

Article

A Submerged and Buried Mesolithic Site off Svanemøllen Harbor, Copenhagen, Denmark: Acoustic Detection (Human-Altered Lithic Detection) and Verification by Means of Coring

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Abstract: Teledyne Chirp III high-resolution seismic data were acquired over a three-year period at a water depth of 6.0–9.0 m, with a clear concentration of acoustic “haystack” features, in the dredged Svanemøllen Harbor, Copenhagen. The recordings show haystacks related to preserved shallow basins and rivers in the paleo-coastal setting. Eleven short vibrocores were retrieved below these pronounced haystacks and a sandy interval, underlain by clayey till and overlain by harbor mud, which represent the basin configuration. Two cores contained four pieces of knapped flint in the sandy interval (statistical density of around 230 pieces per square meter), while the remaining cores did not reach the desired depth. Finite Element (FE) modeling revealed that the small pieces of knapped flint were resonant and that the acoustic impedance of the flint was high. The Svanemøllen Harbor site is a hitherto unknown buried Stone Age site, and this is the first time ever that an unknown submerged, buried Stone Age site has been acoustically detected (using Teledyne Chirp III), verified by means of coring and modeled using FE modeling. The Innomar and Geopulse data acquired at the site did not register any haystacks. Due to the global sea level rise after the Last Glacial Maximum, a significant part of the world’s submerged Stone Age sites must be expected to be buried in seafloor sediments.

Keywords: submerged stone age site; knapped flint; high-resolution seismic; vibrocore; FE modeling



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1. Introduction

In 2015, high-resolution Teledyne Chirp III seismic data were acquired off the coast of Israel in the Atlit Yam area in order to test whether this type of high-resolution seismic data could be useful in investigations of submerged Stone Age settlements [1–3]. Several years of investigation of the site by archeological divers had provided fairly detailed knowledge of the site and confirmed that knapped lithics were present, along with the remains of buildings, graves, wells and workshops, etc. The investigation by divers was only possible because of the re-deposition of the up to 2 m of sand cover by the

dynamic marine environment, which, over the years, exposed different parts of the cultural horizon [4] before sand was deposited again.

In the Chirp III recordings from this site, for the first time, haystack-shaped noise phenomena were observed in the water phase, as was a correlation between the haystack-shaped noise phenomena in the water phase and the registered settlement area. This could not be related to the appearance in the water phase of fish, gas, crooked lines, noise from the boat and engine or other known disturbances but appeared to be directly related to the site's well-documented buried human-knapped lithics in the workshop area [1,2]. The hypothesis of a relationship between the knapped lithics and recordings from the Teledyne Chirp III instrument was tested during controlled experiments in Denmark, where a comparison of the acoustic responses from natural cracked flint and human-knapped flint was carried out using the same instrument and instrumental settings as those used in Israel [2,5]. In addition, FE (Finite Element) modeling was carried out with 3D scans of human-knapped lithic pieces that were embedded in a submerged sediment environment to model their responses to different acoustic signals [6]. On this basis, it was concluded that concentrations of human-knapped flint, when excited by the right frequencies (including the frequencies that are transmitted by the Chirp III), produced haystack features [1,2,6–9].

In 2021 [10], Faught and Smith reported that high-resolution seismics (EdgeTech 3100P) had successfully been used in Florida for systematic surveys of submerged sites with knapped lithics in the sea, as well as in inland rivers and lakes. In their recordings, haystacks were observed, and below these, lithic material had been found, as the lithic material was exposed on the sea-/lake-/river-floor; these sites have therefore allowed for a rather uncomplicated verification process with divers [2,10]. While revisiting older Teledyne Chirp data (recorded with a Datasonics Chirp II/CAP 6000, which is basically the same instrument as the Teledyne Chirp III) from the central parts of the submerged Møllegabet site, Denmark, two haystack features were observed in one of the recorded seismic profiles. Later in that fieldwork period, a Late Mesolithic shell midden that was crossed by the seismic profile was partly excavated. At the Møllegabet site, which is extremely rich in exposed and buried knapped lithics, a preserved dwelling pit with organic remains and a boat grave were also excavated. This provided another case of ground truthing, although not exclusively of buried lithics. In 2021, the term HALD (Human-Altered Lithic Detection) was suggested as the name for this method [2,11,12].

In 2018, while in transit with the instrument running, we acquired some Chirp III seismic profiles in Svanemøllen Harbor on our way to another test area. On one of these recordings, we discovered haystacks. In order to investigate the area where the haystacks were observed, we recorded high-resolution seismic profiles in the years of 2018–2020 during three campaigns in Svanemøllen Harbor, Denmark (Figures 1 and 2), with a Teledyne Chirp III (the same instrument that we used at Atlit Yam, Israel, and using the same settings). The profiles revealed a 200 m (NE-SW) × 300 m (NW-SE) large area with a water depth of 6.0–9.0 m, characterized by a high density of haystack features of various shapes and heights in the water column (examples of these haystacks are shown in Figure 3).

By studying the aerial and naval sea charts and the depth to the seafloor (based on seismic profiles), it is obvious that this part of Svanemøllen Harbor has been deepened by 2.0–2.2 m by means of dredging sometime after 1954, as can be seen on the aerial photos [13]. In order to test the potential for ground truthing of the knapped lithics features, a number of deeper technical cores were examined, and short vibrocores were available from the area in the summer of 2021. The fifteen technical cores were not placed at the locations where haystacks were observed and did not contain knapped flint. Eleven vibrocores, obtained using 2 m long and 2 mm thick plastic tubes with an inner diameter of 7.4 cm, were available from the assumed site area (Figures 1 and 2). The two most central ones (A

and B) were placed approximately 20 m from each other and each contained two pieces of knapped flint, which statistically indicated approximately 230 pieces pr. square m. In core A, with a length of 90 cm, the pieces of flint could be determined to originate from 80 to 90 cm below the dredged bottom of the harbor [3,14].

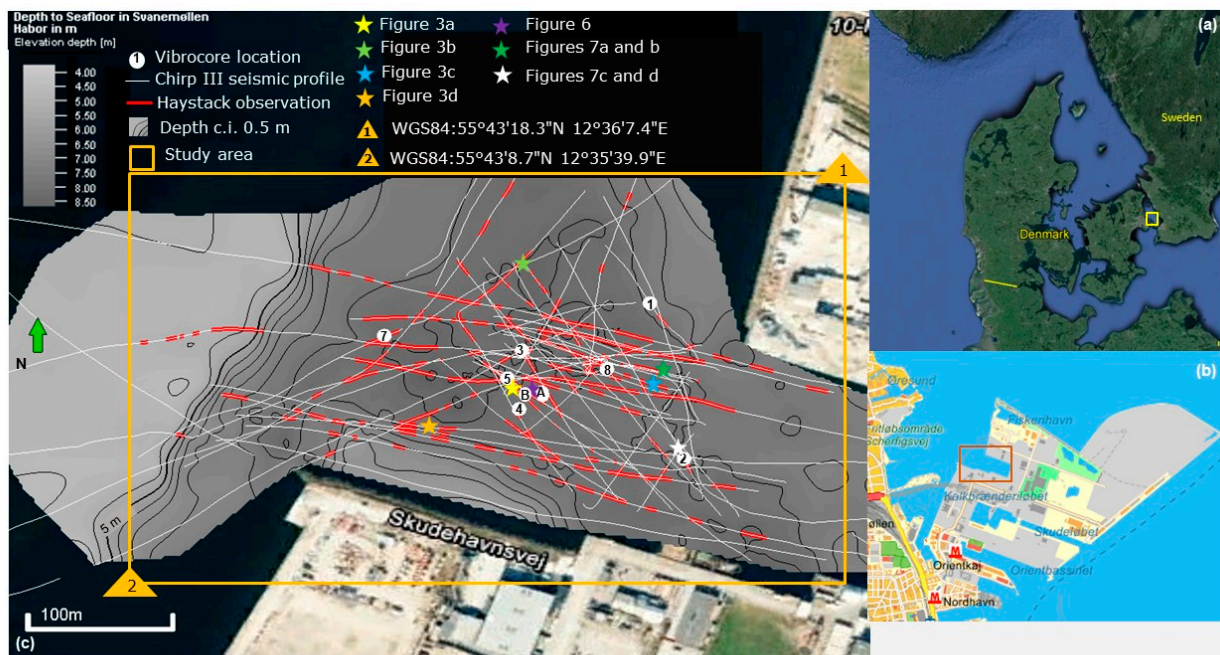


Figure 1. (a) The study area of Svanemøllen Harbor, Copenhagen, Denmark. (b) A location map of the harbor area. (c) A bathymetric map (contour interval: 0.5 m) of the study area with the location of the Chirp III seismic profiles and vibrocores (vibrocores 1–8 and A and B). Red markings along the seismic profiles show observed haystacks. The colored stars show the location of the seismic profiles in Figures 3, 6 and 7. The triangles at the NE and SW corners of the study area mark the coordinates of the study area. Graphics: L.O. Boldreel.

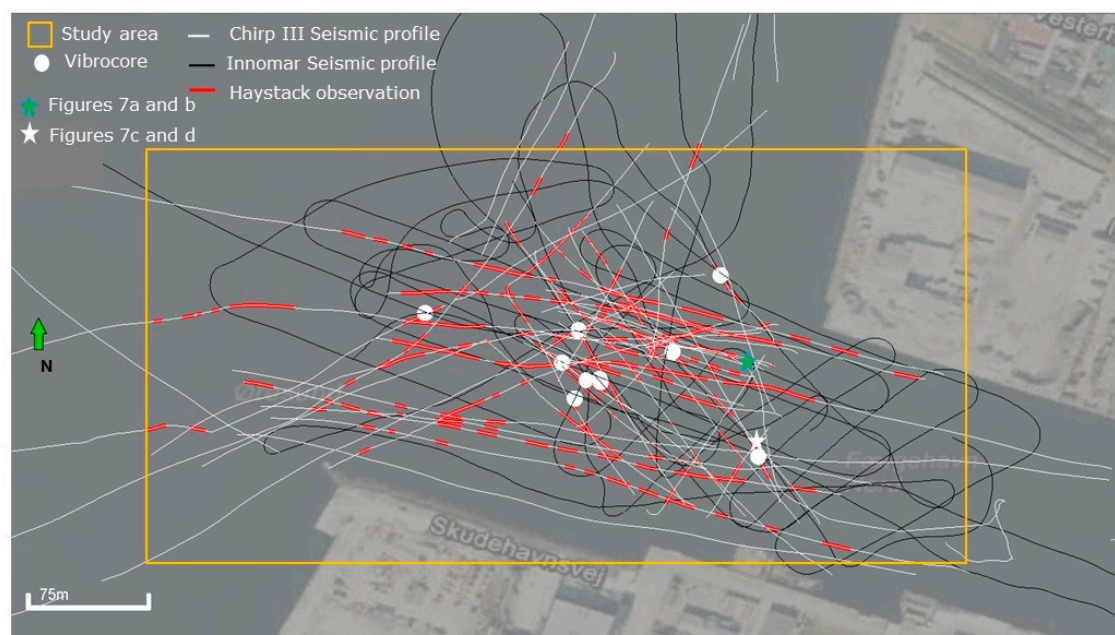


Figure 2. A location map of study area with the Innomar and Chirp III profiles. The red markings along the Chirp III profiles show the haystacks' locations. The white and green stars show the locations where the Innomar and Chirp III profiles were recorded at the same location. The seismic profiles are shown in Figure 7. Graphics: L.O. Boldreel.

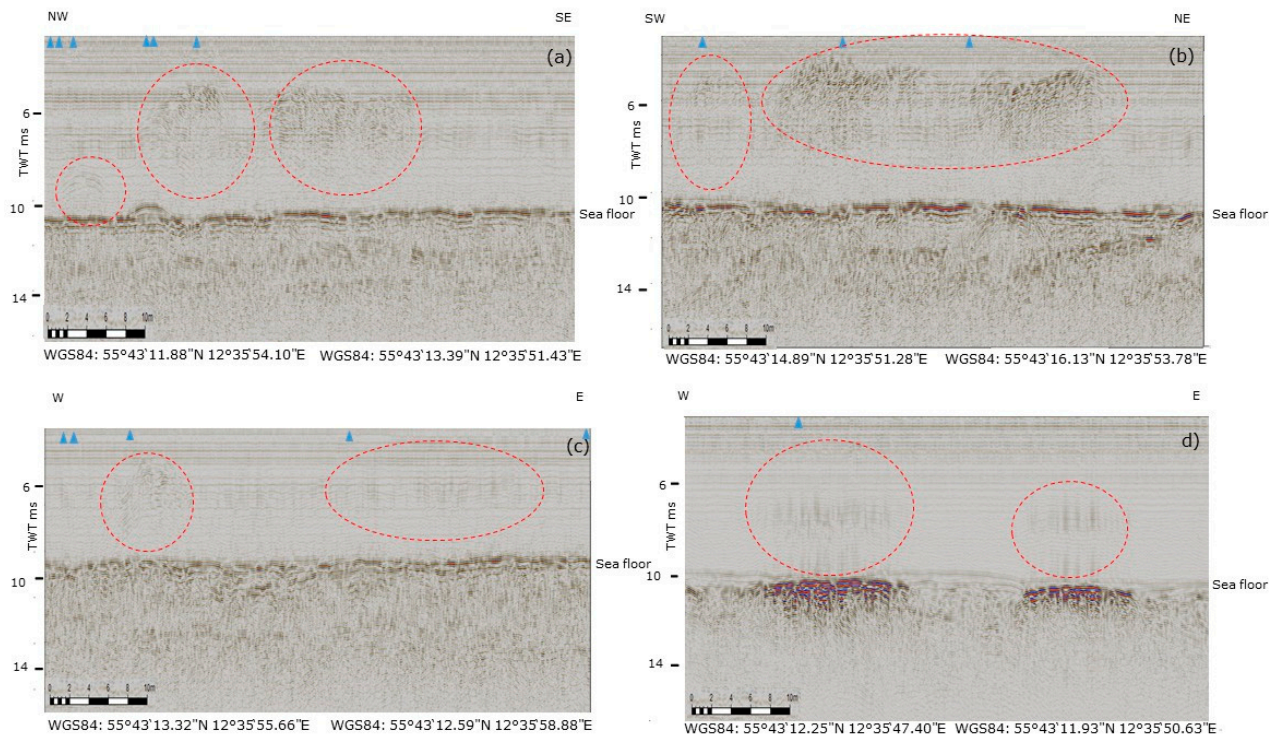


Figure 3. Parts of four seismic profiles: (a) line 0009; (b) line 0024; (c) line 0002; (d) line 0010. For their locations, see Figure 1. Depth is measured in TWT msec; the length of the scale bar is 10 m. The small blue triangles along the horizontal axis on the seismic profiles show intersecting (crossing) seismic profiles. Geographic coordinates are noted for the start and end of the parts of the seismic profiles shown in this figure. The location of the seafloor is marked, and in (a,b) at the seafloor, the reflector is pronounced, whereas it is weak in (c,d). The orientations of the profiles are marked. Selected haystacks are shown on the seismic profiles using red dashed lines. Profiles (a,b) show pronounced haystacks that are located above small basins that are found below the seafloor. Profile (c) shows a small haystack to the left and a series of sub-vertical individual disturbances in the water column. Profile (d) shows pronounced vertical disturbances in the water column, located above two separated areas that are characterized by high reflectivity (large acoustic impedance contrasts) below the seafloor, which shows a material (different from sand) being deposited in a sandy environment. Graphics: L.O. Boldreel.

This paper provides an interpretation of the Chirp III profiles, along with an integrated presentation of the shallow cores, the retrieved pieces of knapped flint, the pieces' physical properties and a Finite Element modeling of the four flint pieces' acoustic responses. In addition, Innomar and Geopulse data were obtained in the area in order to test if these instruments would show haystacks. For the first time, it was demonstrated that acoustic responses from a Chirp III can be used to detect unknown submerged and buried Stone Age sites [3]; that coring below haystacks can be a useful method for ground truthing, even at sites with relatively low densities of knapped lithics; that knapped lithic pieces respond to the outgoing acoustic signals from the ChirpIII, as indicated by the lithic flint that we recovered below the haystacks; and that the recovered flint pieces are resonant, as shown by our FE modeling. This offers an alternative and supplementary method to the modeling approach for the location of, for example, Stone Age sites [15] and a further supplement to shallow seismic investigations that are aimed at reconstructing the paleolandscape.

2. Materials and Methods

The interpretation of marine high-resolution seismic data is traditionally based on “reflection seismology”, a remote sensing discipline that is aimed at distinguishing the

subsurface of the Earth. Reflection seismology focuses on distinguishing the surfaces between different layers on the basis of their impact on reflected single-beam acoustic signals [16,17]. This traditional geophysical approach has a strong focus on what happens from the seafloor and downwards and tends to ignore phenomena in the water phase. The last half century has seen a parallel and increasing focus on related acoustic methods for the distinction of marine species (fish, vegetation, etc.) in the water phase, in some cases relying directly on acoustic resonance and not reflection (e.g., [18,19]). Lately, it has been demonstrated that the Teledyne Benthos Geophysical Chirp III off-the-shelf sub-bottom profilers (TTV-172), apart from providing geological sub-bottom data, can also be used for resonance-based detection of Stone Age sites that are exposed on the seafloor, as well as Stone Age sites that are buried in seafloor sediments and buried shipwrecks [2,3,7,20–22].

The successful use of the Teledyne Chirp III instrument—originally developed for high-resolution reflection seismology—for the detection of submerged Stone Age sites on the basis of resonance-based noise phenomena in the water phase caused confusion and resistance in parts of the traditional geophysical environment, which did not focus on resonance phenomena. In maritime archeology, where there was mainly experience with side-scan sonars and multibeam echosounders, the approach was met with skepticism and denial. However, continued systematic experimentation with lithic pieces that have been knapped by humans, as well as with naturally cracked lithic pieces, has demonstrated the validity and efficiency of acoustic responses (haystack features) for the detection of exposed Stone Age sites on the seafloor, as well as ones that are buried or submerged [2,3,14].

In 1982, the first measurements from the Bang & Olufsen Sound Laboratory showed that knapped flint pieces from the Stone Age had resonance frequencies that varied from piece to piece but that were mainly within the interval of 3–23 kHz, mostly concentrated in the 7–12 kHz interval. This was supported by the first FE (Finite Element) modeling, as well as measurements by an independent research group [1,23,24]. As suspicions arose that there was a problem with measuring low-resonance frequencies, R.B. Tayong developed and applied a more sensitive measuring method, successfully demonstrating that two rather large flint blades (87 and 102 mm long, respectively) of significantly different shapes both had lower resonance frequencies than what had hitherto been measured: 2.178 and 1.698 kHz [6]. This implied that earlier measurements should be revisited, as they will likely have lower resonance frequencies than previously observed. From a detection point of view, this is an advantage, as lower frequencies have better penetration through seafloor sediments than higher ones, and this, therefore, facilitates deeper detection [2].

To excite knapped lithic pieces with one or (mostly) several resonance frequency peaks, each within the frequency spectrum of 1.5–12.0 kHz, a single-beam Chirp sub-bottom profiler (Teledyne Chirp III), sweeping the frequency interval of 2–20 kHz, has been proven to work well and produce a visible response from surface-exposed or buried knapped lithics in the seismic profiles recorded in the water phase [2,3].

Empirically, it has been established that acoustic responses from knapped lithics, apart from appearing as regular haystacks, can also appear as narrow “noise columns” in the water phase. In one well-documented case from a Swiss lake, very narrow vertical noise columns appeared to represent the responses of individual knapped lithic pieces [2].

Since these observed acoustic resonance responses deriving from knapped lithics that are exposed on or buried into the seafloor are likely slightly delayed (because it probably takes a small amount of time to excite the pieces to an energy state where they release a measurable responding signal), they do not correspond with their “correct” vertical position according to reflection seismology [3]. Thus, the narrow noise columns, as well as the haystack response features, will likely be slightly delayed in relation to reflections from the same vertical position [3].

The first observations of lithic responses were solely related to flint, whereas later observations have empirically demonstrated that a wide spectrum of human-knapped silicious minerals respond in the same way [2].

It can be noticed from Innomar surveys in the Danish inner and outer waters that haystacks are not seen in these data. The Kongsberg GeoPulse instrument tested by Boldreel and Grøn in 2022 in Svanemøllen Harbor might show some very weak indications of debitage detection in the upper part of the water column. The absence of haystacks in Innomar recordings has caused discussions among geologists/geophysicists and archeologists on whether the haystack method can be used; whether human-knapped debitage can be brought to resonance; why the haystacks have only been observed in the Chirp III data so far and not in data from other high-resolution instruments; and whether the haystacks really represent human-knapped flint, despite experiments being carried out (e.g., [1]), findings by Grøn using Bentos Datasonic Chirp II [12] and work carried out at Clint's Scallop Hole using an EdgeTech 3100P to identify haystacks [10]. Recently, the authors of [25] denied Chirp III haystack findings being a response to flint debitage and categorized the method as flawed, unreliable and scientifically unrepeatable, mainly because the haystacks cannot be registered on their Edge Tech Chirp 3100_P system, neglecting that Chirp III and Edge Tech Chirp 3100_P are two different instruments and belong to two different generations of instruments. The results from Clint's Scallop Hole are based on the work presented in [10] and would make a good comparison study with [25]. The reason why the haystacks are not recognized on both Edge Tech Chirp 3100_P systems is unclear to us as users of a Chirp III instrument.

2.1. Seismic and Acoustic Modeling Data from Svanemøllen Harbor

Seventy high-resolution seismic profiles were collected off Svanemøllen Harbor with the Teledyne Chirp III instrument, using the same settings, boat, engine and crew during three campaigns from 2018 to 2020 (Figure 1). In 2018, haystacks were observed in one profile while in transit to a test site in another location in Copenhagen Harbor with the instrument running. The following two years, this observation was followed up with systematic recordings to map the occurrence and outline of the lithic responses. The positions of the sailing lines, as well as the distances between them, were decided on the basis of on-site interpretation during the recording in order to focus the recording on localizing the haystacks. In contrast, a geophysical/geological investigation would have consisted of a survey, with the seismic profiles being placed in a regular grid.

The recordings were carried out from a large Zodiac inflatable boat with an outboard engine. Using a Zodiac has the benefit of, e.g., being able to make and respond to quick decisions regarding navigation/sailing, sailing in shallow water, acquiring data in a small area (as tight turns are possible) and operating with a low velocity (1–2 knots). The Chirp III “fish” (the transducer unit that emits and receives the signals) was attached to a frame and located in front of the engine to ensure that propelling-induced air in the water did not disturb the recording. The DGPS antenna was placed exactly above the middle of the fish to avoid recording the positions with an offset. The precision of the dynamic position measurement varied with the satellite constellation but was generally within an interval of a few centimeters. The profiles were recorded while sailing in straight lines with a constant speed of 1–2 knots to avoid disturbances in the water column caused by variations in the speed, as well as artifacts being caused by crooked lines. At the end of the sailing lines, the recording was stopped, and the boat continued the course for approx. 5–10 min before turning. Recording of the new line was started after approx. 5–10 min of sailing along the new course. This was to ensure that disturbances in the water column from the turns were minimized.

The Teledyne Chirp III uses a frequency band (2–20 kHz) and emits and records this interval. The recorded data are displayed in two separate windows, a low frequency covering 2–7 kHz and a high frequency covering 10–20 kHz, on the screen while recording data. This facilitates basic interpretation of the data, as well as optimizing the screen setting during recording. The seismic data are not processed further. Each line is stored in two separate SEG-Y files: one for the high-frequency data and one for the low-frequency data. After recording, the data are loaded, with the option of color changes, AGC, instantaneous phase or other simple processing options in the Petrel 2019 v 4 software. In this study, the data were interpreted on a workstation using two independent interpretation software packages, Petrel and KOGEO, to ensure that the recognition of haystacks did not depend on the software.

The Chirp data were contaminated by lines that seemed to be horizontal, which was most clearly seen in the water column (Figure 3a–d). Careful analysis showed, however, that the lines dipped by approximately 1 degree, and thus, Fourier transformation was not applied, as the line dip prevented removal [26]. Likewise, summing and averaging the seismic traces related to the sequential shotpoint and an AGC (Automatic Gain Control) study did not remove the lines. In addition, on the Chirp III recordings, some mirroring of the subsea surface seemed to occur, which might indicate that the whole signal was recorded with the entire precursor being preserved. Lines, almost horizontal, were also recognized on the Innomar, sparker and Geopulse data, although they were most pronounced in the upper part of the seismic profiles. It was tested if haystacks can be removed through processing, but they were proven to be permanent features, despite thorough processing [26].

Twenty-four Innomar seismic profiles (Innomar Ses2000 standard parametric sub-bottom profiler, with a frequency band of 85–115 kHz) were acquired in the Svanemøllen Harbor area in 2021, and forty-eight GeoPulse (single-beam sub-bottom profiler) data points were obtained in 2022 for comparison with the Chirp data. The Innomar data were recorded using standard instrumental and Chirp mode settings, and both high- and low-frequency data were recorded. All different combinations of the GeoPulse data were tested. The Innomar and GeoPulse data cover the study area, especially the central part in which haystacks were found on the Chirp profiles. Figure 2 shows the location of the acquired Chirp III and Innomar profiles.

2.2. Geological, Core and Flint Data

Grab sampling (Van Veen Grab) and diver inspections of the seafloor were permitted to be carried out in the harbor basin, but not on the sailing route, by the harbor authorities. The inspection was performed beneath a number of the registered haystacks on the Chirp III profiles and it was revealed that no pieces of knapped flint were exposed on the seafloor.

Two types of cores were available for this study. In 2021, a series of 15 deep cores, taken by the Danish Road Directorate, were sampled within the 200 × 300 m area of investigation. The core data were kindly made available to this project by the Danish Road Directorate (email confirmation). The cores terminated in the depth interval of 14–21 m below the seafloor, but none of the cores were located below the identified haystacks. A few samples were taken from the upper 50 cm of the seafloor and 1.5 m below it. A number of samples were taken from a deeper level. The lithology of the cores was described by the coring crew.

Later in 2021, eleven shallow vibrocores, taken by GEUS (the Geological Survey of Denmark and Greenland) at depths of less than 1 m below the seafloor, were made available to the project. The cores were taken with thin core barrels (2 mm) consisting of plastic tubes with an inner diameter of 7.4 cm and lengths of 2 m. The base of the tube was fitted with a core catcher so that material did not slide out of the barrel. The tubes were driven into the seafloor with a vibrator that was placed on top of the plastic tubes. The coring was

carried out from a small vessel, which, during this process, was kept in position (located using DGPS) at the chosen location by anchors. When coring could not advance due to the stability of the plastic tubes and resistance from the sediment layers beneath the seafloor, the vibrator was stopped, and the plastic tubes with sediments were pulled up. The cores from the investigated area had a maximum penetration of 90 cm into the seafloor (Figure 4).

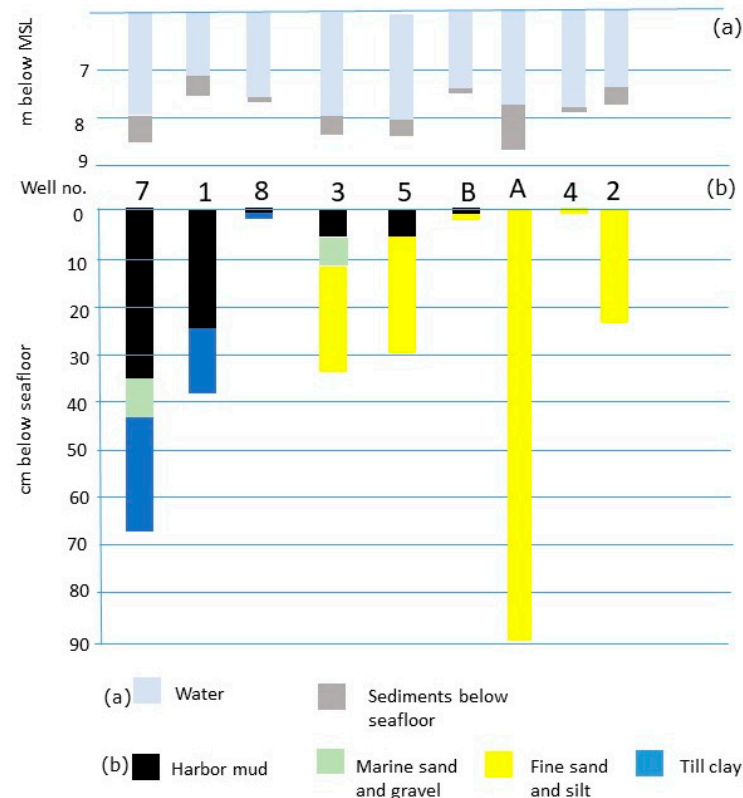


Figure 4. The short vibrocores 1–5, 7–8, A and B. (a) The water depth at the locations of the cores and the length of the cores, measured in m below the seafloor. (b) The lithology of the vibrocores. The arrangement of the cores shows the distribution of the cores, in that the cores to the left represent the outer part of the study area, where harbor mud, marine sand, gravel and clayey till are present. The cores in the central and eastern part of the study area are characterized by fine-grained sand/silt. Cores A and B contain flint pieces. Graphics: L.O. Boldreel.

Nine cores provided lithological information, while two cores were lost, as the material slid out of the barrel before being secured.

The positions of the 11 vibrocores conjoined horizontally with the observed haystacks in the area, which displayed various shapes, intensities and distances from the seafloor in the water phase (Figure 1). Nine locations were chosen in which the till was located close (less than 1.5 m) to the seafloor and with the thickness of the recent harbor mud at a minimum, while the two remaining core locations were taken below very pronounced haystacks, although a layer of “harbor mud” was suspected.

Core A went 90 cm into firm sediment and was well-preserved, with two pieces of knapped flint located in situ at a depth interval of 80–90 cm. Core B went approximately 100 cm into firm seafloor, but some of the material was lost when the plastic tube was pulled out of the seafloor, which is why the knapped flint from this core was not registered at its in situ depth. The recovered cores were inspected and registered before being wet-sieved. The inspection of the material from the shallow vibrocores by Grøn and Madsen led to the identification of two pieces of knapped lithics from each of the two most central cores in the haystack area: A and B (Figures 1 and 5).

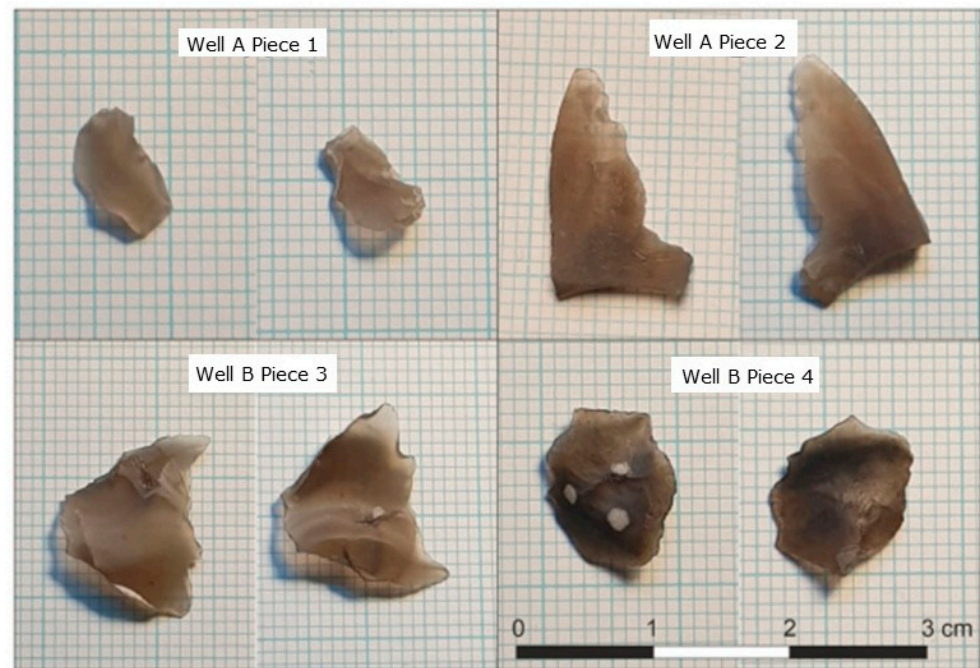


Figure 5. The four flint pieces retrieved from cores A and B. The images are intended for archeological inspection and show the pieces from both sides. Photo: O. Grøn.

In order to integrate the seismic profiles with the core information, acoustic signal velocities of 1500 m/s in the water phase and 2000 m/s in the sediment were used to correlate the seismic reflection pattern of the layers with the information from the cores.

The structural behavior of the four flint pieces that were obtained from cores A and B was numerically investigated. A Finite Element model was developed to analyze the pieces' structural response to acoustic excitation.

3. Results

3.1. Cores

The samples taken from the geotechnical cores were inspected by Grøn and Boldreel, who found no knapped flint pieces in them. The lithology of these cores was in good agreement with that of the shallow vibrocores made by GEUS, both in terms of their relative lithologies and depths below the seafloor. In descending order from the seafloor, the encountered lithologies were as follows: harbor mud, marine sand, gravel with shell fragments and fine-grained sand/silt muddy sand of a postglacial age. Below this, we found clay till of a glacial age. This lithological information thus provides good correlation points for the seismic profiles and facilitates an integrated interpretation of the seismics, shallow vibrocores and geotechnical cores.

Nine cores (1–5; 7–8; and A and B) contained lithological material, whereas two (6 and 9) were empty (Figures 1 and 4). The cores were located at a water depth of 7.22–8.02 m (Figure 4a). Most of the cores (7, 3, 1, 5, 8 and B; listed in order from the outer part of the harbor basin towards the inner part) demonstrated that the seafloor sediment consisted of up to 36 cm of harbor mud (Figure 4b), whereas at the locations of cores A, 4 and 2, the seabed consisted of fine-grained sand and silt. Below the silt, marine sand and gravel were located on top of fine-grained sand/silt or clayey till. The fine-grained sand/silt layers did not contain plant or animal remains and were interpreted as Late Glacial sediments. The thickness of the silt showed variation within the study area and was thickest in the northwestern part of the study area, while it seemed to be mostly absent in its central part. The lithology indicates that the clayey till was covered

by fluvial material before being transgressed by the sea. The harbor was extended after 1954, and dredging was carried out in the study area, during which part of the sediment (likely marine sand) was removed. Rather recently, a part of the study area was covered by harbor mud. The cores (2, 4, A and B) in the central and southern parts of the investigated area showed minimal or no mud at the seafloor above the fine-grained sand/silt. In this area, the lithology of the fine-grained sand/silt appeared to reflect a paleoenvironment that was characterized by fluvial processes or near-coastal conditions, indicating that the land area was located in a SE-ern direction covering the central and southeastern parts of the investigated area.

3.2. High-Resolution Seismic Data

In seismic marine reflection methods, a seismic sound wave is emitted from a source that is attached to a vessel, and the reflected signal is received by a receiver (e.g., hydrophone, cable), which is connected to the vessel. When the seismic wave travels downwards, it will meet different boundaries in the subsoil. Upon meeting a layer boundary, a part of the seismic signal is reflected and registered by the receiver, and a part is transmitted further down into the sub-bottom. A boundary between two layers is detected when there is a difference in the acoustic impedance (defined as the velocity of the material multiplied with the density of the material) that the sound wave travels through. The boundary can be limited or wide in terms of its geographical extent, as well as continuous or disrupted (see, for example, [17]). A continuous boundary between layers is seen as a seismic “reflector” in the recorded profiles—sometimes called a seismogram or a seismic section (e.g., Figures 3 and 6)—whereas a non-continuous boundary or a disrupted signal is named a “reflection”.

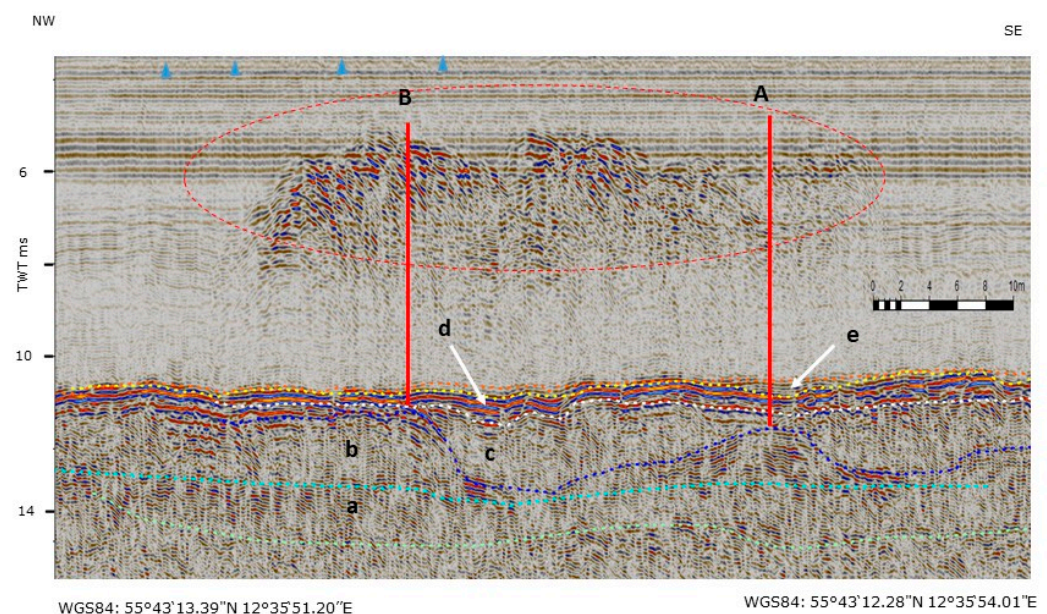


Figure 6. A pronounced haystack (shown by the red dashed line) at seismic profile 0007, with the location of cores A and B (for location, see Figure 1). The blue triangles at the top of the seismic profile show intersecting Chirp III seismic profiles. The depth scale is in TWT ms. Geographic coordinates are shown for the start and end of the part of the seismic profile that is shown. Five interpreted geological units a through d are marked. Cores A and B terminate in unit c, which forms a paleolandscape that is characterized by high areas surrounded by low-lying areas, likely in a fluvial or near-coastal area. The haystack extends over the two high areas and the low-lying area between them. The scale bar is 12.5 m. Graphics: L.O. Boldreel.

The interpretation of the seismic profiles was carried out using seismic stratigraphy (see, for example, [17]), a method that identifies units (similar to layers) both in time (stratigraphic depth) and lithology by use of, for example, reflector terminations, facies and amplitude studies.

The depth of reflection seismic is measured in time, TWT (Two-Way Travel Time, measured as the recorded sound wave travels down and up from the measured boundary), and is most often reported in milliseconds (see Figures 3 and 6). The depth in meters can be calculated as follows: $\text{depth (m)} = \text{velocity of material traveled through (m)} \times \text{TWT}/2 \text{ (m/s)}$.

Using high-frequency seismic equipment, a high degree of detail (at a high resolution) can be obtained from the subsea bottom, but high-frequency seismic signals do not penetrate far into the sub-bottom. The first geological reflector in marine data is the seafloor. In case the seafloor consists of a material such as sand, a strong reflector is created, whereas a weaker reflector is obtained if the seafloor consists of silt or mud.

Between the sea surface (recording time: 0 millisec. TWT) and the seafloor, disturbances may be observed, which are often ascribed to gas or fish. The gas will form disturbances up to the surface of the sea, and fish do not remain in the same location—thus, in Figures 3–6, the disturbances in the water column reflect neither the presence of gas nor fish, but the type of features that we call haystacks [1,2]. The presence of the haystacks above the seafloor is remarkable, as the first geological feature to cause a “reflection” is the seafloor. This shows that the haystacks are not “reflections”, as in reflection seismics, but features of a different character, caused by a different type of response to the acoustic signals that are emitted by the Chirp III. These disturbances were observed for both the high- and low-frequency data. On the basis of the results of extensive seismic fieldwork, experimentation and FE modeling, we suggest that the observed phenomenon was caused by the delayed resonance of human-knapped lithic pieces. It is possible that the orientation of the pieces may influence the degree, as well as type, of the acoustic response that is emitted from them, which we observed on the intersecting seismic profiles.

The recorded Innomar data provided geological information below the seafloor and appeared to be smoothed out to enhance the continuity of the geological boundaries, thus simplifying the picture compared with the very detailed information obtained from the Chirp III recordings that are seen in Figure 6. In the water column, no signs of haystacks were observed in the Innomar data (Figure 7), neither in the high- or low-frequency data or from using the Innomar in Chirp mode.

3.3. Interpretation of Seismic Data from Svanemøllen Harbor

In the investigated area, a large number of disturbances in the water phase can be recognized in the Chirp III seismic profiles. The individual noise features vary in their extent, shape and height above the seafloor, from cloud-like features to vertical disturbances of other shapes (examples are presented in Figures 3, 6 and 7), which correspond to earlier observed features (e.g., [1]). The noise features that were recorded in the area during the three-year period with the same Teledyne Chirp III, using the same instrumental settings and sample rates, as well as the same Zodiac with the same speed and motor, are unchanged and consistent over time with regard to their location and are not related to gas, fish, engine noise, crooked lines or variation in the speed of the Zodiac. The features are mainly found (Figure 1) in the central part of the investigated area, with a lower density of smaller and generally more patchy features in its peripheral part. Intersecting profiles do not necessarily show the same type of response [2], which indicates that variation in the distribution/orientation of the material producing the haystack response can be of importance for the creation of the resonance.

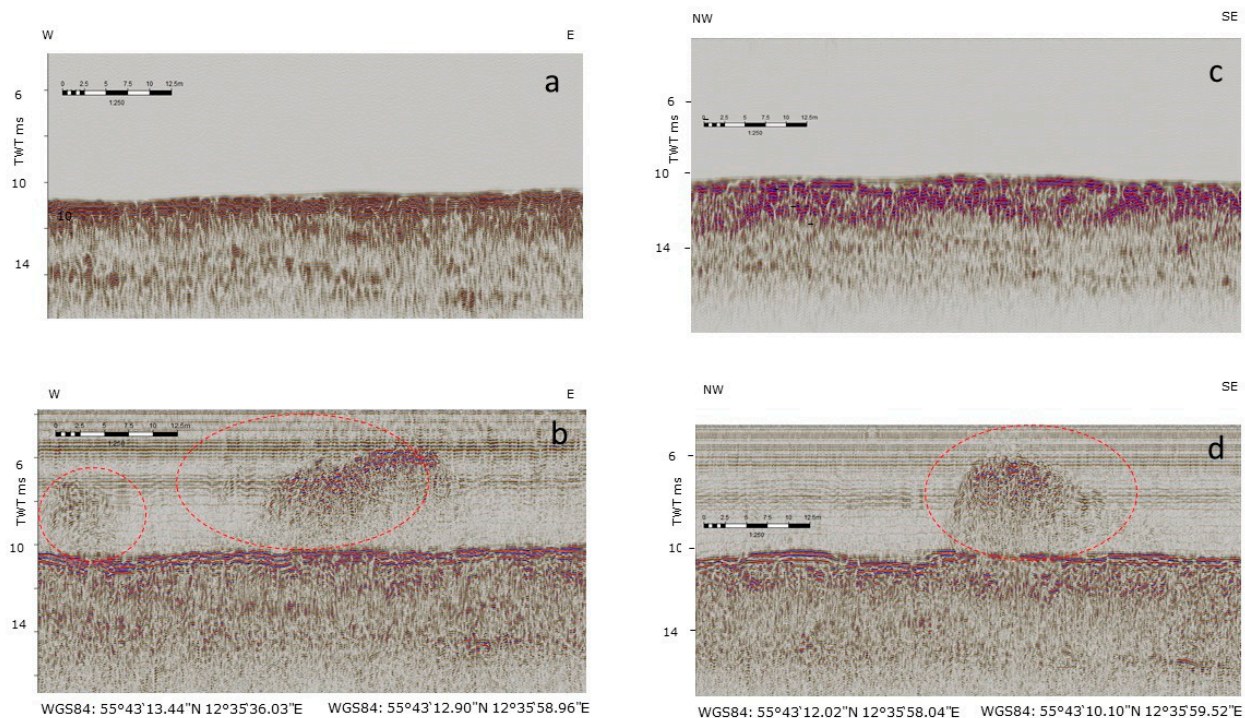


Figure 7. Comparison between Chirp III and Innomar seismic profiles, acquired at the same positions. The location of the profiles is shown in Figures 1 and 2. Geographic coordinates are shown for the start and end of the parts of the seismic profiles that are shown. In this figure, the Chirp III data show haystacks (marked by red dashed lines), whereas the Innomar data do not show these structures. The geologies below the seafloor that were revealed using the Chirp III and Innomar profiles correspond closely to each other. (a) Innomar profile W0022_06072021_105227; (b) Chirp III profile 0008; (c) Innomar profile w0005_06072021_101446; (d) Chirp III profile 0020. Graphics: L.O. Boldreel.

In most places, the locations of the haystacks seem to be related to the postglacial landscape below the seafloor, as they were found at small heights and at the rim of the small basins, indicating that the distribution of haystacks is related to paleolandscape features or the near-coastal zone (Figures 3 and 6). In some places, e.g., in the westernmost part of the investigated area, single vertical disturbances seem to be related to the small basins that are located in the paleolandscape, where a high acoustic response can be observed within a limited part of the otherwise sand-covered area at a depth of approx. 40 cm below the seafloor (Figure 3d).

The seismic profiles from the study area show a large part of the seafloor as a rather weak reflection, which is best distinguished in the high-frequency data from the Teledyne Chirp III but which is also visible in the low-frequency data and the Innomar data (Figures 3, 6 and 7). In smaller areas, the seafloor constitutes a pronounced reflection.

Based on seismic interpretation using the method of seismic stratigraphy, five seismic units were identified in the Chirp III data (Figure 6), which were confirmed by the Innomar data. Unit a is the lowermost (oldest) unit that can be followed across the entire investigated area. It is bounded by a pronounced reflector at the top of the unit. Its lower boundary can be observed as a reflector that, in places, has a rather high amplitude and constitutes a transition to a layer characterized by lower-amplitude reflections. The internal reflection seismic pattern consists of segmented parallel beds that in some places become chaotic.

Unit b is located above unit a, and its upper boundary is characterized by parallel bedded reflectors, and, in places, as top lap at the top of a number of antiforms and prograding subunits. The base of unit b is characterized in places by the downlap of the prograding reflectors towards the top of unit a or where the antiform raises. The

internal reflection pattern is characterized by pronounced reflections that are bended or parallelly bedded and in places give the impression of upthrust reflections or prograding clinoforms that show downlap towards the lower boundary. The antiforms have a thickness of approximately 1 m in some places. The internal pattern resembles till (see, e.g., [20]). From interpreting the profiles and connecting the interpretation to wells 1, 7 and 8, it was confirmed that unit b consists of till. This shows a paleolandscape with minor high areas and low-lying areas.

Unit c is generally located in front of unit b and fills out the low-lying areas that are surrounded by unit b. The lower boundary consists of unit a, and the upper boundary is placed at the base of the pronounced layer above (unit d). The shape of unit c was recognized as a channel shape or paleocoastline, and the internal pattern (fill) showed onlap towards the side of the channel/channels or downlap into one side of the channel/channels or sea/near-coastal area. The interpretation of the unit was based on tielines to sediment cores 2–5 (A and B), which show that unit c consists of fine sand/silt. The basin area surrounded by unit b becomes deeper in the north and northeastern parts of the study area, where it becomes approx. 2.5 m deep in the area between cores 1, 3 and 8. The fine sand/silt with no plant or animal remains indicates a fluvial environment, likely representing a channel or a meeting with a near-coastal area in the western and northern parts of the study area.

Unit d is located next to units b and c, and its lower boundary is characterized by a pronounced reflector of a high amplitude. The upper boundary is placed where there is a transition to a unit that is characterized by low-amplitude reflections. In a few areas, the upper boundary of unit d constitutes the seafloor. The internal pattern consists of reflections with high wavy or mounted amplitudes. Unit d corresponds to the stratigraphic level of the marine sand/gravel in the northern and western parts of the study area based on the tieline interpretation of cores 1 and 3. The stratigraphic level of the marine sand/gravel turns into fine sand/silt in the central and eastern parts of the study area. This indicates a near-coastal environment in the northern and western parts and a fluvial low-lying area in the central and eastern parts of the area.

Unit e constitutes a unit of weak reflections of a low amplitude and is located between unit d and the seafloor. Based on our interpretations of the seismic data, this unit correlates to wells 1, 3, 5, 7 and B and consists of harbor mud. The upper boundary of unit e constitutes the seafloor in most of the investigated area.

Despite the various forms (extent, size and height), the haystacks show a significant concentration in the study area within the minor basins and basin edges that are bounded downwards in terms of stratigraphy by unit b (Figures 3, 5 and 6), which indicates that the material producing the signature of the haystacks is located in unit c. At limited locations, a number of haystacks that show up as vertical forms are located geographically above a layer that is characterized by very strong reflections/acoustic impedance with a limited extent of approximately 10 m on the seismic profiles (Figure 3d). The layer seems to be embedded in a sandy environment and located approximately 40 cm below the firm seafloor. The nature of these signals is different, or a subgroup of haystacks may be pointing to another type of haystack, potentially originating from waste dumps, e.g., kitchen middens.

3.4. Retrieved Knapped Flint Pieces

Four pieces of knapped flint were retrieved from the vibrocores. Two knapped flint pieces (pieces no. 1 and 2, Figure 5) were retrieved in core A at a depth of 80–90 cm in sand and gravel, indicating that this location has been located near an environment of river/fluvial or shallow marine conditions. In core B, located approximately 10 m SW of

core A, two more pieces of flint were retrieved (pieces no. 3 and 4, Figure 5). The material in core B contained a small amount of silt at the top, followed by fine sand/silt.

The small pieces (1 and 4) have regular dorsal negative scars originating from human knapping. Piece 1 has a point-shaped platform and a small amount of chalk cortex left, whereas the platform of piece 4 is broken off. Piece 3 was produced on one side of a larger flake, where some chalk cortex was left. Piece 2 is similar to piece 3 in the sense that it is a fracture from a larger flake. The pieces are small-scale debris of less than 17 mm, similar to materials that have been found in large quantities on surfaces where flint knapping was carried out in Stone Age settlements.

The pieces consist of flint that is typical for the area south of the study area and which is of the “Senonian”/Late Cretaceous age. Piece 4 may be part of a clear and translucent flint of Danian age. The edges of the pieces are dented slightly, which indicates that they have not been transported but have been exposed to near-coastal movement, e.g., small wave action or hightide movement, or are located in situ or close to where they were produced. The geological situation indicates that this material represents a site that was inhabited in the Mesolithic. The flint pieces strongly indicate the presence of a concentration of Mesolithic material at this location, as suggested by the acoustic response that was previously recorded [14]. The four flint pieces are general by-products from the cutting of larger objects of uncertain shapes and cannot be typologically dated.

The flint pieces seem to be located on top of the antiforms of unit c, and many of the haystacks are either related to the antiforms of unit c or the deeper-lying small basin areas of the areas in unit c that are bounded by unit b.

3.5. Finite Element Modeling of the Svanemøllen Harbor Pieces

In this section, we describe an investigation of the flint pieces’ deformation, which was carried out to calculate their natural frequencies and mode shapes. To study their structural behavior, a three-dimensional Finite Element method was used. The Finite Element modeling was carried out on the four pieces retrieved from cores A and B. Figure 8a is a photo of these pieces, including a size scale. First, the pieces were scanned using a 3D Computed Tomography technique. Next, the resulting CAD files were imported to COMSOL Multiphysics (version 6.2), a Finite Element software package, to build the displacement model. Finally, the model was run to calculate the deformation of each piece. Generally, any Finite Element model is built and defined following the steps described below:

1. Creation of the geometry. The choice of a 3D geometry approach was made to simulate the actual behavior of the flint.
2. Definition of the material properties. The mechanical properties, mainly the density, Poisson’s ratio and Young’s modulus, of the flints were measured to feed the numerical model.
3. Establishment of the physics. The Solid mechanics module of COMSOL Multiphysics was used to simulate the structural response of each flint piece under external excitation.
4. Creation of the meshing workflow. Meshing is the process of dividing the geometry into small and discrete elements to facilitate calculations across the geometry. A tetrahedral node with extra fine meshing was chosen. The meshing plays an important role in the stability, computational speed (runtime) and accuracy of the results.
5. Running of the model calculations. Once the above steps are completed, the model is run to calculate the Von Mises stresses and displacements across the entire geometry.
6. Post-processing of the results and plotting. Figures illustrating the results are produced and then displayed.

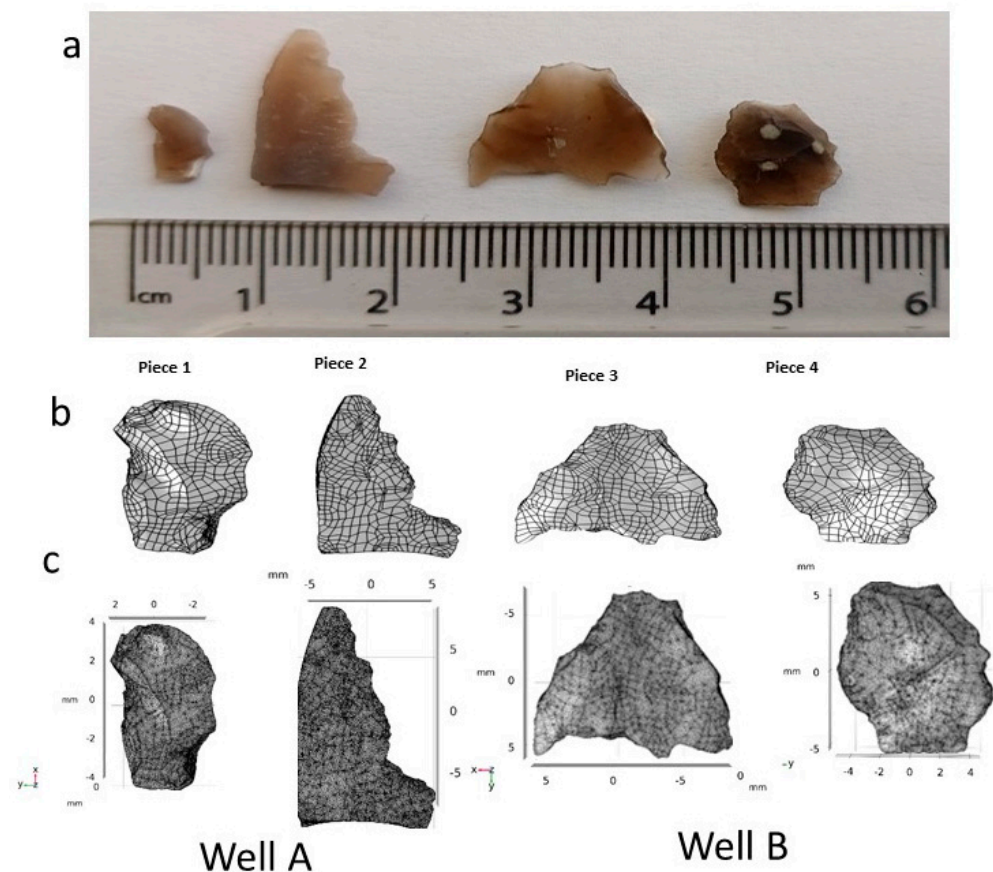


Figure 8. (a) Original picture of the four pieces of flint. The photo is intended for modeling and can be compared with (b,c) (the orientations of the samples differ from those in Figure 5). (b) The CAD geometries that were obtained for the Svanemøllen Harbor pieces using a 3D Computed Tomography scanner. The lines in the geometry were generated using the STL file format to create the exact surfaces at each location. (c) The CAD geometries imported to the Finite Element environment and showing the extrafine meshing that was generated for the four pieces studied. Graphic: R.B. Tayong.

The density of the pieces was calculated as the mass divided by the volume [27]. A high-precision scale was used to weigh the pieces, and the Archimede liquid displacement method was used to estimate their volume. Attempts to measure their modulus of elasticity using classic methods, including the ultrasonic array method [28], were not successful due to the small size of the pieces. Therefore, this mechanical property was estimated using a correlation method and a database of large-scale flint samples, including those described in [24]. Poisson's ratio was assumed to be 0.27, which is a typical value used in other studies, such as the one described in [6]. The physical and mechanical properties obtained for the four pieces studied are presented in Table 1.

Table 1. Characteristics of the four Svanemøllen Harbor pieces. Poisson's ratio is assumed to be 0.27. Graphic: R.B. Tayong.

	Length (mm)	Width (mm)	Thickness (mm)	Density (kg/m ³)	Young Modulus (GPa)	Poisson's Ratio	Number of Elements	Runtime
Piece 1	8.23	5.11	2.21	2510.83	76.65	0.27	1,922,694	6 min 38 s
Piece 2	16.51	10.34	2.56	2559.58	78.14	0.27	1,758,030	4 min 18 s
Piece 3	15.12	13.06	3.30	2556.50	78.05	0.27	2,083,266	6 min 16 s
Piece 4	10.81	9.74	2.65	2511.10	76.66	0.27	1,746,237	4 min 43 s

Careful attention was given to the modeling. The CAD geometries of the four pieces were obtained using a Computed Tomography scanner, as shown in Figure 8b, and imported to Comsol Multiphysics (Version 6.2) to simulate their structural behavior. As the pieces are not symmetric, a full-scale model was used. In the Comsol Multiphysics environment, tetrahedral elements were used to create the meshing for the geometries, using more than twenty elements per wavelength to ensure good accuracy of the results. The highest measured runtime for the simulation was approximately 10 min, with a setting of some 2,083,266 elements. The generated extrafine meshing is presented in Figure 8c. The simulation assumed free boundary conditions around the pieces. A preliminary simulation was performed to estimate the values of the resonance frequencies. These values were then used to set the Ricker wavelet central frequency to cover the entire range of frequencies studied. Figure 9 represents the error plot against the number of iterations for well A, piece 1.

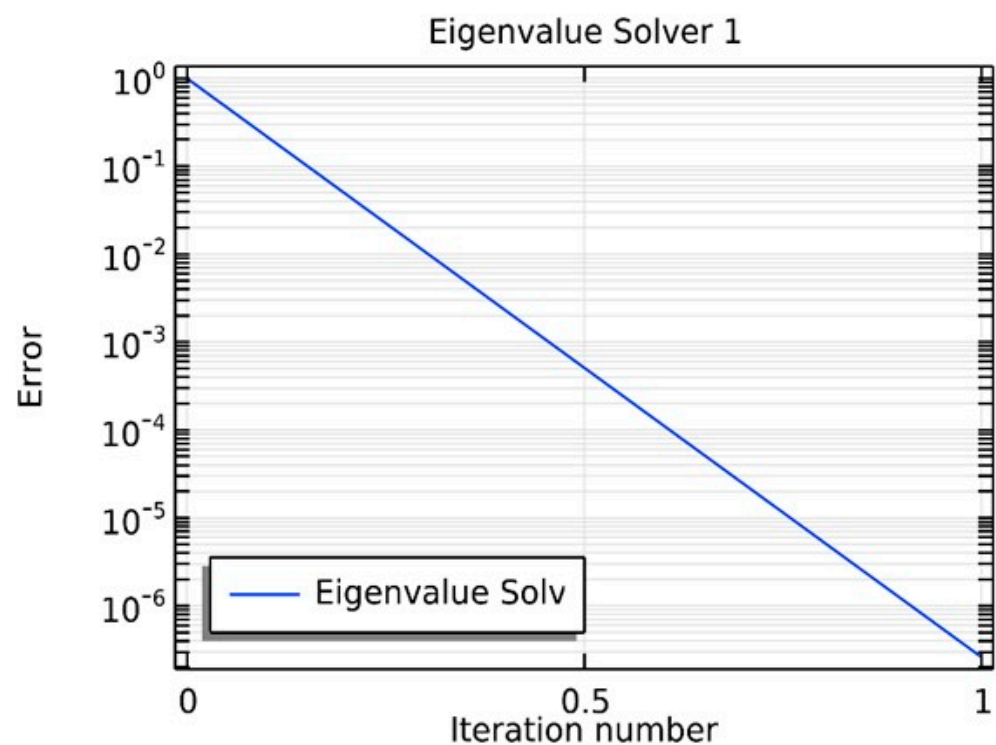


Figure 9. An example of the error function, exemplified by flint piece 1 (shown in Figure 8), obtained for the simulations showing the convergence of the Finite Element model. Graphic: R.B. Tayong.

This figure corresponds to the convergence results that were obtained from the simulations, with similar trends for the other pieces. One can easily observe that the error estimate decreases with the number of iterations, suggesting that the simulations reached a solution that was close to the exact solution, with a tolerance of 10^{-6} .

Figure 10a–d represent the modal shapes for each of the four pieces studied, showing the first four modes in both the front and side views. Both the resonance frequencies and modal shapes of the flints demonstrate that the drilled debitage resonates and deforms physically in accordance with the frequencies of excitation. Such results are important, as they suggest the potential of acoustic techniques for detecting drilled debitage.

The legend represents the displacement, with the red color indicating the maximum displacement and the blue color referring to the minimum displacement. The corresponding resonance frequencies are shown in Table 2.

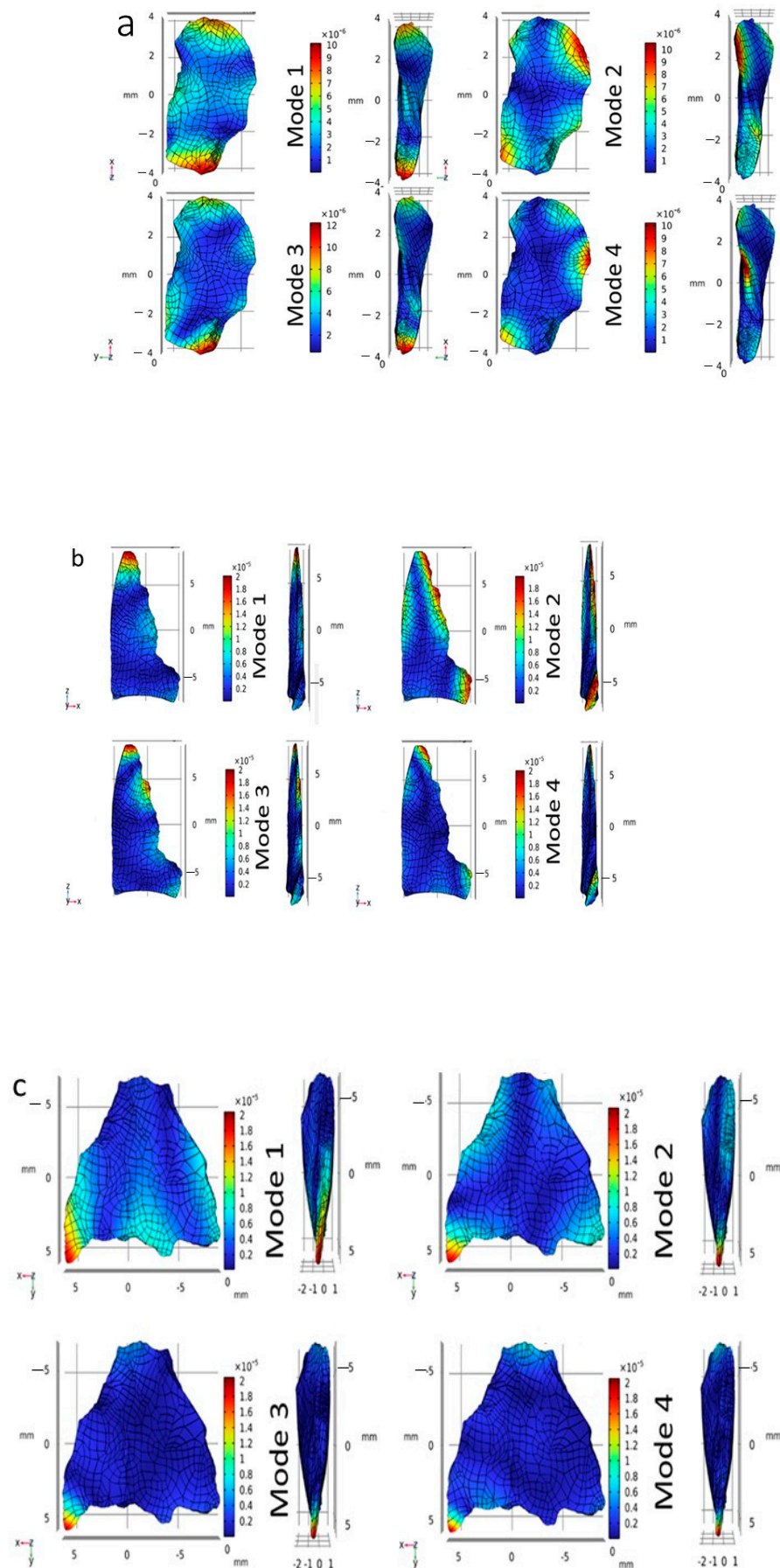


Figure 10. Cont.

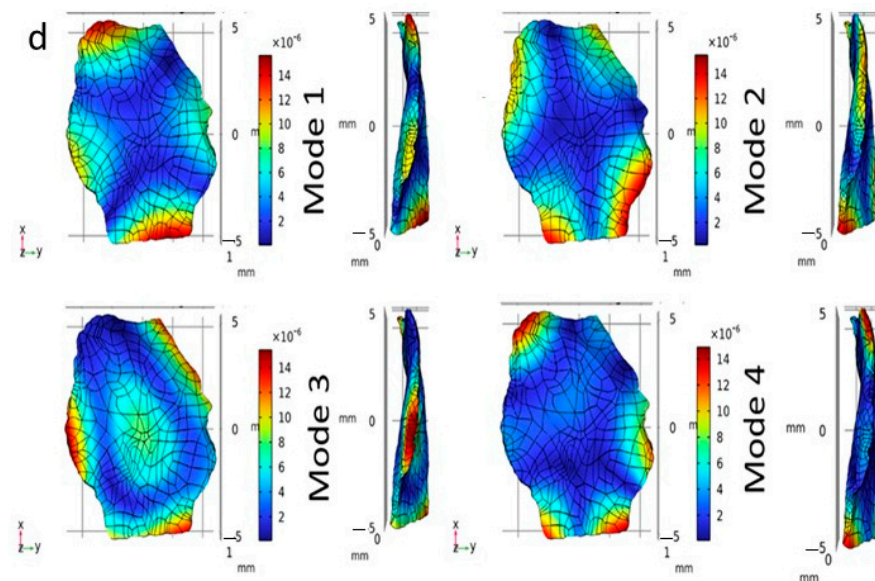


Figure 10. (a–d). The modal shapes (deflection patterns) of the four flint pieces showing the first four modes that were obtained under free boundary conditions. Both the front and side views are presented here. The displacement result is shown in mm. (a) Flint piece 1; (b) flint piece 2; (c) flint piece 3; and (d) flint piece 4. The flint pieces are shown in Figure 8. Graphic: R.B. Tayong.

Table 2. Resonance frequency results obtained for the four Svanemøllen Harbor pieces, showing the first four resonance frequencies in kHz. Graphic: R.B. Tayong.

	1st Resonance Frequency (kHz)	2nd Resonance Frequency (kHz)	3rd Resonance Frequency (kHz)	4th Resonance Frequency (kHz)
Piece 1	112.15	149.17	210.94	249.32
Piece 2	29.01	42.13	59.80	70.66
Piece 3	31.79	38.94	57.07	85.44
Piece 4	42.37	54.03	71.67	83.73

For piece 1, the first resonance frequency is around 112.15 kHz, whereas it is 29.01 kHz for piece 2, 31.79 kHz for piece 3 and 42.37 kHz for piece 4. It is observed that the longer a piece is, the lower its first resonance frequency is, but these harmonics do not follow this rule. Because of their twisted, tilted and complicated shapes, the four Svanemøllen Harbor pieces created irregular modal shapes. This suggests that they are inhomogeneous in their physical and mechanical properties, which would indicate that these properties depend on the size of the piece that was cut off from the flint at the Svanemøllen Harbor site.

Our investigations and testing show that the flint pieces' densities are close to each other, with an average density of approximately 2500 kg/m^3 , and that they are able to resonate. The four pieces' resonance frequencies all lie above the audible frequency range, which is above 20 kHz. Their first resonance frequencies are inversely proportional to their length, and the smaller the volume of a piece is, the higher its first resonance frequency is. The pieces' modal shapes are complicated due to their irregular shapes and inhomogeneity.

Because the classic experimental measurement methods that we applied to these Svanemøllen Harbor pieces were unsuccessful due to the small size of the pieces, advanced methods, including the use of a laser interferometer setup, are being investigated to accurately measure their mechanical properties.

4. Discussion

In recent years, knapped flint has been detected and confirmed to be lying directly on the seafloor by means of EdgeTech 3100P instrumentation in the USA and Chirp III in Denmark [1,2,5,10]). It has also been confirmed to be located below the seafloor at Atlit Yam, Israel, through diver investigations [1]. However, in situ findings of knapped flint, based on the prediction of acoustic means, below the seafloor have not been reported so far.

A large number of Chirp III profiles were collected in Svanemøllen Harbor over three years, and haystacks were consistently observed in the water column on seismic profiles, similar to those observed in Atlit Yam [1]. Based on refs. [1,2,5], it was suspected that the haystacks could be related to the occurrence of knapped flint. Selected Chirp profiles showing haystacks were subjected to a significant amount of processing [26] to try to remove the haystacks, but the disturbances in the water column were persistently present after processing. Diver inspections and grab sampling did not find flint at the seafloor or in the mud within selected areas below the haystacks. In order to test the validity of the haystacks, Innomar and GeoPulse profiles were acquired for comparison with the Chirp III profiles. The Innomar and GeoPulse data did not show the same number of geological details as the Chirp data did, but they did show a smoothed picture of the geology, which was very useful for the interpretation, because the geological features are often quite continuous. In addition, it appears that these data are less influenced by noise. These data types (Chirp III, Innomar and GeoPulse) all identify larger geological units and are thus in good agreement, which means that this is a good approach to interpreting the geological part of the seismic profiles that are found below the seafloor and obtaining a picture of the paleolandscape. The Innomar and GeoPulse data did not show signs of haystacks in the water column on the seismic profiles. Haystacks were obtained both by the Chirp II and Chirp III instruments, indicating that this is a special phenomenon of these two types of Chirp instruments. The two Bentos Chirp instruments do not seem to have a modern acquisition mechanism related to the debubbling of marine sources, and thus, they record the full signal while the precursor is maintained. In contrast, modern instruments (such as Innomar and GeoPulse) are concerned with more “clean” signals (see, e.g., [29,30]). This difference in results from the different high-resolution seismic instruments calls for further investigation.

Very low-tech vibrocoring using short plastic tubes at positions below some of the haystacks that were observed on the seismic profiles retrieved flint pieces in two cores. All cores provided valuable lithological information that was used for stratigraphic and geological interpretation of the seismic profiles. Two cores (A and B) penetrated to the deepest level of 90–100 cm below the seafloor and penetrated into unit c, which contained fine sand and silt. Four pieces of flint that were knapped by humans were found in these two cores in the central part of the study area, where the highest number of haystacks were found. Statistically, this equals 230 pieces per square meter, which is comparable to known land sites. Cores 7, 1 and 8 terminated in clayey till at the margins of the small basins, and it seems uncertain whether pieces can be brought up due to the vibrocoring method used. Cores 3, 5, 4 and 2 terminated in fine sand and silt in unit c, and it is possible that they could have contained flint pieces if the coring could have been advanced to 90–100 cm below the seafloor.

The flint pieces were inspected by specialists in Stone Age archeology, and it was confirmed that the pieces were produced by means of human knapping. The pieces were then 3D-scanned and investigated by specialist in acoustics, and it was found that the pieces were brought to resonance when exposed to high frequencies, as was also reported in a study carried out on other knapped flint samples from Denmark [24]. The pieces are inhomogeneous, which might explain the difference in the shapes of the haystacks

on the seismic profiles, as well as those of the haystacks on intersecting seismic profiles. Experiments carried out on very closely packed samples of knapped flint vs. loosely packed samples by Boldreel and Grøn showed that, if packed too closely, the pieces did not have resonance, as it was found that densely packed pieces did not produce haystacks, whereas loosely packed pieces did. The loosely packed pieces illustrate the natural situation when Stone Age settlements are inspected on land, as knapped lithic pieces can appear in quite dense concentrations at settlements, e.g., in apparently cleared-off waste heaps. It seems that the frequency that was sent from the Chirp III built up the resonance among the pieces of knapped flint. This calls for future investigations.

The high acoustic impedance of the flint pieces might be seen on the seismic profiles as strong closely spaced reflections, but further coring is required to confirm this observation. In the outer part of the study area, characterized by the high number of haystacks, subareas of fairly vertical haystack signals were found. In a sandy environment below the seafloor, these haystacks were expressed as reflections of very high amplitudes and impedances, as shown in, e.g., Figure 3d. This was different from the main part of the study area and thus this might reflect another type of human activity than extensive knapping, such as a number of waste dumps.

From the seismic interpretation, which was correlated with the lithology information that we obtained from the cores, we suggest that the study area was a paleogeographic landscape, characterized by till- and small and high-lying areas (unit b). Fine sand/silt (unit c) from the postglacial time was deposited on top of the till and in the basin areas between the tops of the tills, reflecting a fluvial or near-coastal environment. The haystacks are concentrated on the highs and the basin between the highs, which likely shows that the knapping might have taken place on the high areas and that debitage might be found in the basin areas. A part of unit c in the western and northern parts, as the sea level rose, consists of marine sand/gravel, whereas further to the central and southeastern parts of the study area, a non-marine environment still existed. Finally, the area was covered by sand, and after dredging, harbor mud was deposited. The four pieces of flint have not been transported, but they have been exposed to near-coastal movement, e.g., small wave action or hightide movement, or they were located in situ or close to where they were produced.

The location of the Svanemøllen Harbor Stone Age site seems strange, as it is located in the middle of the harbor area. In Figure 11a, the locations of the chirp profiles and cores are presented on a bathymetric map. The map shows that the settlement is located at a water depth that is larger than the surroundings, and dredging is delimited to the west by the closely spaced contour lines. This can also be seen in Figure 11b, where the sailing route is indicated by the white area. Figure 11c shows the Stone Age settlement, plotted on an aerial photo from 1954, where it can be seen that the Stone Age settlement was located north of the “previous” harbor but is now part of the present harbor, as the harbor was enlarged towards the Stone Age settlement. This indicates that the site was originally located at a water depth of app. 4–6 m if the amount of dredging is omitted.

Based on the coring and seismics, it was found that haystacks can occur from human-knapped flint pieces at a depth of min. 90 cm below the seafloor, and indications from Atlit Yam show that flint pieces covered by two m of sand can still produce haystacks [4].

It would be convenient to investigate the study area further by obtaining reflection seismic data and carrying out additional coring, but, unfortunately, no coring was allowed in the sailing route area, and in 2022, a replacement port for sailboats was established due to the construction of a tunnel (Nordhavns Tunnel) south of the Stone Age site (Figure 11b). This replacement port hinders further investigation of the area until the replacement port is removed.

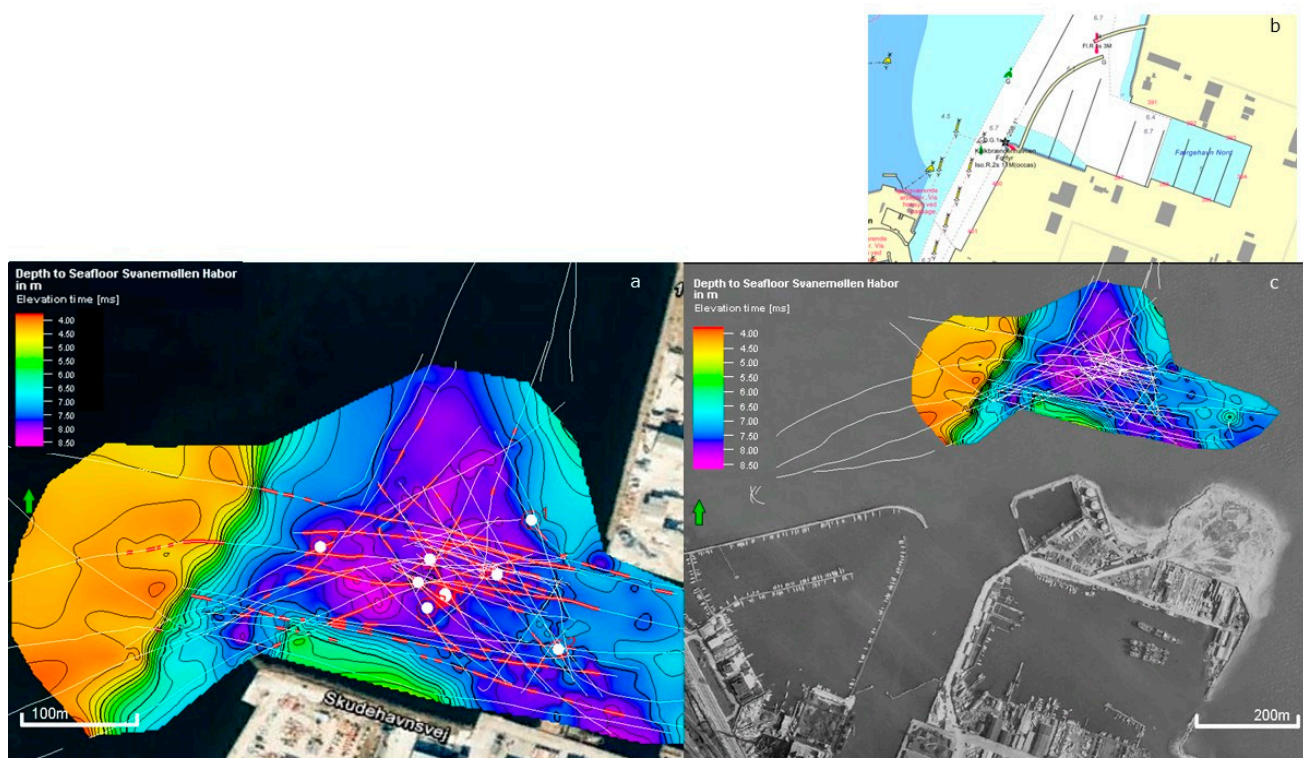


Figure 11. Study area: (a) A bathymetric map in colors, with the Chirp III seismic profiles and vibrocores located (see also Figure 1). The orange-colored area to the west shows the water depth in the study area outside of the dredged harbor basin. The sharp contour pattern shows the scar down to the dredged area in Svanemøllen Harbor, indicating that the dredging is approx. 2–3 m. (b) The present naval chart of Svanemøllen Harbor, where the replacement port was established in 2022 as a result of infrastructure constructions (North Harbor Tunnel) in Copenhagen. Further investigations are prohibited until the replacement harbor is decommissioned. The dredged sailing route shows that the dredged area is in the order 2–3 m. (c) The location of the study area on an aerial photo from 1954, showing that the study area is located at a suitable distance from the present-day coastline in an area where the water depth is approx. 5 m if it is not dredged. The dredging of 2–3 m and the depth to flint pieces 1 and 2 (core A) show that the depth to the pieces is approx. 6 m, giving a relative sea level rise of 7–8 m at the settlement of the Svanemøllen Harbor Stone Age site. Graphics: L.O. Boldreel.

Information on Mesolithic settlements can be found on [31] (a homepage) and in [32]. It appears that all settlements are located on present-day land or in coastal zones with shallow water depths (Figure 12), except for a single Maglemose settlement, which was located by divers on the seafloor [31]. Other places in Denmark show similar results, in that offshore settlements are found at the seafloor or on tidal flats. In 1993, a preliminary marine archeological investigation prior to the establishment of a permanent Øresund connection was carried out in order to investigate Mesolithic settlements in Øresund (the strait between Denmark and Sweden; see Figure 12) and to test the validity of model-based predictions of Mesolithic settlements [33]. In the report, divers in Øresund tested 25 locations, with eight of these (locations 12–16 and 23–25) being located between Amager and Saltholm (Figure 12) just south of our study area. It was concluded that signs of Mesolithic sites were present, and from the report, two sites were tentatively dated as Maglemose and Kongemose; these two locations are plotted on Figure 12. The extent of the sites cannot be judged, as they can be categorized as point observations. Based on the position and depth of the findings in Svanemøllen Harbor, we tentatively suggest the Svanemøllen Harbor site to be from the transition between the Maglemose and Kongemose.

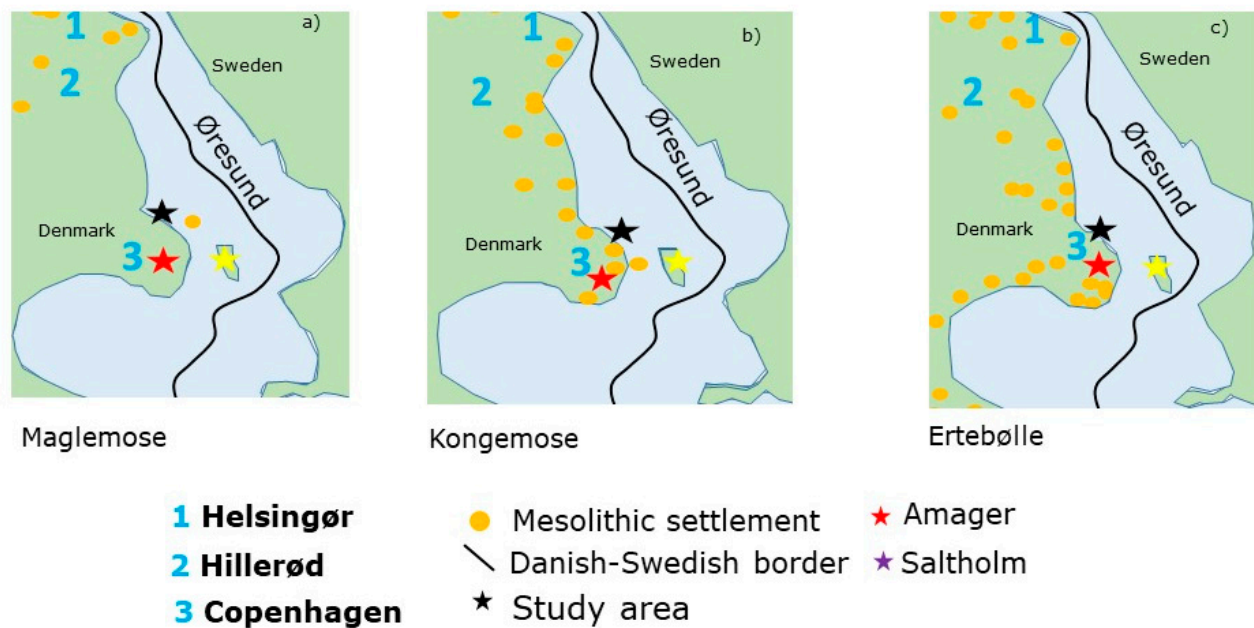


Figure 12. Three maps showing Mesolithic settlements in the region of the study area: (a) Maglemose; (b) Kongemose; (c) Ertebølle. Three major present-day cities are shown using blue numbering. The red star indicates the eastern part of Copenhagen, an area named Amager, and the purple star shows the location of the island Saltholm. All discovered settlements are located on land or in shallow water, apart from one settlement from Maglemose and one from Kongemose, which were located by divers [31–33]. Graphics: L.O. Boldreel based on [31,33].

A few offshore finds are the results of digging related to new infrastructure, the deepening of sailroutes or sediment extraction from the near-seafloor for construction usage. It is thus shown that submerged settlements are present, but no method apart from digging has been available so far. The present paper suggests that the geophysical Chirp III method can be used for localizing flint debitage, as has been shown in Svanemøllen Harbor. Where the Chirp III data showed haystacks, flint debitage was found using low-tech vibrocore, and it was shown that flint pieces can be brought to resonance. A number of questions remain to be investigated regarding the HALD method: for example, are the different shapes of the haystacks related to the size and depth of the flint debitage? Is there a lower limit of resonance for the flint debitage? Is it possible to recognize the flint debitage or piles of flint on the seismic profiles? Is it possible that large flint pieces, e.g., axes, can resonate? Is it just flint that can be brought to resonance, or can other types of material that were used in the Mesolithic, e.g., basalt and volcanic glass, also resonate? This calls for further investigations, such as collecting Chirp III seismic data; collecting samples that are located below haystacks; inspecting flint debitage pieces; and modeling the resonance and other physical properties of materials that are connected to haystacks or are suspected of being able to produce haystacks. Although these issues remain to be investigated, we suggest that the HALD method is so far the only non-destructive method for localizing Stone Age sites with flint debitage. It is suggested that the use of the HALD method would enable researchers to reveal buried Stone Age sites, which were submerged as a consequence of the rising sea level since the Mesolithic. Thus, we suggest that the HALD method is a potentially cost-effective supplement or additional method for identifying locations for maritime excavations in order to investigate whether knapped lithic materials are present and to outline the geographic extent of such an area.

5. Conclusions

Teledyne Chirp III profiles acquired in Svanemøllen Harbor showed a large concentration of haystacks of various configurations, which were consistent throughout the three years of seismic recording.

Simple vibrocoring, carried out at locations below the haystacks, retrieved four human-knapped flint pieces that statistically corresponded to a density of around 230 pieces per square meter within the non-marine fine-grained sand/silt deposit of a postglacial age.

The correlation between the seismic profiles and the lithology of the cores showed that the haystacks are related to preserved shallow highs and basins/rivers in a fluvial or near-coastal setting.

Finite Element modeling showed that, regardless of their relatively small sizes, the flint pieces that were obtained in the cores were capable of producing sharp resonances.

This study demonstrates, for the first time, that the use of a high-resolution seismic instrument (Teledyne Chirp III) can produce acoustic responses to detect unknown submerged and buried Stone Age sites, at least at a depth of 1 m below the seafloor. This was confirmed by means of coring and FE modeling.

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