing stage of the 2017 and 2018 field data, sidescan and subbottom data. The datasets were processed to account for varying gains, slant range corrections, and bottom tracking to identify anthropogenic areas of interest (targets) and environmental features. Sidescan and subbottom data, along with their real-time locations were analyzed in Chesapeake's Sonarwiz 7 and Innomar's ISE2 processing software.

To analyze the sidescan data at the highest resolution and furthest range, both dual frequency datasets, 600 and 1600 kHz, were used in the processing and interpretation phase of the study. Low frequency data were first processed to view the study area at a broader range, yet at a low resolution. To obtain higher resolution imagery of the seafloor, high frequency data were then processed and interpreted; however, this was at the expense of lower range extents over the seafloor. The high frequency data were then overlaid on the low frequency. All sidescan lines collected in sites A and B yielded well over 100% coverage, even with nadir gaps below the sidescan towfish and vessel off-track gaps. Within the sidescan imagery, hard returns represented high-amplitude backscatter articles, such as boulders or shell piles. Low-amplitude backscatter articles were seen and representative of soft returns, such as clays or muds. The high returns were depicted in a sharper-lighter coloration and the low amplitudes were represented as a darker image or potential shadows if the sound was blocked by high backscatter regions (Fish, 1990).

All sidescan data were analyzed in full coverage mode to assure a full and in-depth investigation of the site. For visual purposes, the mosaic was produced at a map resolution of 15 cm (5.9 in) pixels. Accuracy of the georeferenced pixels are a function of towfish heading accuracy, position accuracy and range (distance from the sidescan sonar center). The processed data, including the waterfall displays and mosaic, were slant range corrected once the nadir was reviewed (Figure 20). In addition to the mosaic, individual targets were selected for each line.

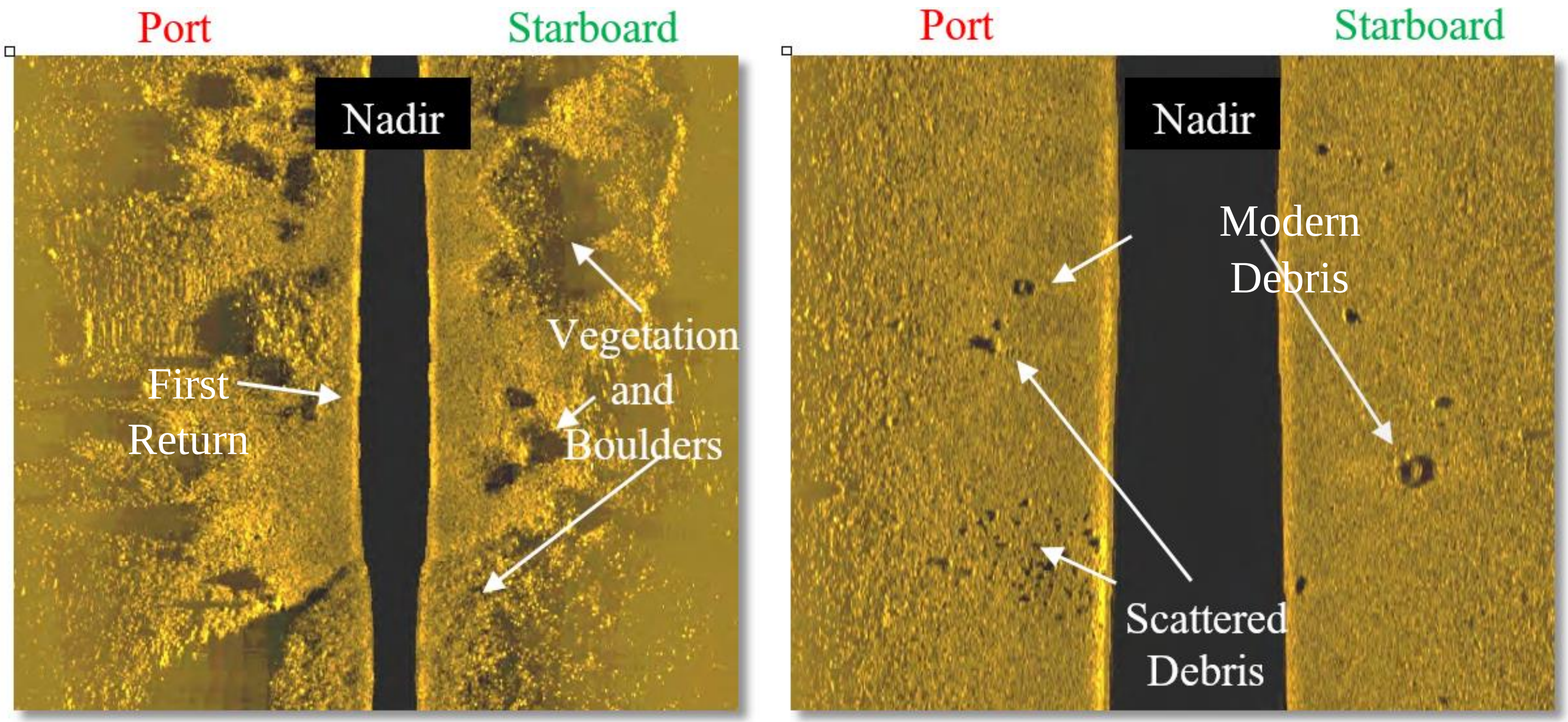

Figure 20: Waterfall display of high-backscatter sidescan targets that are attributed to debris, boulders and aquatic vegetation on the seafloor. Both panels depict a nadir as depicted in the acquisition phase of the survey.

The waterfall displays, as depicted in Figure 20, were used for seafloor interpretation purposes to identify and highlight any environmental and culturally significant features. A systematic methodology was created to identify potential targets through the analysis of individual lines to generate a full and clear view of the site. Both high and low frequencies were viewed and analyzed in the waterfall display to identify any potential targets. After the sidescan files were analyzed and digitized accordingly, two separate mosaics were created, both high and low frequency. These were then stacked within ArcGIS for further analysis and visual reference.

The sidescan data and subbottom data were processed to identify and digitize surface and subsurface features that might not be visible to the human eye. The seismic subbottom data were imported in both the Innomar ISE and Sonarwiz 7 post processing software. Sonarwiz is a comprehensive and versatile processing software, which allows the congruent representation of geophysical subbottom and geotechnical data to be viewed in a variety of formats, including the ability to portray the data as a 3D model. This is observed in Figure 21, with the addition of seismic tracklines overlaying on the sidescan mosaic. ISE encompasses the ability to extend signal processing capabilities past that of Sonarwiz and in addition allows the overlay of sediment cores.

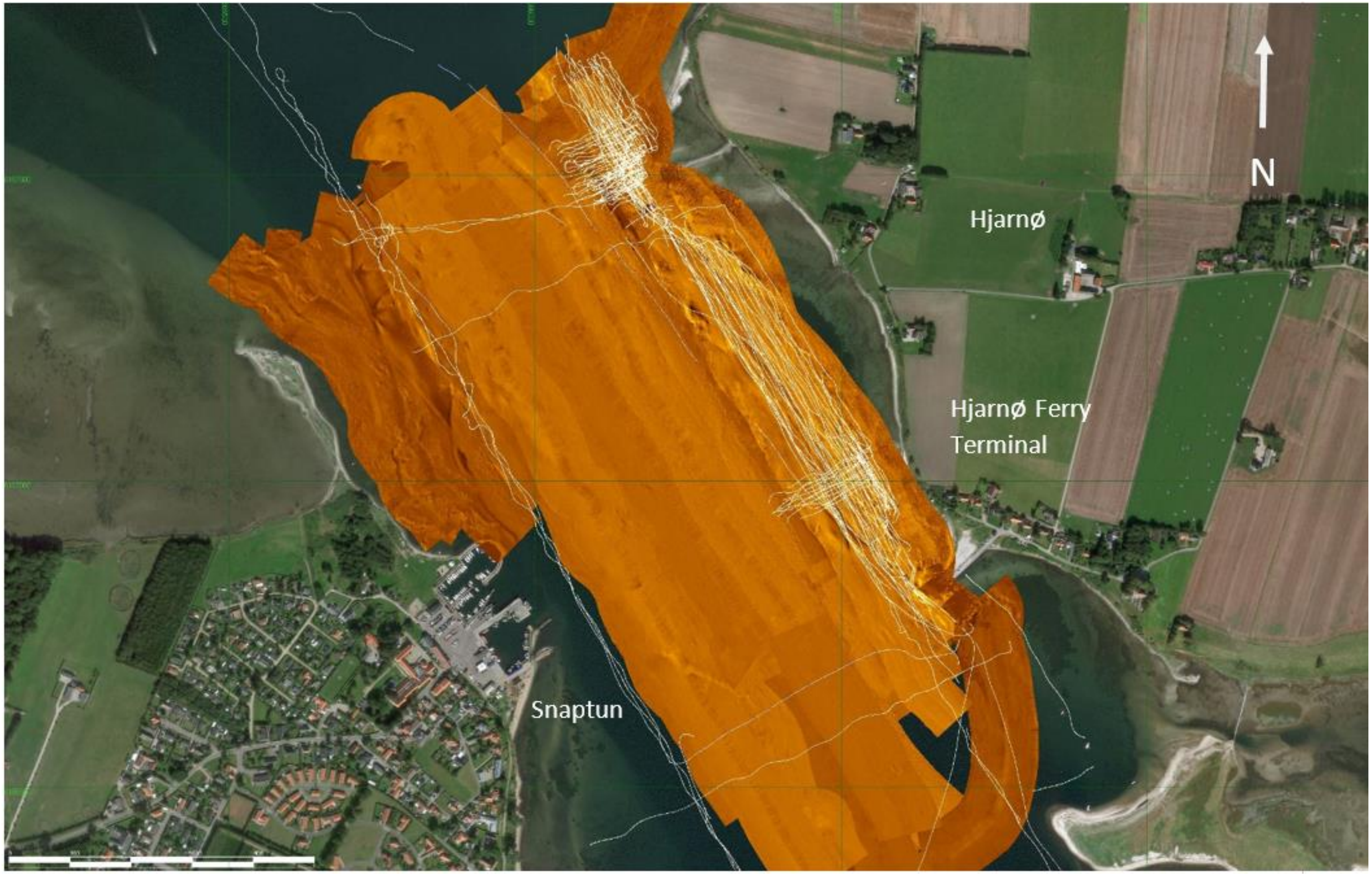

Figure 21: Sidescan mosaic with overlain subbottom as-built tracklines from the 2018 survey operations.

The SES-2000 system's echo plots were processed in both Sonarwiz and ISE for comparative data analysis of the fjord's seafloor and subsurface. The data were analyzed and illustrated in a variety of colored pallets and a grayscale pallet. To further assist the signal processing phase, the signal-to-noise-ratio was improved with algorithms Algo 1P and Algo AMP. The comparison and analysis with both algorithms allow for a better display of amplitude data from the echo returns. Stacking was applied to visualize and digitize stratigraphic layers across the data set.

Geotechnical data were collected and used to ground truth the geophysical data. After the geophysical and geotechnical data were collected they were then incorporated into the processing software (Figure 22). In addition, seismic datasets were cross-correlated with ground truthed samples collected by Moesgaard Museum and the DHSC team. The use of the ground truthed samples assisted in the identification and recognition of geological stratigraphic layering and anthropogenic activities. Any cultural material identified were exported as a target file for further analysis within GIS.

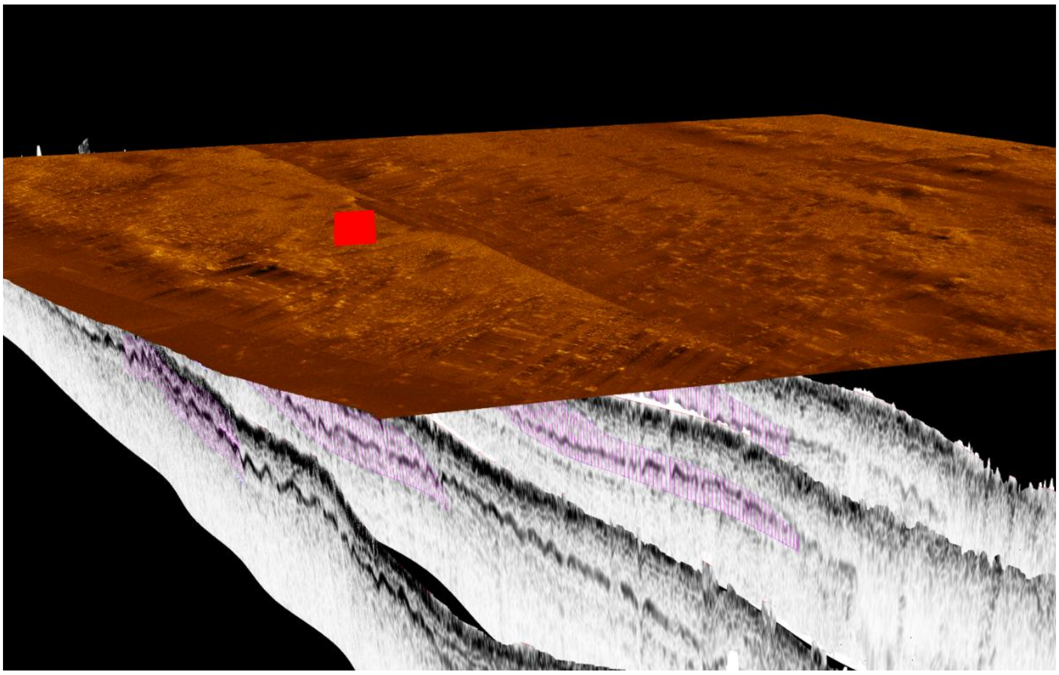

Figure 22: 3D results representation of overlain sidescan mosaic and excavation site (red) on subbottom transects with digitized subsurface shell midden (purple).

3.5 Geotechnical Equipment

To assist with the geophysical data analysis and interpretations, geotechnical samples were collected via an auger corer and grab samples. The gouge auger corer, used throughout the duration of the field operations, is a light weight and transportable sampler (Figure 23). Soil samples are collected by puncturing the surface layer of the seafloor to depths of 1 m. Once punctured, the auger is rotated in a clockwise manner to collect the soil samples, enabling the researcher to retrieve and view the sample virtually undisturbed. In addition to the auger corer, grab samples were also collected.

Figure 23: Geotechnical sample logging through the use of an auger corer (photo: J. Benjamin).

3.6 Geotechnical Investigations

Disturbed sediment samples were collected with a hand auger corer at predefined locations selected based upon geophysical data and the research set by MOMU to determine soil type, texture, classification, and stratification. Surface samples were also collected using a hand trowel method within the excavated trenches. The samples were collected along the seafloor surface, excavation walls and various exposed regions of the excavated trenches. Some samples were viewed in real-time and recorded for future correlations to the geophysical data. Other samples were analyzed infield and kept for future tests in a lab setting. Samples obtained in and around sites A, B, and C were analyzed in coordination with the processed seismic data and the sidescan data via GIS analysis and geoprocessing software. Further geological samples, outside of the excavated site were collected for analysis and geophysical ground truthing purposes (Figure 24).

Figure 24: Archaeologist collecting sediment samples from the midden site during the 2017 field season.

The collection and analysis of all geological samples were obtained among Snaptun and Hjarnø, focusing efforts on the western portion of Hjarnø Island. All geotechnical data samples were continuously analyzed and logged in the field for modeling purposes. The digitized samples were also analyzed using geophysical data to identify underground structures beneath the seafloor. The use of these auger cores (Figure 25) assisted with the identification of strong reflectors, to allow digitization of the geological layers across the seismic profile section. Each auger core was plotted in Sonarwiz and ISE2 seismic processing software to assist with geological and archaeological analysis.

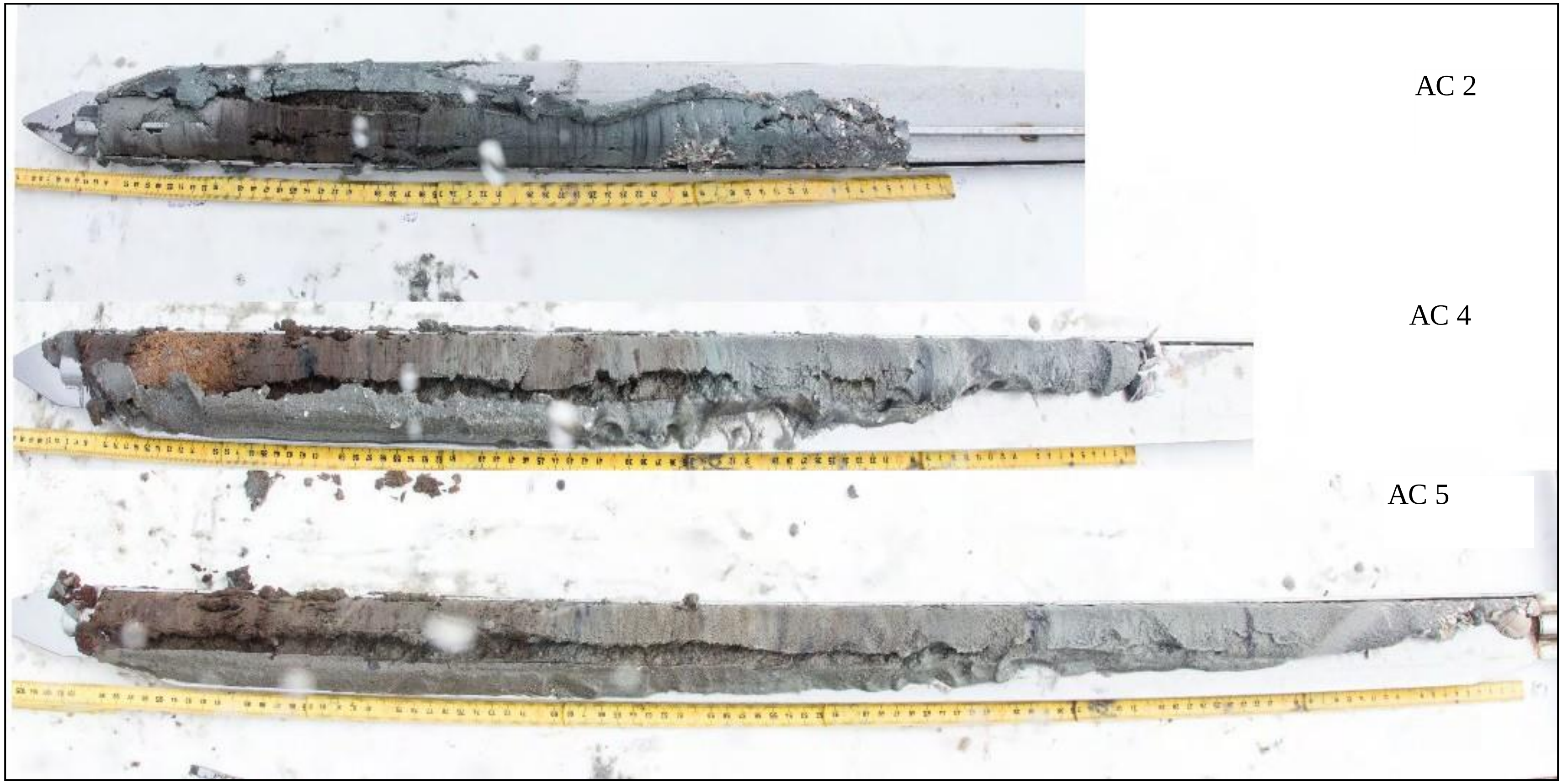

Figure 25: Auger core sediment samples collected from the bottom trough of the 2017 site A excavated midden site.

3.7 Volume Estimates and 3D Modeling

To account for the volume estimates of the shell middens and any other environmental features, the subbottom data were digitized in Sonarwiz 7 and further analyzed in *Golden Software, Inc Surfer (V13)*. Once the subbottom data were imported into the Sonarwiz, anthropogenic and natural environmental features were then digitally digitized, as seen in Figure 26. The digitized features included items such as the seafloor, clay or gyttja layers, vegetation, and shell layers. To further assist with the data interpretation, geotechnical data were plotted in the processing. Once the geologic layers were identified, they were then traced throughout the dataset. Reflectors or multiples did prove difficult in the data interpretation, omitting some of the geologic record in the subbottom data. Despite this, a majority of the geologic subsurface layers were digitized. After features, such as the seafloor surface, midden and paleochannels, were digitized, a thickness file was then created. To determine the midden's total area and thickness, the surface and the lowest most observable portion of the midden were digitized. From the digitization, an X, Y, Z chart was exported from Sonarwiz in an excel format. The data were then imported into *Golden Software, Inc Surfer (V13)* and converted into a grid file. Shell midden extents were also imported into the *Golden Software, Inc Surfer (V13)* in ESRI's shapefile format. The grid files that represent the midden position and thickness, was then converted in *Golden Software, Inc Surfer (V13)*'s volume tool. The volume tool takes the middens shapefile's boundaries to analyze the outer limits. A detailed isopach map was created with calculated volume estimates and profile views.

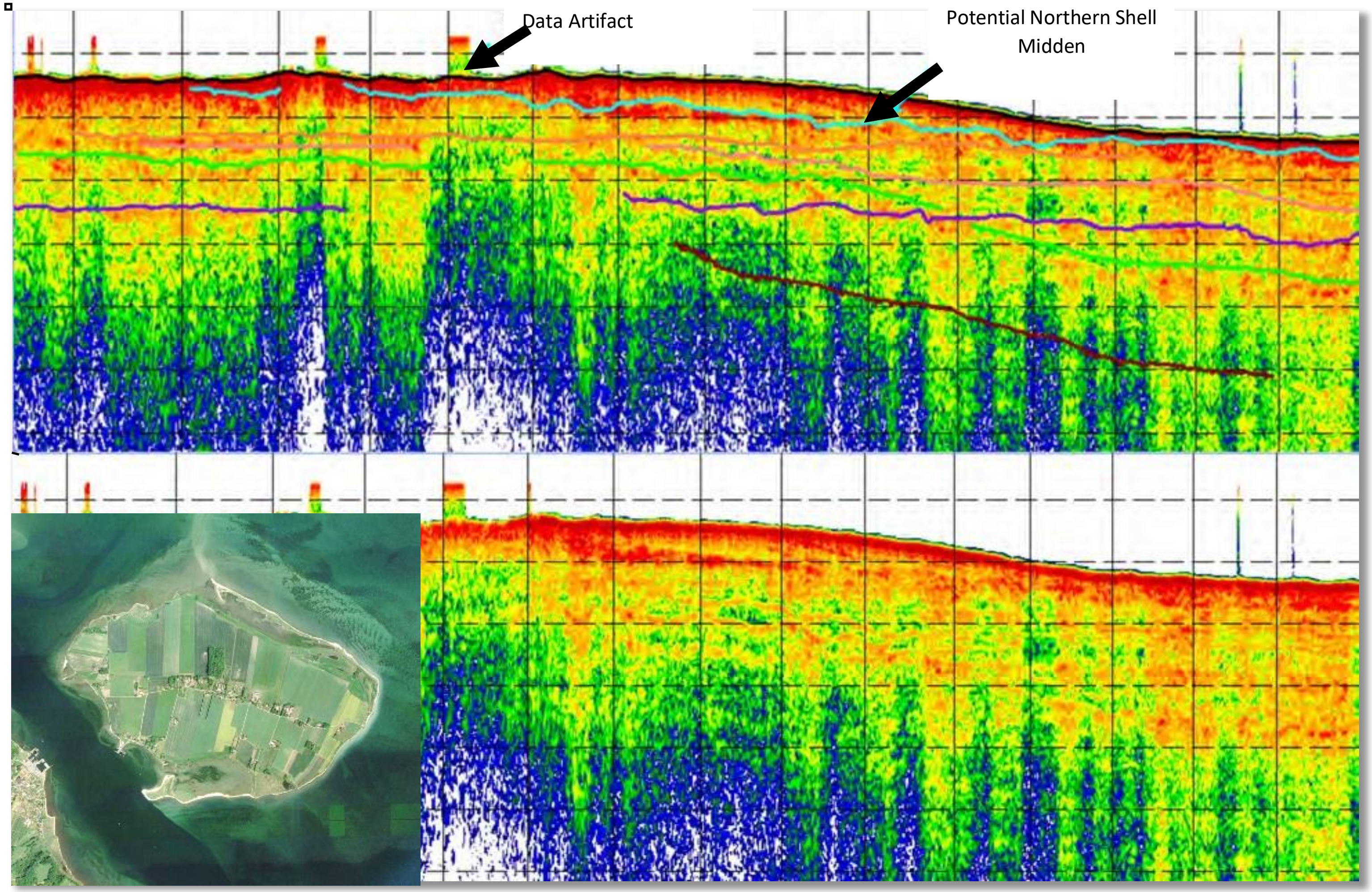

Figure 26: Northern study area (site B) depicting a potential shell midden, represented as a strong reflector digitized in a light blue color.

Calculations for volume estimates were performed with the use of Golden Software, Inc Surfer (V13) and their equations in three methods, 1) Extended Trapezoidal Rule, 2) Extended Simpson's Rule and 3) Extended Simpson's 3/8 Rule (Surfer, 2015). These are all based upon cut and fill volume estimates. Positive values represent the amount of material present at a site and negative values represent the amount of material needed at a site. Since, no additional material was needed, all negative volumes were given a 0 value (Surfer, 2015). This specific equation, found below, was used from Surfer's software program (2015):

$$\text{Volume} = \int_{x_{\min}}^{x_{\max}} \int_{y_{\min}}^{y_{\max}} f(x, y)\, dx\, dy$$

Where f (x,y) is defined by a double integral, integrating x, the columns, and y, the rows to estimate the areas under the rows to obtain the final volume (Surfer, 2015).

3.7.1 Extended Trapezoidal Rule

The extended trapezoidal rule for volume estimates, acts by approximating the definite integral or region under the graph function representing a trapezoid to identify its area (Surfer, 2015). The pattern of the coefficients is {1,2,2,2…,2,2,1}:

$$\mathrm{A}_i = \frac{\Delta x}{2}\left[G_{i,1} + 2G_{i,2} + 2G_{i,3} \cdots + 2G_{i,nCol-1} + G_{i,nCol}\right]$$

$$\text{Volume} \approx \frac{\Delta y}{2}\left[\mathrm{A}_1 + 2\mathrm{A}_2 + 2\mathrm{A}_3 + \cdots + 2\mathrm{A}_{\mathrm{nCol-1}} + \mathrm{A}_{\mathrm{nCol}}\right],$$

Where Δx is the grid column spacing, Δy is the grid row spacing, and G_{ij} is the grid node value in row i and column j. The reported volume is reported as a positive volume (cut), material above the lower surface (Surfer, 2015).

3.7.2 Extended Simpson's Rule

The extended Simpson's rule is based on the numerical value of an integration to provide an approximate integral, essentially breaking up the interval into two small subintervals for calculation (Surfer, 2015). A formulation for calculations is provided below. The pattern of the coefficients is {1, 4, 2, 4, 2, 4, 2,…,4, 2, 1,}:

$$\mathrm{A_i} = \frac{\Delta x}{3}\left[G_{i,1} + 4G_{i,2} + 2G_{i,3} + 4G_{i,4} + \cdots + 2G_{i,nCol-1} + G_{i,nCol}\right]$$

$$\mathrm{Volume} \approx \frac{\Delta y}{3}\left[\mathrm{A_1} + 4\mathrm{A_2} + 2\mathrm{A_3} + 4\mathrm{A_3} + \cdots + 2\mathrm{A_{nCol\text{-}1}} + \mathrm{A_{nCol}}\right]$$

Similar to the Extended Trapezoidal Rule, Δx is the grid column spacing, Δy is the grid row spacing, and G_{ij} is the grid node value in row i and column j. The reported volume is reported as a positive volume (cut), material above the lower surface (Surfer, 2015).

3.7.3 Extended Simpson’s 3/8 Rule

The Simpson’s 3/8 rule is a combination of integrals where the calculations are based on cubic interpolations as opposed to quadratic interpolations (Surfer, 2015). The Simpson’s 3/8 rule is twice as effective as the original Simpson’s method; however, an additional value is used. Volume equations can be found below. The pattern of the coefficients is as follows {1, 3, 3, 2, 3, 3, 3,…,3, 3, 2, 1}:

$$\mathrm{A_i} = \frac{3\Delta x}{8}\left[G_{i,1} + 3G_{i,2} + 3G_{i,3} + 2G_{i,4} + \cdots + 2G_{i,nCol-1} + G_{i,nCol}\right]$$

$$\mathrm{Volume} \approx \frac{3\Delta y}{8}\left[\mathrm{A_1} + 3\mathrm{A_2} + 3\mathrm{A_3} + 2\mathrm{A_3} + \cdots + 2\mathrm{A_{nCol\text{-}1}} + \mathrm{A_{nCol}}\right]$$

Just as in the Extended Trapizoidal rule and the Extended Simpson’s Rule, Where Δx is the grid column spacing, Δy is the grid row spacing, and G_{ij} is the grid node value in row i and column j. The reported volume is reported as a positive volume (cut), material above the lower surface (Surfer, 2015).

Volume calculations were based on the input grid file created from Sonarwiz thickness models. Each measurement is provided in cubic units. Considering the input grid with XYZ units in meters, a net volume was calculated as follows: Net Volume = (meters* meters * meters). Regions of

0 input were excluded from any volume calculations.

A planar area calculation was computed with the cut and fill portions of the surface depicted onto a plane and calculating the area of the projection. Additionally, a polygonal shape of the midden was taken into consideration based on subbottom data. Since there were no negative planar areas based on the calculation, and there was an absence of regions at the value 0, a positive planar area was calculated representing the upper surface, in this case the midden, from a horizontal plane.

Figure 27: Photomosaic of excavated shell midden extending 5 m from the 2017 field season.

3.8 Underwater Excavation Methods

Excavations were conducted at one meter increments from northeast to southwest. Excavated depths were continued down to a clay or gyttja layer, or until no further shells were observed from the midden site (Figure 27, 28 and 29). Excavations primarily took place at the Hjarnø Island sites, sites A and B, during the two field seasons in 2017 to 2018. The underwater excavations were conducted with a variety of techniques including hand fanning, hand tools and dredging. Site A's excavation extended 5 m throughout the subsurface midden location. Site B was excavated in four separate 1 m trenches.

Underwater SCUBA surveys and excavations at both sites involved the use of survey stakes, square 1 m units, tape measures, a hand trawler, 2 m survey rods with an attached GPS for positioning and a water pump from the sea surface with a dredge hose extended to the excavation site. A mesh bag was fastened to the outflow of the dredge and was positioned down current to avoid any further limited visibility from suspended sediments. Once the mesh bag was filled with excavated material, operations ceased. A new bag was placed on the outflow for the researchers to continue with underwater excavations again. The filled mesh bag was carried to DHSC team members on land for sifting and further analysis.

Oyster and cockle shells (Table 4) were recovered throughout the midden (Figure 28 and 29). Additionally, charred wood and animal bones were observed along with chipped flint, representative of worked blades. Excavated material that was collected in the large mesh bag were sifted according shell species and further sifted to search for any artifacts that might been have missed below the water's surface. In addition to underwater excavations, sediment surface samples were collected to further analyze geological material. To further document the site, underwater photographic survey, as well as photogrammetry, took place throughout the entirety of the site operation.

Table 4: Midden Shell Scientific Classification.

Common Names	Scientific Names
European Flat Oyster	*Ostrea edulis*
Common Cockle	*Cerastoderma edule*
Blue Mussel	*Mytilus edulis*
Common periwinkle	*Littorina littorea*

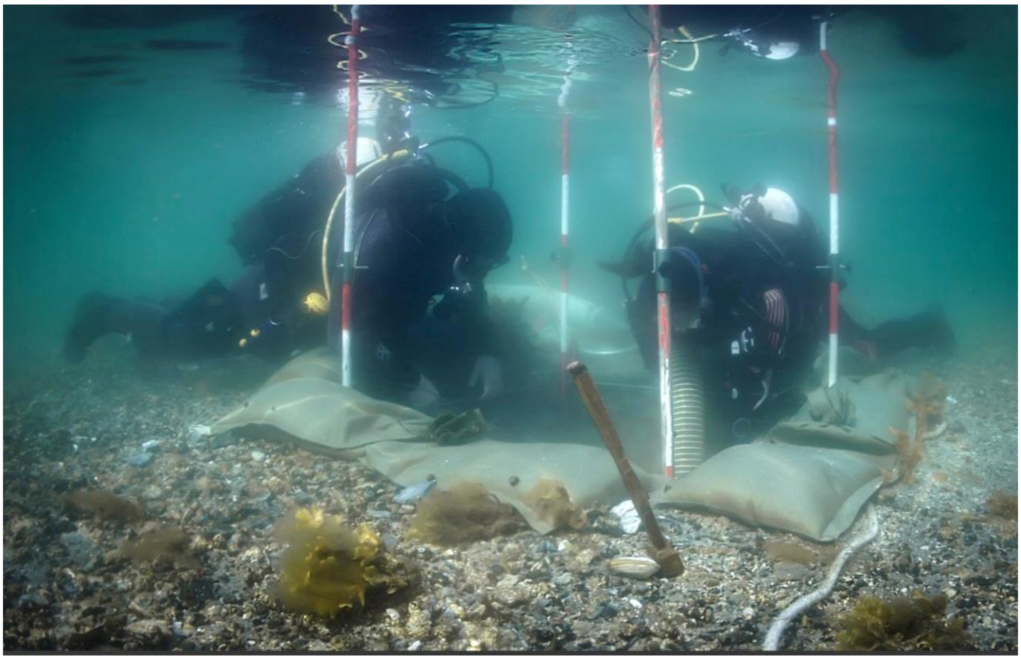

Figure 28: Marine archaeologists excavating a potential midden site during the 2018 field season with an underwater dredge.

3.9 Weather and Survey Conditions

In addition, seas conditions would generally worsen in the afternoons. Shallow water vessel operations would quickly become unsafe due to increased weather. Wind and wave heights would increase steadily, creating up to 0.6 m sea conduction. With a low lying vessel and instruments mounted on and below the sea surface, operations were commonly put on hold. Throughout the field seasons, there were eleven (11) attempted geophysical operational days in 2017 and ten (10) attempted geophysical operational days in 2018. These days included both mobilization and demobilization of the vessel, as it was not a closed or secure cabin, and transit to the sites. In many cases, winds would increase from midday on. These weather and time constraints would prevent efficient geophysical data collection on numerous days throughout the 2017 field season due to heighted wind and wave conditions.

4.0 Results

The focus of the study was split over two research sites and field seasons, 2017 and 2018. The two sites covered two locations on the western end of Hjarnø Island, an area approximately 107 km^2. All environmental features and locations, where archaeological material was present, were analyzed in a north to south and east to west search pattern, starting nearest to site A (2017) and later transitioning to site B (2018). Processes and interpretations were based on a multidisciplinary approach, primarily focusing on geophysical methods, classifying surface and subsurface environmental features. This approach yielded the interpretation and identification of the subsurface shell middens, gyttja layers and paleo-environments. Figure 29 depicts the observed shell midden subsurface with illustrated excavation trench and shells. Results are discussed below.

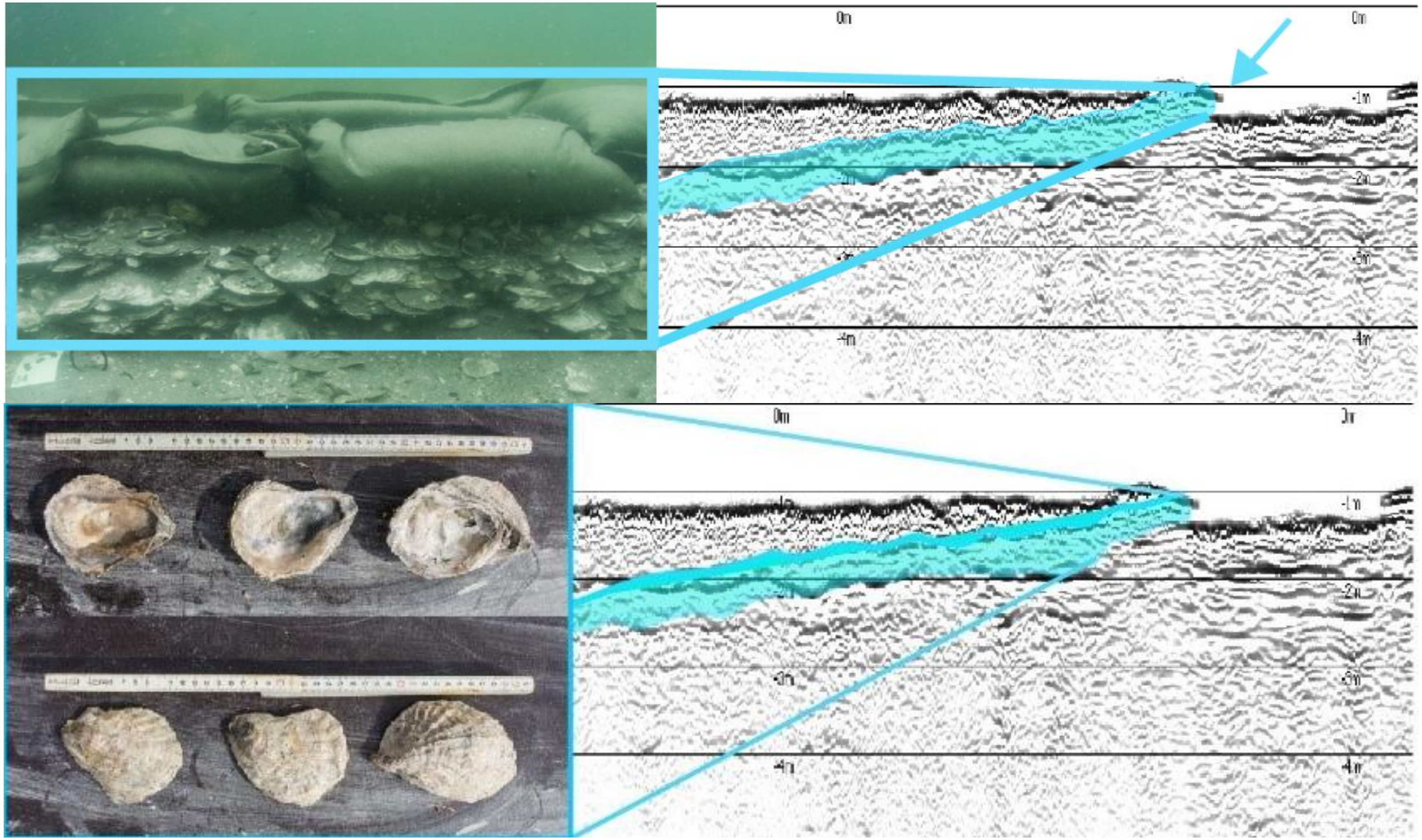

Figure 29: Seismic profile depicting shell material from the midden (highlighted in light blue). The midden layer is unique from the surrounding geology due to its strong return.

4.1 Geophysical Operation Results, 2017

Through geophysical analysis, the shell midden at site A was identified. The subsurface high reflective shell layer was primarily observed through the use of a parametric subbottom, with the assistance of underwater excavations and auger cores. Auger cores used in the geophysical interpretations were taken in the base of the excavation trench and around the research area to further ground truth the geologic layers. No shell midden was observed in the sidescan sonar acquisition data or in the processing stages. Within the sidescan sonar, clustered shell material or hard structure items were typically viewed as high return signals, depicted as a lighter image in comparison to the surrounding areas. The sidescan data around the excavation trench, site A, depicts low return values. These dark valued colorations are similar to that of a semisoft sediment. Further supporting the sidescan data, the reflective shell layer, as observed in the subbottom, did not appear to break the seafloor's surface.

All subbottom data were ground truthed with visual infield observations and geotechnical samples, either grab or auger core samples. The ground truthed data, as with all geophysical data, is considered invaluable in comparing data sets (Reynold, 1997). Any significant geological layers, as observed within the auger core samples and within the excavation trenches, were correlated to the subbottom's stratigraphic data layers. This method was similarly used in the reconnaissance stage of the subbottom survey.

Similar to site A and B, a large portion of the reconnaissance lines were collected in shallow waters. Collection of geophysical data in shallow waters caused some amounts of distortion, noise and data loss in the outer range bands. Within the sidescan sonar, distortion and data loss in the outer bands were observed in shallow waters of 1 m and less. The depiction in Figure 30 portrays this distortion and inflated item's shape, size and shadows, eclipsing the preceding items. The range and data quality is also diminished in the outer range bands of the sidescan as shallower waters are approached and mapped, omitting any recognizable submerged items.

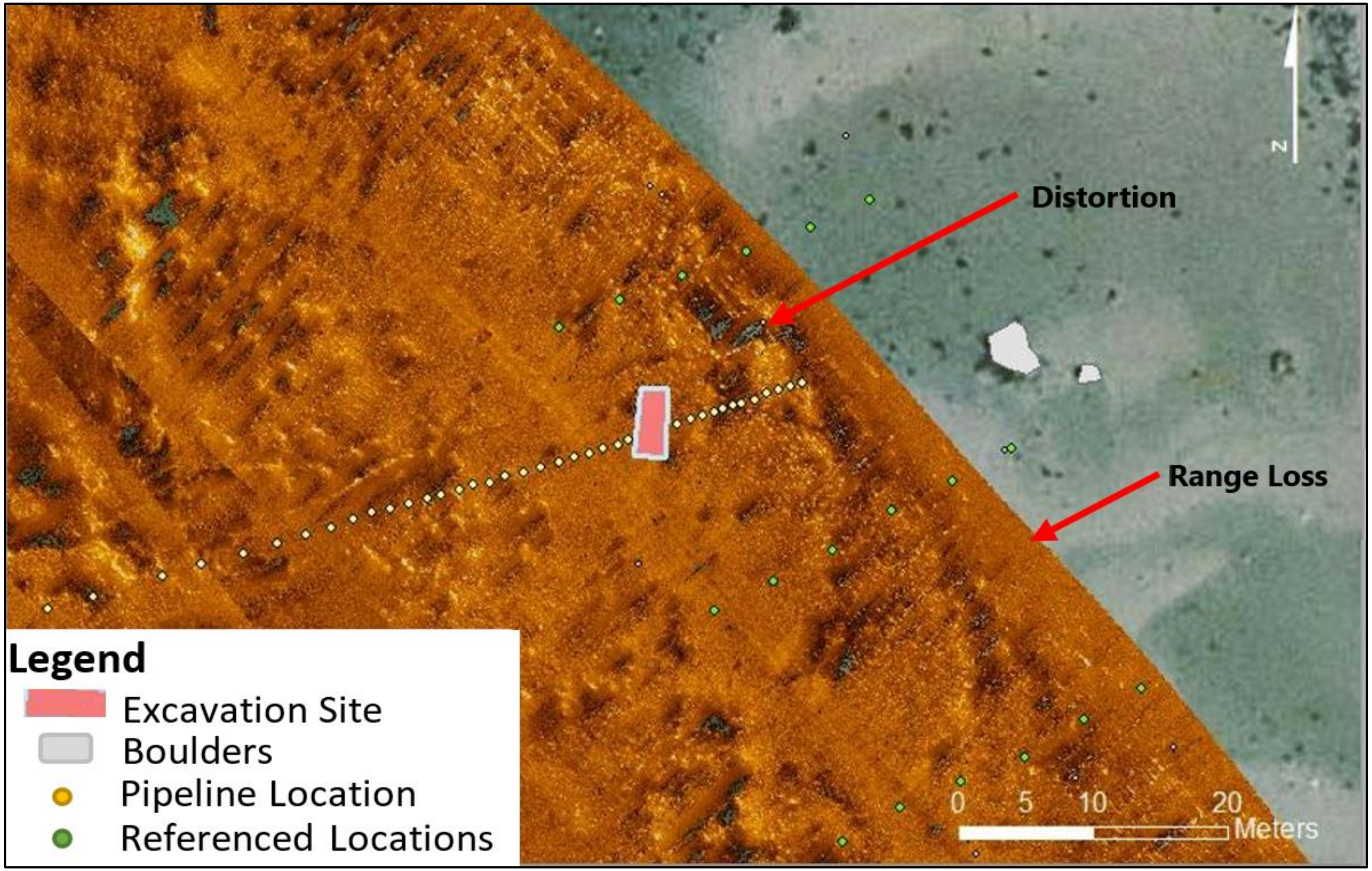

Figure 30: Sidescan imagery with overlain GPS point fixes collected from the 2017 infield research at site A. Polygons were created around excavation sites and boulders based on GPS fixes.

Though the shell midden at site A was the primary focus of research in the 2017 field season, surrounding biological and geological processes were analyzed using the geophysical systems to assess the environmental conditions for submerged Ertebølle sites. The channel among Hjarnø Island and Snaptun, which included sites A and B, were mapped in their entirety. The reconnaissance sidescan survey lines that were collected around the circumference of Hjarnø Island, Glud Hab and Alrø Island, revealed numerous paleo environments throughout the fjord.

The wester portion of Horsens fjord was not studied due to weather and time constraints. Weather and sea conditions caused numerous issues and limitations throughout the 2017 field season. Winds and sea conditions would generally increase around noon and worsen throughout the afternoon, creating hazardous conditions. In addition, submerged hazards including erratic boulders, wooden stakes, ferry terminals and shallow water depths were avoided for safety purposes (Figure 31).

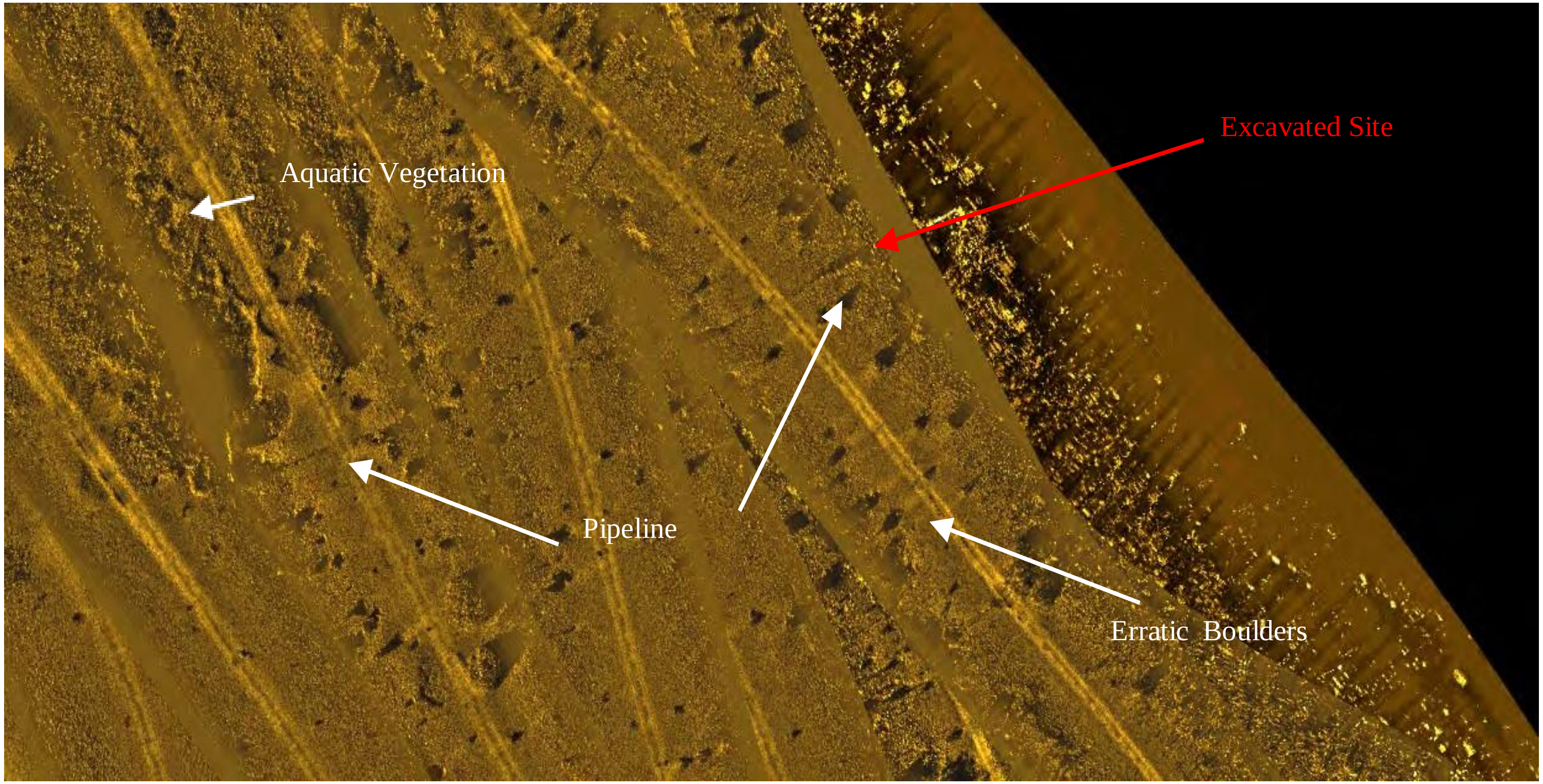

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Figure 31: Sidescan mosaic of site A from the 2017 field season depicting environmental and anthropogenic features observed about the midden site A, excavation site.

Despite the submerged hazards, a carefully conducted and focused subbottom survey was conducted over site A, located on the western portion of Hjarnø Island. From the detailed survey, site A was processed and interpreted to identify the location and outer limits of the submerged midden. The data was reviewed in .RAW format and then converted to .SES format for processing in both Innomar's and Chesapeake's software. The total area surveyed, in the channel, among Hjarnø and Snaptun encompassed approximately 855 km^2. Along with the natural stratigraphic layers, the shell midden features were distinguishable in the subbottom data. The midden features were observed in the subbottom data as hard returns, darker and solid in color to the surrounding stratified layers. These digitized midden layers are observed just below the fjord's seafloor surface and within the subsurface layers. Leading away from the excavated trench, the midden reflector layers were traced to depths of 2 m below the seafloor surface. The overall shape of the midden is oblong and irregular (Figure 32). The shell midden site, originally mapped without the use of geophysical equipment was observed at a total area of 120 m^2 (Skriver, et al., 2017). Geophysical methods depict the shell midden in the subbottom in a total positive area of 817 m^2 and a total area of 1,443 m^2. The southern portion of the midden site appears to have eroded away over time, accounting for nearly for a quarter of the total area. This eroded section gives the distorted shape of the midden's original appearance.

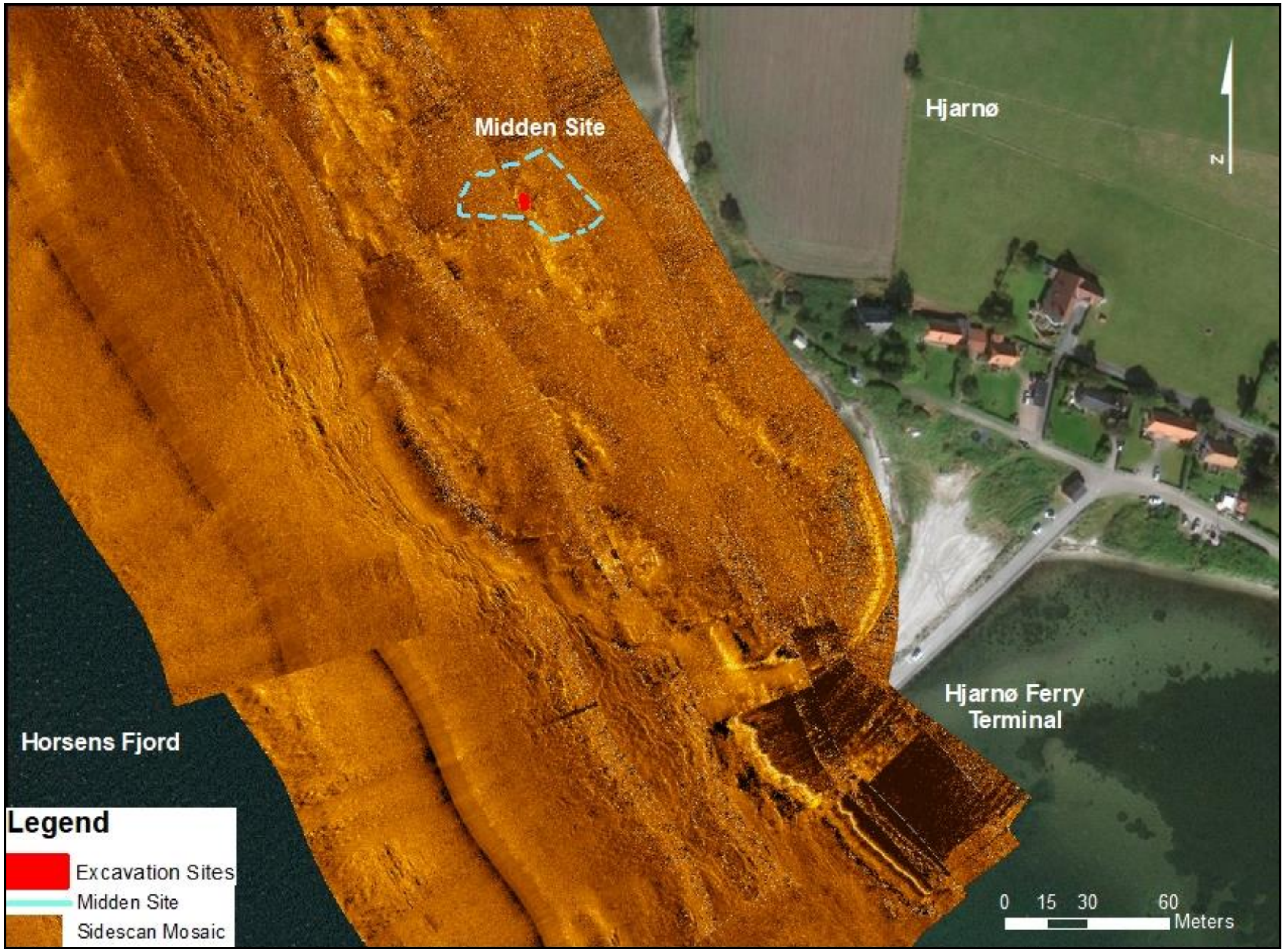


Figure 32: Sidescan mosaic of Hjarnø Island, western end with interpreted midden site from 2017 research.

To ground truth the geophysical data, a number of methods were used, this included underwater excavations, grab samples, and auger cores. The samples were not only collected at the primary sites, they were collected throughout the entirety of the sites, both the detailed and reconnaissance areas. During the underwater excavations, side-profiles of the excavation trenches were recorded for their geological and potential anthropogenic material layering correlations. While grab samples allowed for geological interpretations at the submerged seafloor surface, auger cores were collected to analyze the geologic material subsurface. The ground truthed data were then incorporated into the geophysical processing software, further assisting with the interpretation of the data. In addition, natural or anthropogenic references, such as the excavation trench at site A, were used to correlate and truth the geophysical data (Figure 33). Similar to the image (Figure 33A), the parametric subbottom data (Figure 33B) depicts a steep edged lip of the excavation trench, roughly 0.5 m. The depth of the trench at the time of the geophysical survey was measured to 0.5 m or 1.3 m in depth. A pale returned reflector, on the top portion of the excavated trench, represents soft sediment infill and algae. This soft sediment infill and algae is observed just above the deepest portion of the excavation trench, represented as a sandy clays with shell hash. No further shell material was found below this layer, as the remaining layers were sandy clays, silty clays with some sands and clays (Figure 35).

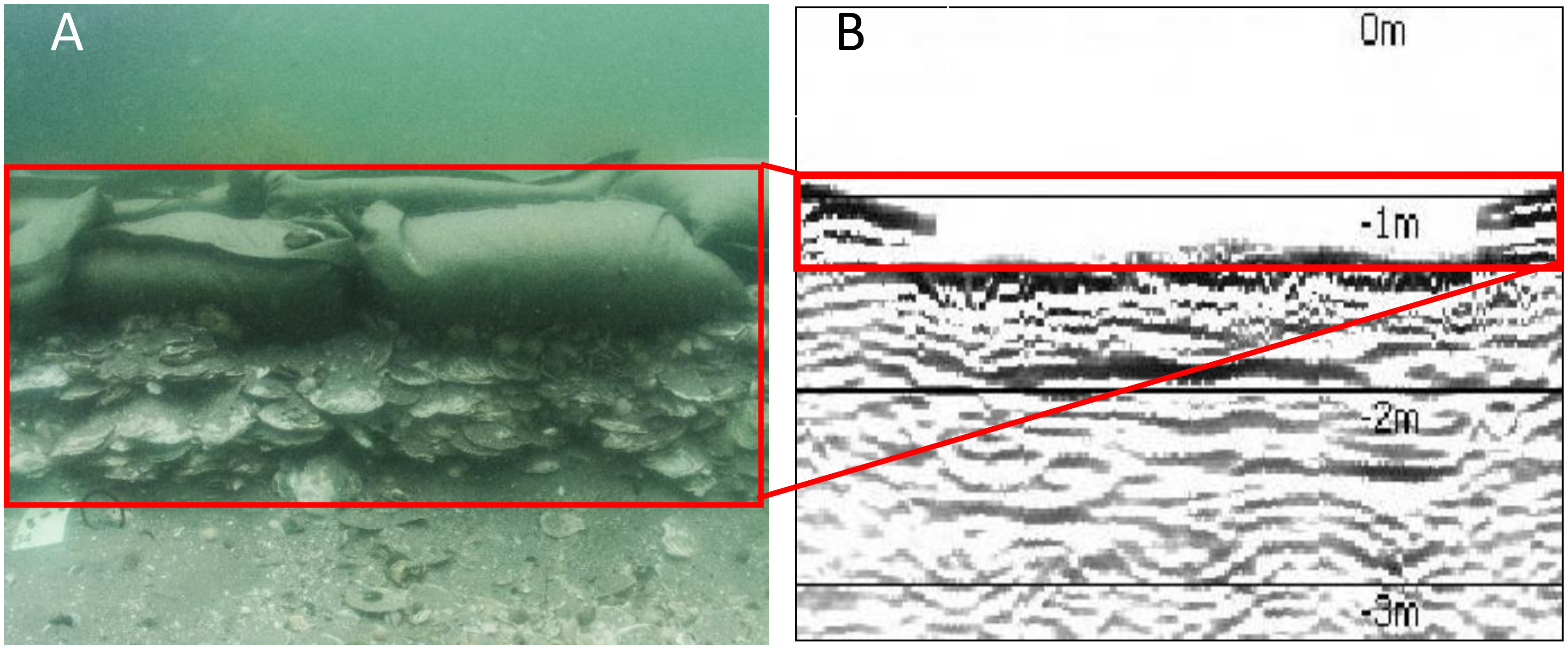


Figure 33: Photographed excavation site (A) and parametric seismic profile (B) of excavation area at site A.

4.2 Geophysical Operation Results, 2018

The 2018 field season resulted in a much broader use of the subbottom profiler, providing a more auspicious subsurface for survey results. The subbottom tracklines were collected at a line spacing of 5 meters and in some cases, collected directly over the previously surveyed 2017 lines for data quality checks. The subbottom's detailed survey data revealed the site A and B midden extents, paleo-environments, and geological makeup including a gyttja layers (Figure 33, 34, and 35). In addition, reconnaissance subbottom lines identified numerous paleo-landforms throughout Horsens Fjord. Similar to the 2017 field season, the sidescan data yielded little clues as to the location of the shell middens or paleoenvironments.

Figure 34: Aerial imagery and sidescan mosaic at site B from the 2018 data collection, depicting interpreted and digitized shell midden features, as identified in the subbottom profiler.

Throughout the entirety of the subbottom data, seafloor features were digitized and illustrated in various colors representing strong reflectors or varying geological material. This process assisted in the identification of the shell midden at sites A and B. The subbottom profiles (Figures 35) depict several distinguishable geological features ranging from gyttja, shells, clays and coarse sands. This data was ground truthed with the use of an auger core and excavated at 1 m squares. The cores were then plotted with the subbottom data to assist digitize the features, depicted in light blue, representing the subsurface shell midden (Figure 34). An auger core, XCS-1, taken at the base of the excavated trench at site A, was cross referenced with the subbottom data to further truth the data interpretations. Auger core XCS-1 depicts sandy clays with some shell to 20 cm subsurface, transitioning in to soft clays down to 36 cm subsurface, followed by silty clays to 53 cm subsurface and thick clays down to 69 cm subsurface (Figure 35).

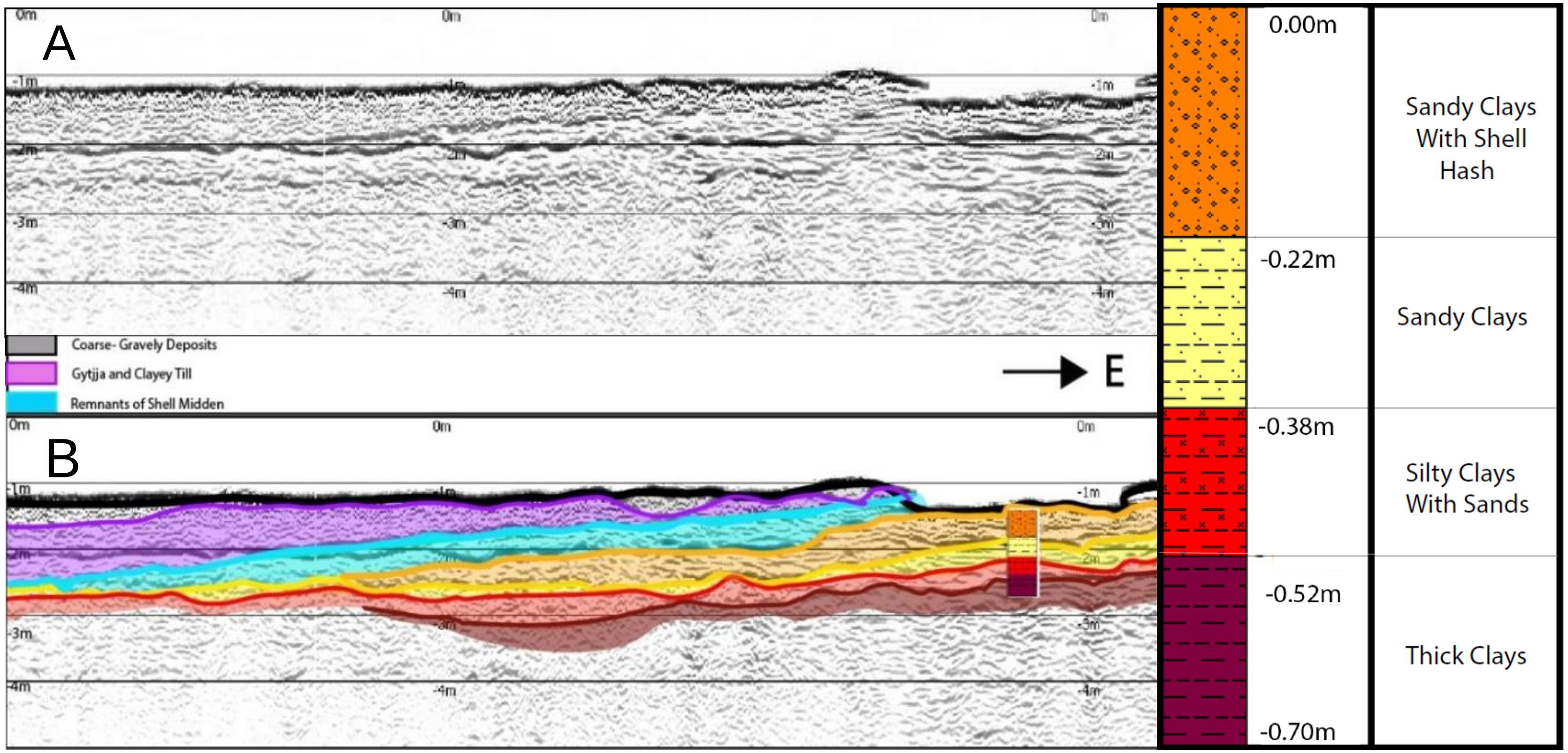


Figure 35: Parametric seismic profile with RAW (A) and digitized (B) stratigraphic layers at site A's excavation trench depicting the extent of the midden.

Much of the seafloor is covered with a thin layer of coarse-gravelly sands. Below these modern strata are clayey till and gyttja, as observed in the excavated trench. Just below the gyttja lays a shell layer, indicative of the midden. The shell layer was identified in the auger cores and within the excavation trench. The clayey till, below and surrounding the shell midden, is an indication of a residual floor from past exposed environments (Figure 35). Strata conformity is also observed in the subbottom profile transitions from shell midden to laminated sediments. Due to the shallow water depths, a multiple of the surface is identified roughly at 2 m below the sea surface. There is also a slight angular conformity, at a miniscule slope just below the interpreted midden. This is represented in the core sample taken at the base of the excavation trench as sandy clays with some shell hash, silty clays and thick clays.

Numerous paleochannels (or relic inlets) were identified and correlated to known archaeological sites and artifacts identified in the vicinity of Horsens Fjord (Figure 36). The overall widths of one paleochannels varied throughout the fjord. Located at the western end of Hjarnø, among the detailed survey sites of A and B, was a 78 m wide paleochannel. Another paleochannel was located directly north and measured to a much smaller size. The seismic image of the southern relic inlet depicts an unconformity intersecting laminated stratigraphic layers and a strong reflector on the upper portion of the laminated layers. More surveys are needed to potentially correlate the relic inlets to one another.

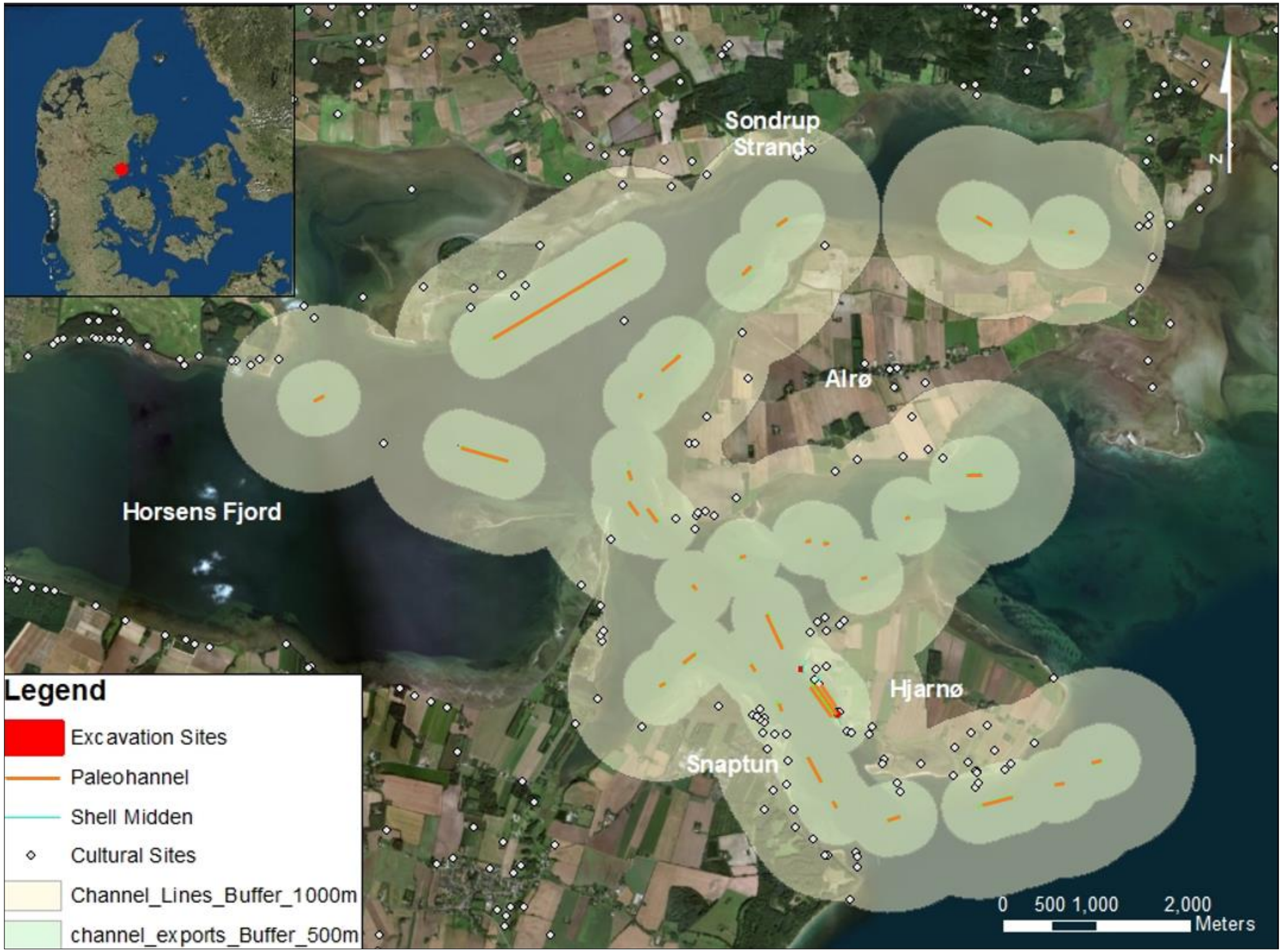


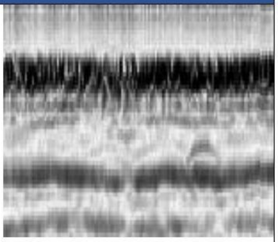
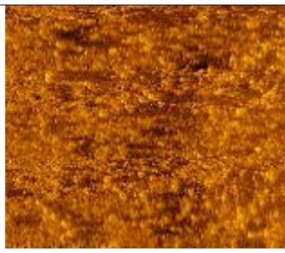
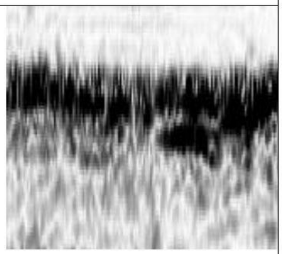
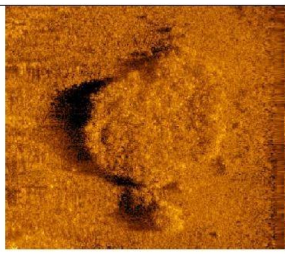
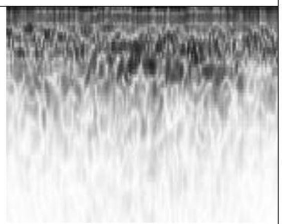
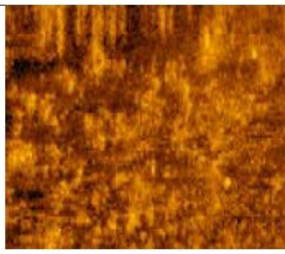
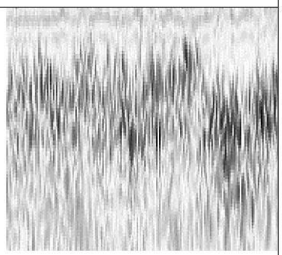
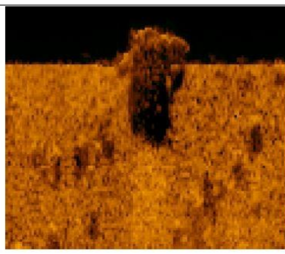
Figure 36: Digitized Paleochannels in 500 and 1,000 m buffers emphasizing nearest archaeological artefacts.

Once digitized in the subbottom processing software, paleochannels were then buffered at 500 and 1000 m increments. Artifacts identified in and around Horsens Fjord were input in a GIS database with the newly created buffers. Numerous prehistoric artifacts were highlighted within 500 m of the paleochannel. A total of 176 artifacts and settlements were identified within 1 km of detailed and reconnaissance geophysical surveys on the eastern portion of Horsens Fjord. Of these, 30% of the previously documented cultural resources indicated prehistoric artifacts and settlements within 500 m of a paleochannel. Although the paleochannels and recorded artifacts were correlated to one another, no specific pattern was observed when comparing the surrounding artifact quantities identified about the fjord to the paleoenvironments. Further statistical analysis is needed to observe any potential patterns among paleochannels.

4.3 Combined 2017 and 2018 Field Season Results

The 2017 and 2018 field seasons identified prehistoric resources and paleo environments. The sidescan sonar yielded little to no information in support of shell middens. The sidescan data did identify environmental features indicating current site status and changes among the two field seasons. Subbottom data proved useful in identifying Ertebølle culture resources and paleolandscapes. In addition, benthic features, as identified in the sidescan, were also observed in the subbottom (Table 5).

Table 5 Environmental characteristics of Horsens Fjord as seen by photo imagery, sidescan sonar.

Submerged Environment	Photo Imagery	Sidescan Imagery	Subbottom Grayscale Imagery
Sand			
Cobble Stones and Shell			
Eel Grass			
Algae (Brown, Red and Green)			
Boulder			

Seafloor features, such as aquatic vegetation were primarily identified with the use of the sidescan sonar. Once plotted in ESRI GIS and measured with the analysis tools, it was estimated that 20% of the seabed in the study area was covered by aquatic vegetation. Though primarily determined using sidescan sonar, the subbottom profiler confirmed vegetation coverage and the transitions from vegetation to sediment. Figure 37 depicts the aquatic vegetation coverage as it was during the field seasons. Backscatter return signals from the sidescan sonar varied considerably from hard substrate to aquatic vegetation due to seafloor irregularities and reflective surfaces. At the time of the survey, eelgrass (*Zostera marina*) was identified as the dominant vegetation type. Typically, macro algae were observed on hard substrate and eelgrass was observed in areas of soft substrate, allowing for the root structures to hold fast (Ærtebjerg et al. 2003). The highest concentrations of aquatic vegetation occurred in the southern and northern portion of the study area. Differentiating among vegetation types (eelgrass and macroalgae) is difficult within the sidescan sonar imagery. Small randomized regions, such as erratic boulders which acted as a foundation for the opportunistic macroalgae, were not included in the vegetation coverage map due to their minuscule size.

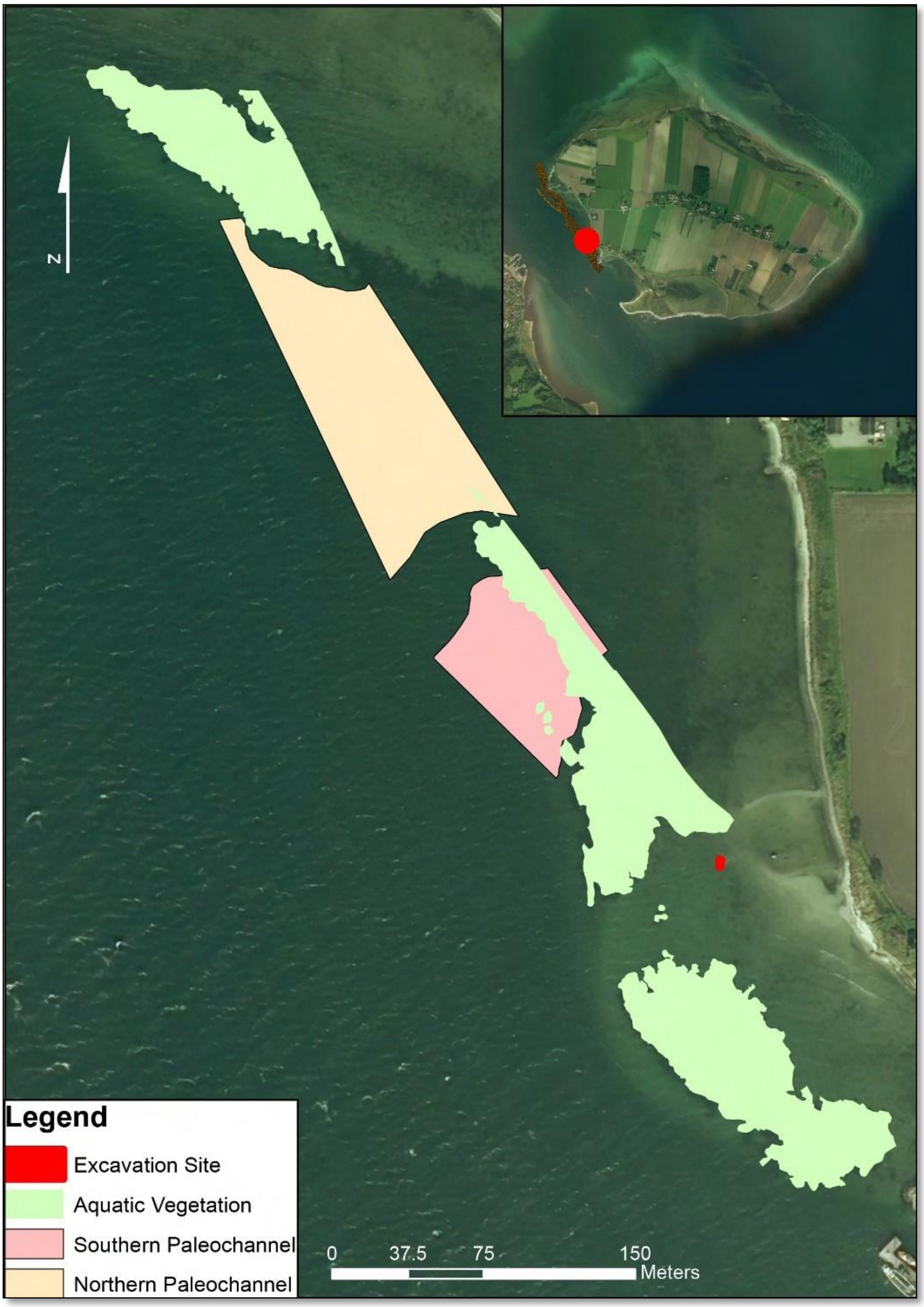


Figure 37: Aerial imagery of digitized aquatic vegetation and paleochannels using the sidescan sonar and subbottom profiler. The representations depict the extents of the sonar data.

Areas of high aquatic vegetation, were geophysical data were collected, diminished the signal returns back to the receivers, attenuating the overall signal strength in the geophysical data. In sidescan data, aquatic vegetation are depicted as a darker, irregular surfaces when compared to the sand flats (Figure 38).

The attenuated returned signal in the subbottom profiler data masked any recognizable stratigraphic layers which might otherwise be used for subsurface geological interpretations. In addition, gas pockets were easily recognized in the subbottom data, diluting any recognizable stratigraphic layers within the data.

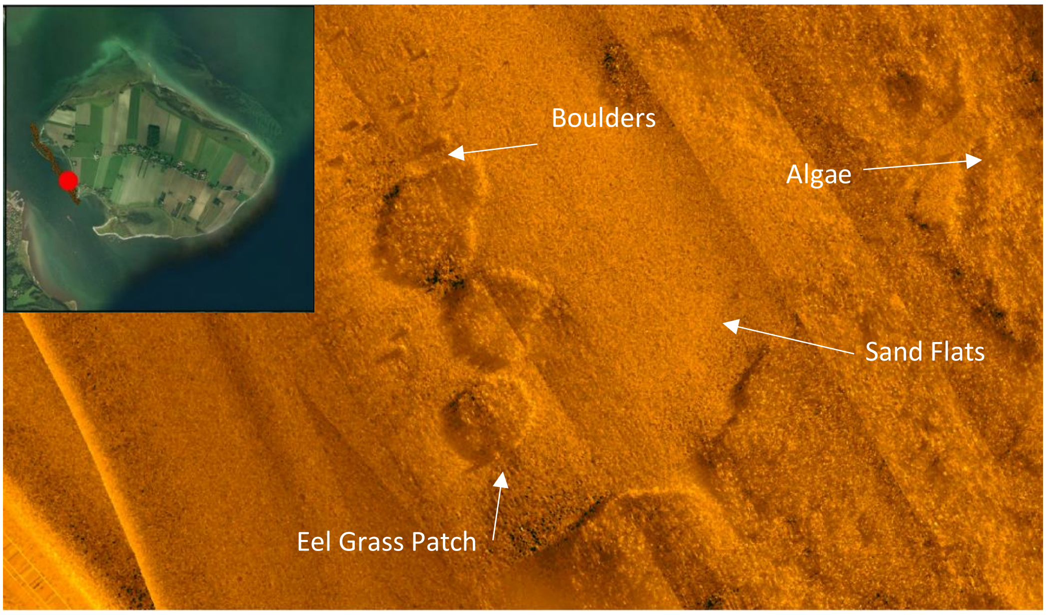


Figure 38: Sidescan Imagery depicting benthic features of Horsens Fjord.

Despite the return attenuated signals from areas with aquatic vegetation, stratigraphic layers of the geological profiles were observed throughout the majority of the subbottom strata for geological interpretation. In the shallow water regions of the research sites and between, exposed and eroded surfaces of the fjord's bottom are visible. The aquatic macroalgae and eelgrass meadows are visible in large patches of the sea bottom, however, they appear to diminish with deeper waters. The seafloor depicts a flat surface, transitioning to a gentle slope of 0–2 m. The slope steepens the closer to the center of Hjarnø Sund. With such shallow depths in Horsens Fjord, the eastern portion of the shell midden site leading to the landward end, could not be recorded by the sidescan.

Numerous tracklines and tie-lines were surveyed along the western portion of Hjarnø Island (Figure 39). Each line was collected at a 5 m line spacing running shore parallel, with intersecting perpendicular tie-lines. At site A, one seismic line was collected directly over the excavated trench in

2017 and again in 2018. One pass was attempted over each proposed excavation trench, either during or prior to any excavation. Other potential transect lines over the excavated sites were avoided due to submerged hazards or operating divers. Seismic lines within the vicinity of site A and B indicate the limits of the shell midden observed subsurface, within the excavated site and leading away from the site.

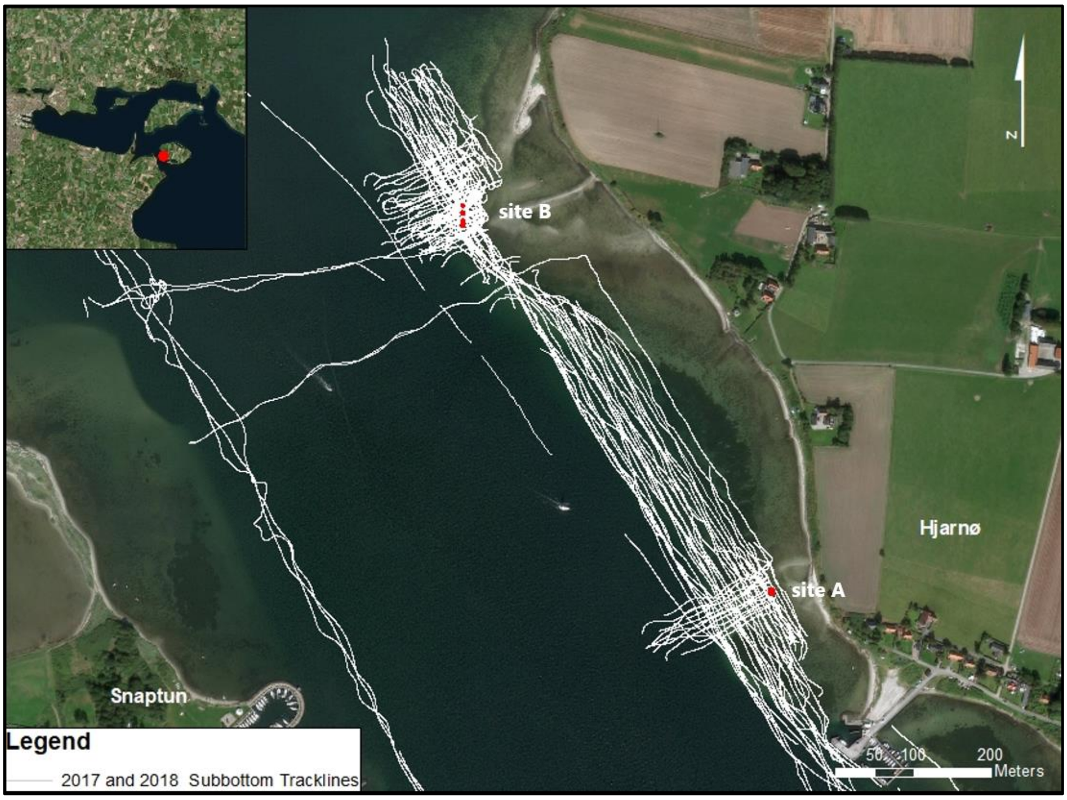


Figure 39: Aerial image of Horsens Fjord, Denmark with sites A and B, with overlain subbottom tracklines.

Analyses of the subbottom data via Sonarwiz and ISE2 rendered pros and cons on both ends. In terms of resolution, the overall data quality of the Innomar subbottom was inferior to the data processed in Innomar's ISE processing software. The ISE2 data quality appears to surpass the data quality of Sonarwiz. This was evident in the reconnaissance lines around Hjarnø Island and to the north of Alrø Island (Figure 40). Paleochannels would need to be properly identified according to interpretations, which required the high quality data displays; however, Sonarwiz portrayed the data in 3D model to a much higher extent then ISE2. Both software were used to complement each other's strengths throughout the entirety of the project.

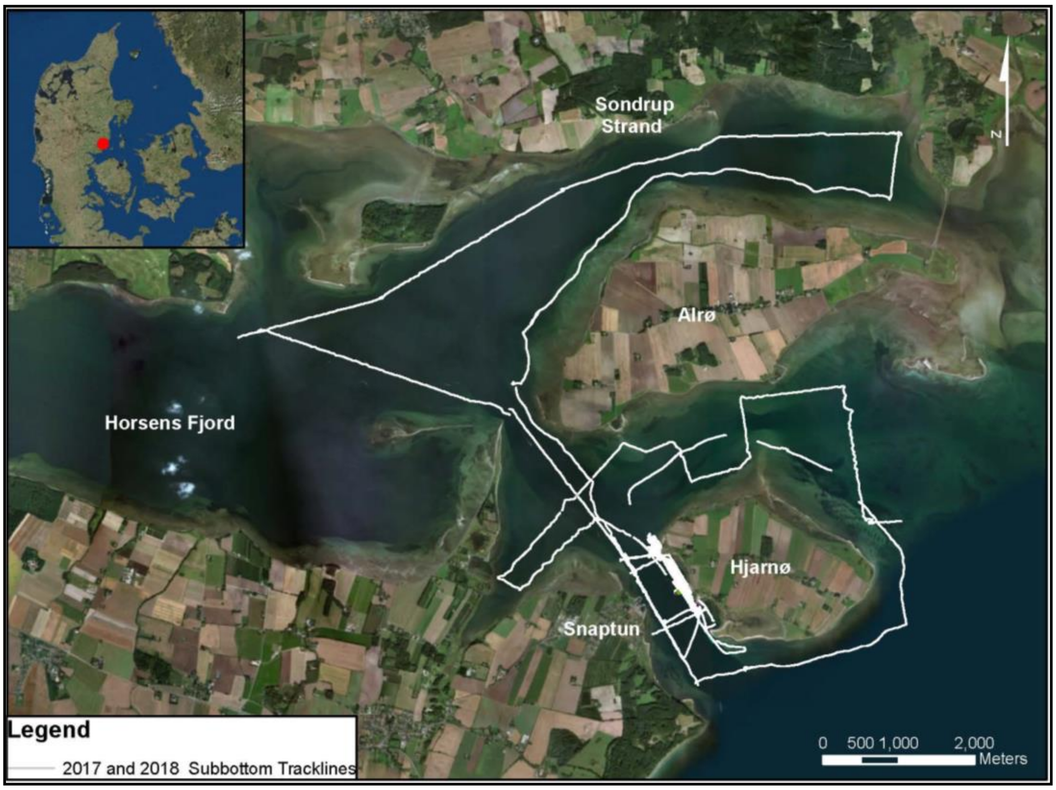


Figure 40: Reconnaissance and densely spaced subbottom tracklines from the 2018 field season.

4.4 Geotechnical Results

Geotechnical data were acquired and used throughout the entirety of the field research operations. Historical geotechnical survey data were acquired from the MOMU datasets from 2013−2015. Geotechnical samples were also collected in 2017−2018. The geotechnical datasets, auger cores and diver grab samples, revealed a variety of stratigraphic layer throughout sites A and B. Distinguishable features from the auger cores included shell, gyttja, stiff clays and sandy features.

In addition to the detailed core plots, cores were entered in a processing software for further analysis and added assistance to the subbottom data. The plotted cores allowed for the interpretation and revelation of different stratigraphic layers below the seafloor surface layers. Although the cores did not follow the subsurface features to their entirety, the cores allowed for the geophysical subbottom data to be truthed, enhancing the understanding of environmental features as they lay in the Mesolithic period. The cores assisted in the identification of geologic soils, preferable for artifact preservation, and prehistoric settlements, such as shell middens.

4.5 Volume Estimates and 3D Modeling

Data interpretations through Innomar's and Chesapeake's processing software allowed for the revelation of numerous stratigraphic features, paleochannels and anthropogenic features such as the shell midden at sites A and B. These features were exported from the processing software's reflector manager and further analyzed in *Golden Software, Inc Surfer (V13)* volume analysis tool. Isopach maps (Figure 41) were created depicting average thickness from the individual digitized seismic profiles. The image in Figure 41 is a color coded to illustrate region of the highest volume and thickness of shells within the midden, red depicting the least amount of shells and blue depicting the largest thicknesses.

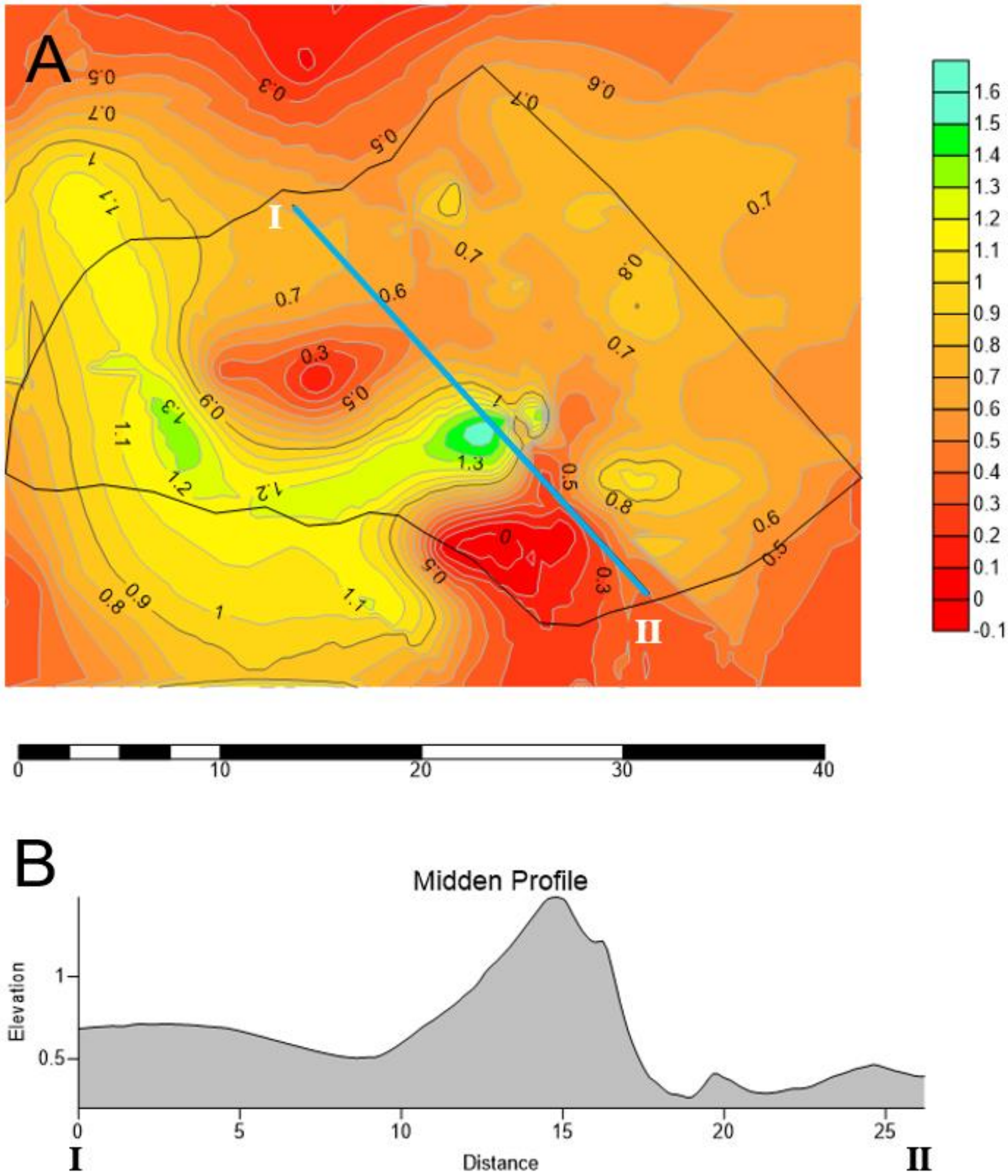


Figure 41: Isopach map in meters (thickness map) (A) of the observed subsurface shell midden as interpreted within the subbottom sonar and a profile view (B) of the midden thickness. (Vertically exaggerated).

Volume estimates for the midden at site A averaged 572.2 M^3 (Table 6) and encompassed a total positive area of 817.2 square meters (m^2), representing the areas with a positive thickness value and omitting any area with zero thickness value. The total area of the midden was 1443 m^2. The grid files created in *Golden Software, Inc Surfer (V13)* were then imported back into Sonarwiz's processing software for further analysis and viewing, revealing another look into the midden composition. The digitized thickness values gave volume estimates throughout the approximate region of the survey and were portrayed on the subbottom profiles. To further delineate and detail the survey region, a polygonal 3D surface was built with exported subbottom profiles and digitized reflector thicknesses created from the isopach map 3D viewer (Figure 42). The 3D viewer gave a better understanding to the size of the midden.

Table 6: Volume estimates based on interpreted midden thickness and form.

Total Volume By:	Volume Measurement
Trapezoidal Rule:	572.2 m^3
Simpson's Rule:	571.9 m^3
Simpson's 3/8 Rule:	572.1 m^3
Surface Area:	817.2 m^2
Total Planar Area:	1443.0 m^2

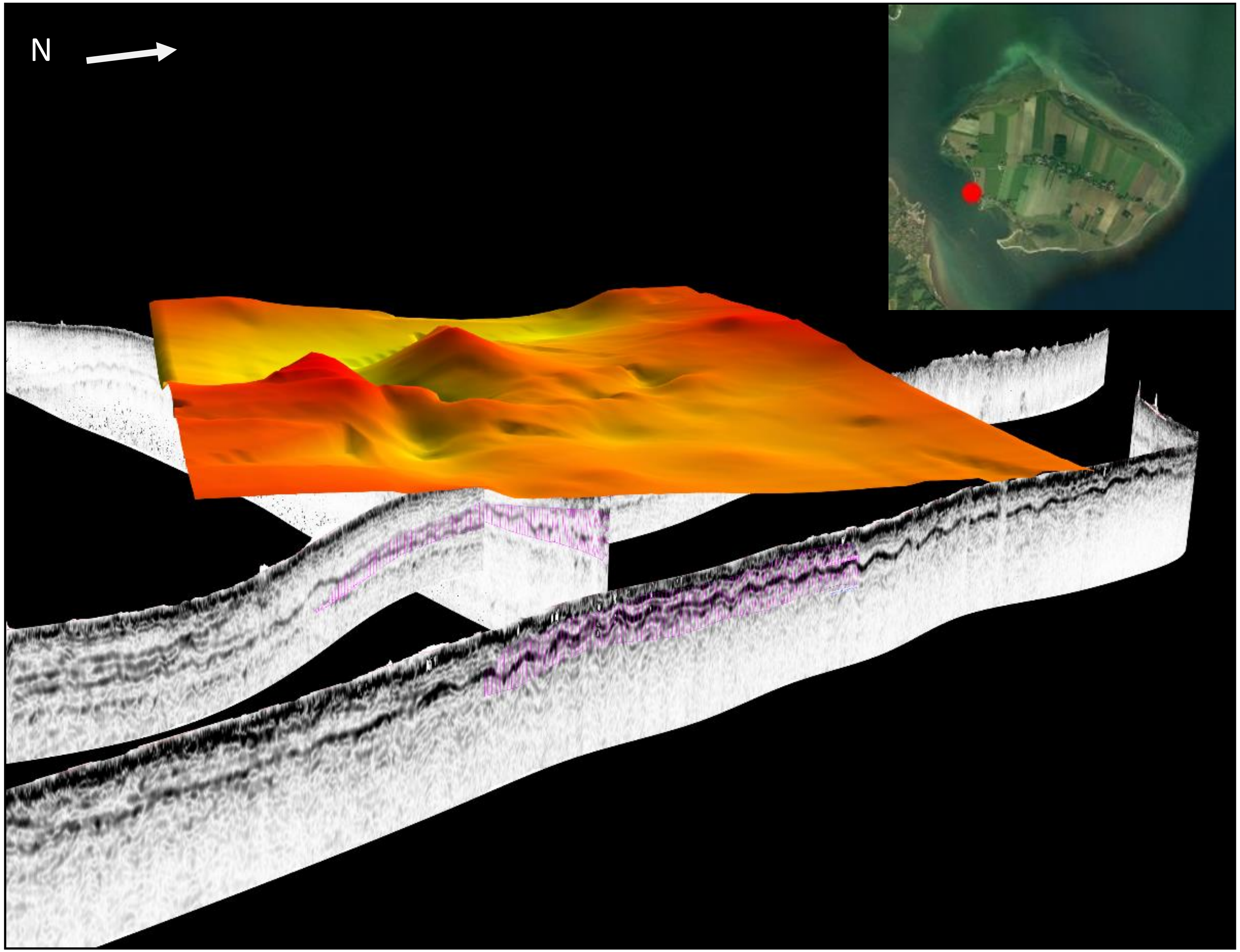


Figure 42: 3D representation of subbottom tracklines at site A, the southernmost submerged subsurface midden with an overlain thickness isopach.

5.0 Discussion

The results from the marine geophysical and remote sensing operations were successful in the identification of Mesolithic shell midden remains and submerged paleoenvironments at Hjarnø Island and its surrounding waters. The majority of the research field operations were conducted on the eastern portion of Horsens Fjord, from Hjarnø Sund to the northern waterways of Alrø Island. The overall intention of this thesis was to utilize and further develop a systematic exploration strategy to investigate submerged prehistoric landscapes that are in need of more attention. This was accomplished through a multidisciplinary approach using a suite of methodological applications which focus on marine geophysical and geotechnical techniques. In doing so, the research focused on three primary aims 1) to delineate and map the extents of submerged settlements, such as shell middens, 2) to correlate findings into a methodical system to create volume estimates and 3D models, and 3) to identify potential correlations among paleolandscapes and prehistoric sites.

To fulfill this research project, numerous tasks were completed to support the delineation and mapping of submerged settlements. These tasks included the 1) review of historical and archival studies, both archaeological and geological, 2) the collection of historical geophysical data by GEUS for the planning stages of the survey; 3) incorporation of historical geotechnical data logs from Moesgaard Museum to assist with the interpretation of the 2017 and 2018 geophysical data; 4) collection of Innomar subbottom and Edgetech sidescan sonar data in the 2017 and 2018 field season throughout the eastern regions of Horsens Fjord, with the primary focus on the western end of Hjarnø Island; and 5) processing all geophysical datasets.

Danish archaeologists have studied prehistoric archaeological sites since the 1800s. The primary support for archaeology throughout the country is through the museums, with each museum focusing on a specified region of Denmark. The research conducted at the site near Hjarnø Island was in coordination with the MOMU. The knowledge and resources provided by MOMU were invaluable. Numerous aerial, geotechnical, and historical datasets, were provided by MOMU. These datasets not only assisted with the background information pertaining to Horsens Fjord and its past, but also the 2017 and 2018 geophysical data interpretations. The obtained historical MOMU cores (Figure 43) revealed numerous geological layers, such as an anoxic gyttja layer. The extents of geological layers, such as gyttja layers, were identified and truthed in the subbottom profile data via the MOMU cores. The indication of gyttja illustrates a high potential for site and artefact preservation since the soils are anoxic (Andersen, 2013; Astrup, 2018; Skriver, 2017). To further support the interpretation of site A's and B's subsurface environments and potential anthropogenic items, additional auger cores were collected in 2017−2018.

Image removed due to copyright restriction.

Figure 43: Auger cores collected by Moesgaard Museum in 2013, 2014 and 2015 within vicinity of site A excavation trench which highlight the extents of the gyttja layer (Astrup, 2017).

In addition to the cores, underwater excavations were carried out in the 2017−2018 field seasons which revealed a plethora of information on the Ertebølle culture at the time of site burial and subsequent environmental processes. Once each excavation trench was completed, the side profiles were cleaned and photographed, revealing real-time views of the subsurface environment. The trench profiles were interpreted and projected in the geophysical data, in coordination with the geotechnical core data. The interpretation and analysis of the subsurface environments assisted with the geophysical interpretations to determine the extent of the human-impacted areas that remained hidden. The correlation of subsurface environmental data to settlement sites may be used to further identify prehistoric sites which were previously unknown.

Since both sites A and B were located in water depths of 2 m or less throughout the duration of the geophysical surveys, numerous issues arose with the geophysical methods in the shallow conditions. Both sidescan and subbottom data returns were limited by beam pattern, distortion, and multiples. In addition, submerged hazards including erratic boulders, wooden stakes, ferry terminals and shallow water depths were avoided for safety purposes. To compensate for any disproportional data, aerial imagery, underwater photo imagery and ground truthed geotechnical and excavation data were used as a reference and guide for further interpretation of the study sites. Through these research efforts, the shell middens in the subsurface environments around Hjarnø Island were identified using geophysical techniques.

Since the settlements were identified, further data analyses were concentrated to estimate the total midden areas and volumes. Volume estimates are used to represent anything from river basins to population density (Longley, et al., 2005). Volume estimates and the total area of the sites were completed through three techniques, 1) anthropogenic and natural reflectors within the geophysical datasets sites were digitized both at the surface and subsurface, 2) an isopach map was created of the subsurface shell middens and 3) the digitized site was then calculated to illustrate the total area and volume of the shell midden regions.

The sidescan and subbottom data were processed and analyzed to calculate the volume estimates of the submerged landscapes. However, the sidescan sonar did not reveal any anthropogenic sites that represented the Mesolithic period, such as a shell midden. The sidescan sonar, such as the Edgetech 4125, has the capability to locate and map surface expressions of a shell midden due to its hard-reflective surface, height above the sea surface and area covered. Since a large portion of the site consisted of depths of 1 m and less, it was difficult to discern certain shallow-water features due to signal reverberations and beam patterns. This led to a large amount of distortion occurring on the outer ranges of the sidescan. The distortion and over amplification of shallow water features shadowed any items that lay directly behind, omitting any valuable data. Additionally, the midden site was not observed distended above the sea surface, it was observed relatively flush with the seafloor surface. The major geologic material observed at site A included sands, clays and glacial till. Return sound signals to the sidescan depicted low values, with some high values. This indicates a high concentration of semisoft, non-reflective sediments encompassing a large portion of the seafloor around the midden site. The lack of high return data and increased distortion in the shallow sites omitted the use of the sidescan to identify the any shell middens.

If a shell midden had been further exposed and to some extents, protruding from a seafloor surface, with clustered shells, it would likely be identified with high confidence in the sidescan data. The sidescan data collected the Coastal Protection and Restoration Authority (CPRA) in Louisiana, USA, represents a good example of a high returned signal shell material of a "potential oyster reef" with a similar makeup to shell middens. The image of the "potential oyster reef" is observed to protrude from the seafloor surface and contains, what is hypothesized to be clusters of shell representing an oyster reef (Figure 44). A few key elements were observed when comparing the "potential oyster reef" to the Hjarnø shell midden sites: 1) the sidescan data in Louisiana was collected in deeper water depths of 1 m or more, this appears to prevent data distortion, 2) the "potential oyster reef" image depicts a high signal return of tightly clustered objects, not observed in the Hjarnø data, 3) the data collected for CPRA was collected with a lower resolution sidescan sonar, and 4) the overall area of the anomaly is visible from the returned signal, indicating that the "potential oyster reef" is protruding from the seafloor enough to cast a pronounced and definite shadows. If the Hjarnø data had a similar structural makeup, raised surface and collected in deeper water, the shell midden would have been easier to identify with the use of the high frequency sidescan in Denmark.

Image removed due to copyright restriction.

Figure 44: Imagery of a potential oyster reef with the use of an Edgetech 4125 sidescan sonar (References: CB&I 2015).

Although it is sometimes difficult to identify aquatic features in shallow depths in the geophysical data sets, aquatic vegetation was successfully identified in the sidescan sonar. In portions of Hjarnø's waters, where water depths exceeded 1 m, the submerged features, such as aquatic vegetation was more easily identified and digitized with Sonarwiz's processing software. The amount of vegetation observed about the affects the data quality that is collected by the subbottom profiler. Although the amount of aquatic vegetation detected is a positive sign of environmental stability, it negatively impacts the subsurface data returns for interpretations, particularly within the subbottom.

Dense clusters of aquatic vegetation resulted in diminished seismic signals in the data or attenuated signal strength. The attenuated returned signal omitted any recognizable stratigraphic layers which might otherwise be used in the interpretation phase of the operations. In future surveys it will be beneficial to take more core samples along these regions of high vegetation to further interpret subsurface stratigraphic layers that are otherwise unrecognizable, while leaving the vegetation undisturbed.

In addition to the vegetation, there were numerous noise sources that were encountered throughout seismic data collection. The noise was negated to the best of the team's ability; however the shallow water depths proved troublesome. Some of the signal to noise attributes that were negated to the best of the team's ability included electrical inputs, thermoclines, gas and shallow depths. In deep and shallow waters, common sources of noise originate from the sea surface and the reflecting interface (Lowrie, 2007). These noise sources or multiples, are generally located in the seismic profile at twice the water depth and are more problematic in shallow waters. In addition, gas is observed as a noise source in the subbottom data, which is typically found in regions of high organic matter with bacterial decomposition, such as peat or gyttja (Tegowski, et al., 2002). Where organic matter is located in subsurface, gas bubbles are generally formed and trapped in the upper subsurface layer, blocking any acoustic signal from penetrating deeper layers, which is reflected as an echo layer (Tegowski, et al., 2002). Gas is typically observed to dilute and omit the stratigraphic layers, hindering data that may identify thesis supportive paleochannels. Despite three large dissuading factors (i.e. aquatic vegetation, gas, and shallow waters), the subbottom data, were successful in supporting the main hypotheses of this research thesis. In many cases throughout the subbottom data processing data multiples were observed; however, the stratigraphic layers were mapped past the multiple to a depth that met the reaches of the specifications. This allowed for paleolandscapes and shell middens to be identified and mapped throughout the sites A, B and the reconnaissance areas.

In the marine geophysical field, there are a number of subbottom systems, including chirps, boomers, etc., which collect high resolution data. However, once these systems approach shallow waters, their data resolutions diminish for a variety of reasons, including signal reverberations and beam patterns. An example of this is found in Figure 45, with the use of an Edgetech 216. Edgetech's 216 chirp subbottom has a data resolution of 6-10 cm in their ideal operating depths, anything shallower and the data signal becomes degenerated (Table 8). The data displayed in Figure 44 and 45 was collected in support of the Coastal Protection and Restoration Authority (CPRA) of Louisiana, at waters depths of 1.5 m. Although an interpreted hard bottom/potential oyster layer is digitized in the chirp data, shallow stratigraphic layers appear indistinct and lacking definition. The parametric subbottom that was used to identify the Ertebølle shell midden sites allowed for high resolution subbottom data collection in both deep and shallow waters to 0.5 m (Table 7). With this type of depth, it was important to correlate all parametric subbottom in the Horsens Fjord survey to ground truthed samples. This allowed for the sediment layer recognition down to 2.2 cm, as observed in comparisons among auger cores and the parametric subbottom in the ISE2 processing software.

Image removed due to copyright restriction.

Figure 45: Data example of a shallow water potential oyster bed (green) via an Edgetech 216 subbottom in Louisiana, USA (References: CB&I 2015).

Table 7: Innomar SES-2000 Specifications

Innomar 2000 Subbottom	Specifications
Frequency Range	10 and 100 kHz
Vertical Resolution	1-7.5 cm
Sediment Penetration	20 m
Penetration in Hard Sands	Poor

Table 8: Edgetech 216 Chirp Subbottom Specifications.

Edgetech 216 Subbottom	Specifications
Frequency Range	2-16 kHz
Vertical Resolution	6-10 cm
Penetration in Coarse Calcareous Sands	6 m
Penetration in Clays	80 m

Data exports were typically displayed in 2D representations; however, within software systems such as *Golden Software, Inc. Surfer (V13)*, ESRI

GIS, and Sonarwiz, a 3D representation of the data can be created. 3D datasets were integrated in ways to benefit research scientist, their peers, stakeholders and the public that may be interested in the archaeological research. The 3D representations can be set to portray the multidisciplinary approaches to studying the site including subbottom, sidescan, cores, isopach maps, bathymetric data, draped imagery from drones and more. The approach used in this research displayed data in subbottom profile view, isopach and sidescan profile views. The datasets, when in a digital format, allow for fly thrus and video exports. This is additionally beneficial to a community and researchers for visualizations purposes to identify a relation among cultures and surrounding prehistoric lands.

The local geomorphology must be modeled to locate and identify areas of high potential for the identification of prehistoric archaeological settlements both on the seafloor and in the subsurface (Masters and Flemming, 1983). Some of the recognizable prehistoric anthropogenic features, such as a shell midden, previously existed with basic environmental connections such as access to fresh water, food sources, and protection from environmental exposure (Masters and Flemming, 1983). This thesis sought to identify a correlation among naturally formed paleolandscapes and prehistoric sites from the Ertebølle culture. Subsurface features were observed to potentially correlate to prehistoric sites. This goal was to identify and categorize any potential correlations between subsurface features by 1) the parametric subbottom data, 2) previously mapped prehistoric settlements provided by SPLASHCOS and the Danish Ministry of Culture; and 3) importing all digitized features into ESRI GIS for geospatial analysis to identify any correlations among submerged archaeological sites and subsurface paleoenvironments. Unfortunately, no specific pattern was observed when comparing the surrounding artifact quantities identified in the fjord, via SPLASHCOS' and the Danish Ministry of Culture's database to the paleoenvironments. Further statistical analysis is needed to observe any potential patterns between paleochannels. The analysis of these processes may potentially benefit research in the Mesolithic period in methods that are both productive and efficient by using data that is already collected.

In addition, Benjamin (2010) elaborates on the need for an extension of the “Danish Model” globally in a quick and predictive manner to better future research operations. Similar to Muckelroy’s (1978) underwater archelogy, not including nautical nor maritime, prehistoric underwater archaeology is an outlier from all other archaeological fields. Extensive knowledge of prehistoric environments is needed to obtain an understanding of prehistoric settlement patterns and processes. The research and mapping of these subsurface environments, including paleochannels identified through the use of a subbottom profiler, alludes to past prehistoric land arrangements. These research strategies, closely correlated to the “Danish Model” (Fischer, 1993) can be applied to other coastal sites throughout the globe, with some modifications depending on environmental conditions.

6.0 Limitations and Recommendations

6.1.1 Limitations

Site preservation is never guaranteed in the marine environment. As such, numerous variables including natural and anthropogenic processes affect the stability of an archaeological site. Both of these variable are known to have impacts on Horsens Fjord’s submerged environments and sites, both in the nearshore environments and in the deeper waters. The erosional surfaces may expose archaeological artifacts, such as those at Hjarnø Island (Andersen, 2013), which is evident from the findings by Astrup (2019) and Skriver (2017). Thus, it is important to map submerged environments in their current state and at a later time, to monitor the sites stability.

The use of geophysical techniques to map regions around Horsens Fjord is useful to map an unknown site and to monitor a known site’s stability. However, due to the shallow survey depths of less than 1 m, geophysical operations were limited. Some sidescan acoustic-beam angles in shallow waters were distorted and exaggerated in shallow depths. As the sidescan passed raised targets, such as a boulder or debris in the shallow waters, the shadows created from this target blocked or diluted any signal directly behind the raised item. With such shallow depths in Horsens Fjord, the eastern portion of the shell midden site, leading to the landward end, could not be recorded by the sidescan.

In addition, the subbottom profiler had a number of limitations due to the survey water depths. Multiples were observed within the subbottom data at twice the depth of the seafloor. These multiples are noise that are too common within numerous subbottom sonars; however, it becomes troublesome in shallow water depths. At these shallow water depths, the multiples would overlap stratigraphic layers within the data string. This would make it difficult to follow important layers, such as shell or gyttja, in extremely shallow water depths.

6.1.2 Recommendations

This thesis research study, which contributed from and to the DHSC multidisciplinary project, further assisted in the identification of prehistoric sites through submerged subsurface investigations. However, several additional research interests arose, which should be pursued in further studies. Along with the subbottom and sidescan data sets, bathymetric data should be collected and processed allowing of the entire fjord for further research into surface (modern) and subsurface (prehistoric) interpretations. Erosional rates along the site and coastlines should not be ignored and be added as a benefit to the research operations. Based on the erosional rates, a site's stability, in the past, present and future, maybe predicted to further assist with a sites and artifacts protection. Additionally, further statistical analyses may be applied to identify prehistoric settlements through statistical analysis of geophysical and geotechnical like characteristics in the area. These potentially future studies would benefit the understanding of the site predictions, formations and preservation.

The supplementary bathymetric data may allow for the upper most

Holocene sedimentary layer to be removed, exposing Mesolithic period environmental processes. The bathymetric data may be applied with the use of a sonar mounted unit on an ocean going vessel and an aerial unit, mounted onto a plane or drone. These datasets would therefore allow for the theoretical modeling of the historical or subsurface bathymetric layers subbottom interpretation in comparison with modern day bathymetric layers. Currently, the only known LIDAR data available depicts terrestrial data, not the marine environment. Access to bathymetric LIDAR in Horsens Fjord may allow researchers to identify environmental features that are beneficial for prehistoric settlements identification in and around the sites not previously identified. In addition, volume estimates based on the subsurface anthropogenic and environmental features, may allow insight as per the size of the culture. The portrayal of the prehistoric culture's size, via volume calculations, may prove beneficial for researchers and the everyday overseer to visualize the lost culture in its original state.

Furthermore, geophysical and geotechnical data analysis with the addition of satellite or aerial data may be processed and interpreted to calculate shoreline changes along an archaeological site. The digital shoreline analysis system (DSAS), an ESRI GIS extension to calculate the shoreline rates of change, maybe applied to further assist archaeologists in determining the erosional rates at sites, creating a further understanding for the state of preservation or degradation for settlements.

7.0 Conclusion

In this project, the use of several geophysical and geotechnical techniques allowed for the anthropogenic-disturbed sedimentary layers to be delineated from the natural environment in an extreme shallow water setting (2 m-0.5 m). The combined 2017 and 2018 fieldwork proved advantageous for the marine geophysical portion of the study and equally for the DHSC research team in Hjarnø, Denmark. Upon completion of the field seasons, researchers were able to identify prehistoric submerged cultural resources, such as shell middens and paleo-environments, including paleochannels and gyttja layers. Area and volumes estimates identified via the geophysical survey revealed similar results to those obtained by Astrup et al. (2017) geotechnical data interpretation. Slight variations were observed among the two datasets volume estimates. This maybe a result of geophysical signal to noise resolutions and distortions due to shallow waters depths, interference from aquatic vegetation diminishing the returned signal, gas pockets within the subsurface layers and interpreted regions where geotechnical data lacked information. The detailed geophysical survey covered an area estimated at 69.1 km^2 on the western end of Hjarnø Island, encompassing two excavation and geotechnical archaeological sites.

The use of the high resolution geophysical equipment was advantageous to view the submerged environment at such a fine scale in the shallow environment. Within reasonable depths, environmental features were separated and categorized within the sidescan sonar to a centimeter resolution acrosstrack. Similarly, the stratigraphic layers, as observed in the subbottom, were mapped and tracked in depths as shallow as 0.5m with centimeter resolution.

Although advantageous due its fine detail and return signal, no prehistoric cultural resource features were observed within the sidescan sonar to indicate an overall size and shape of the submerged shell midden. Shallow water depths prevented high resolution and detailed data returns. At these shallow depths of 1 m or less, the sidescan sonar is susceptible to distortion, as well as artifact and multipath interference, making any target recognition and benthic classification difficult. Skewed high return reflectors and distorted shadows from the raised seafloor items give an anamorphic view of target heights and the region in which they encompassed. In addition, shadows from these distorted features, blocked any potentially useful data directly behind the features.

As a benefit, within waters deeper than 1 m, seafloor features were less skewed and more easily identified in the sidescan sonar. This gave a high resolution and detailed image of the seafloor. Although the sidescan differentiates between surface material such as hard substrate, aquatic vegetation, clays and sands; it is difficult to differentiate between individual shells and cobblestones or any similar features when mixed along the seabed. Due to these constraints in the sidescan sonar, the submerged midden site was primarily located with the parametric subbottom profiler and ground truthed methods.

As discussed both sites A and B are located in water depths of 2 m and less, diminishing to water depths of 1 m and less within the vicinity of the excavation trenches. Operating seismic equipment in shallow water depths, such as this, are known within the geophysical communities to cause what is called a “ghost reflector” or “multiples” (Reynolds, 1997 and Wunderlich, 2005). Due to the increase of ghost reflectors or multiples in the subbottom at the near subsurface, it was difficult to obtain the true depth of some geological and anthropogenic layers within the research sites. This led to partial subsurface reflector interpretations in some areas of the survey sites. However, a large portion of the survey areas allowed for data interpretations down to 5 m, the primary investigation depth subsurface. With the subbottom profiler, the primary research shell midden was located 50 m westward from Hjarnø Island shoreline at site A. Site B excavation trenches was located roughly 150 m westward of the Hjarnø shoreline and interpreted as a midden site through underwater excavation, geotechnical and geophysical surveys.

The use of these two geophysical techniques, sidescan and subbottom sonar, identified and confirmed varying seafloor and subsurface environmental and anthropogenic features that may have otherwise been unknown. This was accomplished in an efficient and cost effective manner in which a large area was researched in a short time. Knowledge of the surrounding environmental features at the sites, such as aquatic vegetation and paleolandscapes allows researchers view the past, present and future dexterity of the site. In addition, it may also allude to further needed research to identify regions of high interest, such as regions with meandering coastlines. This may allow regions to be highlighted according to a sites stability.

Factors affecting subsurface and surface environments with a majority of the geological and archaeological study sites located within the vicinity of coastal environments, such as Hjarnø, result from numerous environmental conditions such as high energy storm systems and erosional acts. Erosion and the removal of biological material by storm activity increases the likelihood of artifact exposure. More specifically to Horsens Fjord, gyttja deposits and archaeological resources are increasingly exposed due to erosional processes (Mentoni, 2012). These processes maybe directly or indirectly related to isostatic rebound, sea-level changes, storm surges, or the result of anthropogenic influences.

Despite storm activity and erosional acts on the site, the archaeological sites within Horsens Fjord represented a well-preserved and well-protected environment to study. This location, in addition to the other surrounding prehistoric sites located in Horsens Fjord, depict the resilience and durability of the Ertebølle culture resources and the well-preserved environment in which they lay subsurface. The techniques and data results from this research may allow archaeologists to make judgments concerning the preservation of prehistoric sites in somewhat similar conditions from other parts of the world (eg the Americas and Australia). In addition, these results may allow researchers to expand on techniques and archaeological practices to better research submerged landscapes for the benefit of global studies to identify sites more clearly.

The analyses among the 2017 and 2018 field seasons determined various pros and cons of the data planning, collection, and processing stages of this research. The key points and methodology highlighted in this thesis may benefit future investigations of prehistoric settlements globally. Although shallow-water geophysical surveys were not ideal, in terms of data resolution and quality, the multidisciplinary approach encompassing historical datasets, ground truthed datasets and high resolution geophysical data were successful in locating prehistoric settlements. In addition, the multidisciplinary approach identified and documented the once exposed and now subsurface environmental features as the Ertebølle culture lay.

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