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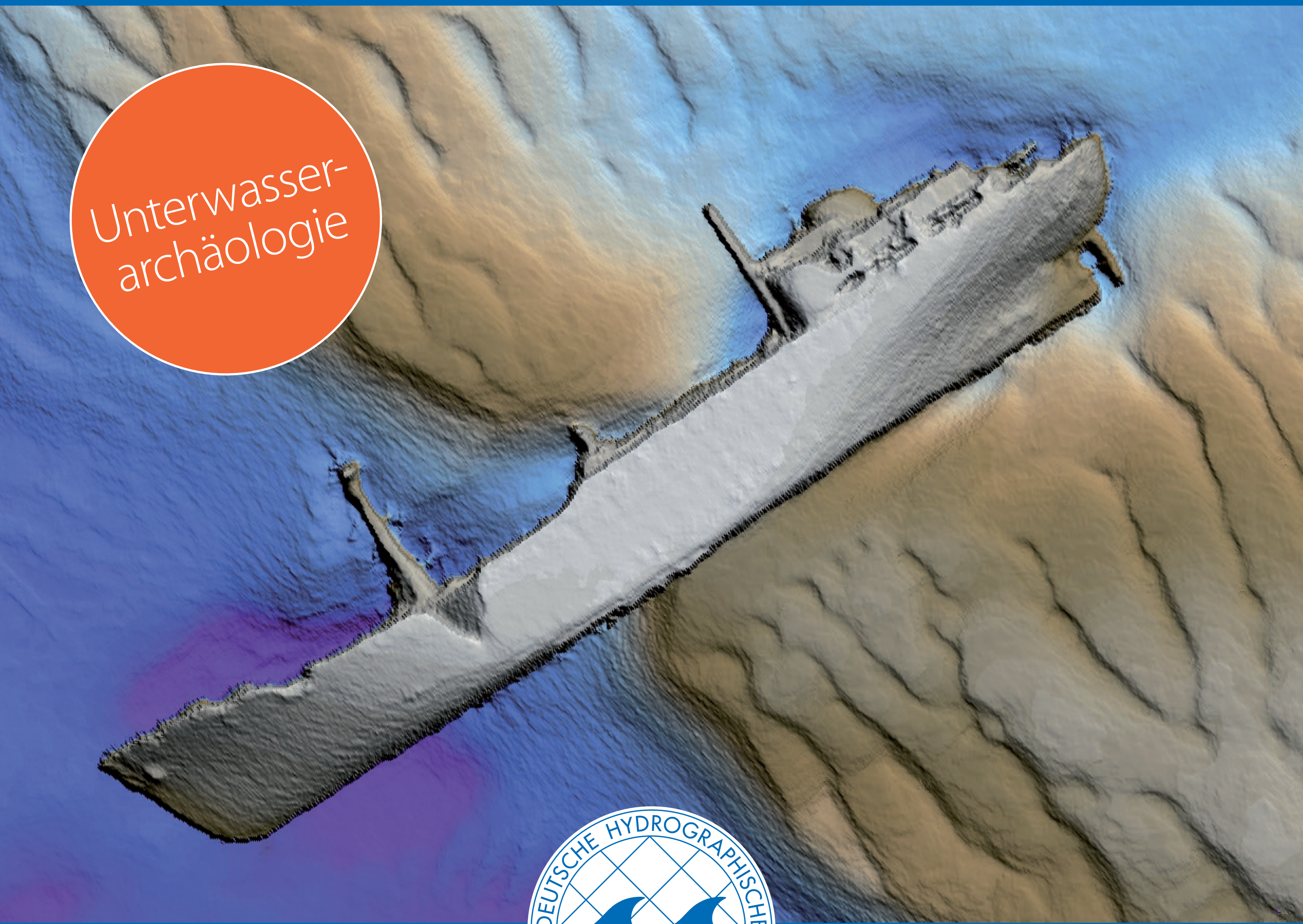

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Rapid investigation of shallow underwater archaeological sites with parametric multi-transducer sub-bottom profilers

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Non-invasive remote sensing techniques, such as shallow seismic acoustic imaging methods, are frequently used to explore palaeo-landscapes hidden below seabed, to survey and map underwater archaeological sites. This includes identification of buried archaeological artefacts, such as shipwrecks or artificial constructions from the past. A parametric multi-transducer sub-bottom profiler was applied to image the archaeological site of the medieval harbour of Puck, one of the largest medieval harbours in the Baltic Sea. The acquired high-resolution 3D shallow seismic dataset allowed the identification of a previously unknown and buried wooden shipwreck, to outline the harbour boundary of the medieval port and to trace the palaeo-channel of the local Plutnica River in the Puck Bay. This case study focuses on the results of the sub-bottom profiler survey, but data were fused with results from other remote underwater sensing surveys at the heritage site of Puck during an extensive investigation, such as multibeam and photogrammetric surveys.

parametric acoustics | sub-bottom profiler | medieval harbour | 3D shallow seismic | acoustic imaging
parametrische Akustik | Sedimentecholot | mittelalterlicher Hafen | 3D-Flachseismik | akustische Bildgebung

Nicht-invasive Fernerkundungstechniken, wie z. B. seismische Akustikbildgebungsverfahren, werden häufig eingesetzt, um unter dem Meeresboden verborgene Paläolandschaften zu erforschen und archäologische Unterwasserfundstätten zu vermessen und zu kartieren. Dazu gehört auch die Identifizierung archäologischer Artefakte, wie z. B. Schiffswracks oder künstlicher Konstruktionen aus der Vergangenheit. Ein parametrisches Mehrfachschwinger-Sedimentecholot wurde eingesetzt, um die archäologische Stätte des mittelalterlichen Hafens von Puck, einem der größten mittelalterlichen Häfen der Ostsee, abzubilden. Der erfasste hochauflösende 3D-Datensatz der seismischen Flachortung ermöglichte die Identifizierung eines bisher unbekannten und vergrabenen Holzschiffswracks, die Umrisse der Hafengrenze des mittelalterlichen Hafens zu skizzieren und den Paläokanal des lokalen Flusses Plutnica in der Puck-Bucht nachzuzeichnen. Diese Fallstudie konzentriert sich auf die Ergebnisse der Sedimentecholot-Untersuchung, aber die Daten wurden mit den Ergebnissen anderer Fernerkundungsuntersuchungen am Kulturerbeort Puck während einer umfangreichen Untersuchung, wie z. B. Fächerecholot- und photogrammetrischen Vermessungen, zusammengeführt.

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1 Introduction

Acoustical systems are frequently used for the detection of archaeological objects and structures embedded within the sediments of lakes, rivers and the open sea for many years (Quinn et al. 1997; Wunderlich et al. 2005; Missiaen 2010; Wilken et al. 2022). Typically, 2D reflection seismic systems, also referred to as sub-bottom profilers, are applied to survey archaeological sites line by line to detect signal anomalies within the cross-sectional data records, based on amplitude and phase variations or based on distinct morphological features. Different technologies are used for sound generation, such as linear acoustical transmission of continuous wave pulses (CW) in echo sounders and pingers, transient pulses in boomer and sparker systems and frequency modulated pulses (FM) in Chirp systems. The returning pulses may be either received by the same transducer used for the transmission or by separate receivers and hydrophones. Parametric (i.e. non-linear) sound pulse generation (CW, FM) was also applied for marine archaeological applications (Wunderlich et al. 2005). There is a high potential for this technology for such investigations due to the high mobility of parametric systems, improved resolution and the capability to work in very shallow waters (Missiaen et al. 2008). The challenges for the acoustical detection of buried archaeological features may be divided into system related technical limitations and environmental constraints. Such technical limitations are:

- The water depth is shallow, ranging from several metres to a few decimetres where low frequency linear sub-bottom profilers encounter issues due to signal ringing and broadening of the transmit pulse, causing high reverberation levels within the first few metres below the transducer and may prohibit the detection of the desired echo signals from shallow archaeological reflectors.
- The broadening of the transmit pulses in low-frequency linear acoustical systems causes a reduced vertical resolution of the acoustical data, particularly close to the water-sediment boundary, where the signal amplitudes are high.
- The acoustical footprint of the sub-bottom profiler is large compared to the spatial dimensions of the archaeological features which firstly reduces the achievable lateral resolution and secondly reduces the detectability of a reflector depending on signal amplitude variations.
- The sound beam pattern of directional linear acoustical sources exhibits side lobes which causes ambiguities in the echo signals.

Typical environmental constraints are:

- The appearance of multiple echo signals, particularly in shallow water, travelling two or more times between the sediment floor and water surface, which are then recorded and may disturb and mask signals of interest from a greater sub-seabed depth than the approximate water depth (also depending on sediment properties and transducer draft).
- The shape and orientation of embedded objects are irregular and may not cause a direct reflection of the sound waves towards the receiver and produce echo signals of low amplitude only.
- The spatial dimensions of archaeological features are typically small compared to the size of the investigation area, hence full coverage cannot be achieved during a line-by-line survey.
- The embedded archaeological objects are often made of materials (e.g. wood) with a low acoustical impedance contrast to adjacent sediments.
- The sediment properties may prohibit the required penetration due to the presence of dense sand, gravel and shells or layers of small gas bubbles caused by the decomposition of organic material

There are few technical approaches to 3D shallow-seismic reflection systems for archaeological applications, like commonly used systems in the oil and gas industry for the large-scale detection and mapping of reservoirs. Typically, a non-directional or wide beam acoustical source is combined with a relatively large focusing receiver array to create a dense dataset and to achieve better site coverage. This enables the generation of a 3D model of the sub-seabed morphology and embedded features, such as wrecks, harbour structures or remains of historical settlements (Plets et al. 2009; Mueller et al. 2013; Wilken et al. 2019). These systems typically require a high effort in data processing and must deal with acoustic diffraction within a complex medium of unknown sound velocities, with irregular morphologies and unresolvable travel paths, causing ambiguities and degrading the resolution. Acoustical beam steering and focussing with increasingly large angular offsets will also cause a broadening of the echo signals and an increase in side lobes with subsequent loss of resolution. These challenges were illustrated by Grøn and Boldreel (2014), where buried wooden posts of a landing pier at an archaeological site in Northern Germany could not be detected with such a 3D system, but clearly imaged with a common single-beam Chirp profiler. The above-mentioned challenges of large acoustical footprints during transmission and high reverberation levels for linear acoustical transmitters in shallow waters are valid for the fusion of multiple 2D seismic sections and the described 3D systems. The fusion of multiple and densely spaced 2D seismic sections into a three-dimensional data representation has been applied as well (Ravnås et al. 2023). Accordingly, the approach within this study was the acquisition of a dense dataset with high vertical and lateral resolution at a relatively small archaeological site by the combination of multiple parametric acoustic sources within a linear array, employing individual narrow sound beams with a small acoustical footprint for each transducer. This technique has successfully been applied to other shallow archaeological sites before, for example at the Roman and medieval site in the intertidal zone of Raversijde (Missiaen et al. 2018).

2 Archaeological site

The archaeological site of the medieval harbour of Puck is located at the inner northwestern part of Puck Bay within the wider basin of the Bay of Gdańsk (Fig. 1). The water depth of the site ranges from about 1 to 3 m. The site was discovered in 1977 by recreational divers (Stępień 1983). During first investigations, early medieval wrecks were discovered, as well as harbour relics and other traces of a settlement. Ultimately, one wreck was recovered and conserved by the Central Maritime Museum

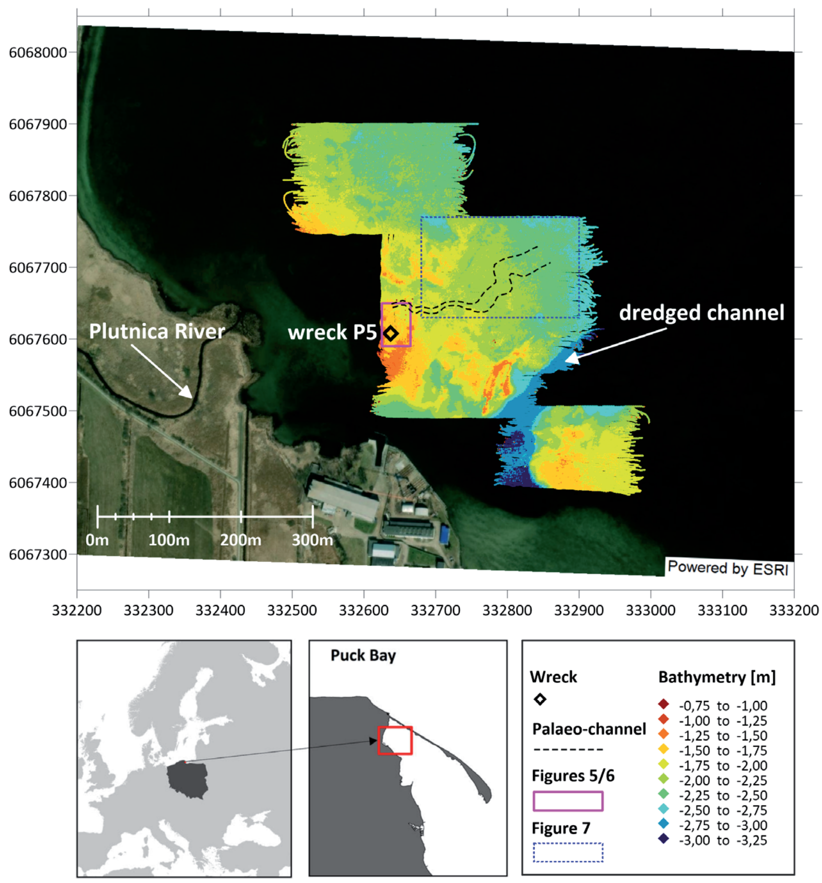

Fig. 1: Overview map of the study area with coloured depth soundings obtained from the 100-kHz high-frequency channel of the parametric system with a sounding density of 50 cm across track (bathymetry data points from two transducers). The location of wreck P5 is marked. The current course of the river Plutnica and the identified palaeo-channel are indicated. Coordinates are given in WGS-84 UTM Zone 34N

in Gdańsk (Szulta 2002). From dating results, three main phases of the harbour development were proposed after the pre-harbour Phase 0 (ranging from the Bronze Age to the 8th century). First, the harbour operational period Phase I (ranging from the 9th to the 10th century), second, the harbour operational period Phase II (occurring in the late 12th century) and finally, the harbour operational Phase III (ranging from the late 13th to the mid-14th century), already showing a significant shrinking in size (Popek 2020). Most of the relics from Phase II were destroyed by the construction and dredging of a channel towards the Puck Mechanical Works. The archaeologically mapped structures of Phase III constituted a jetty, which had a gap in it that formed the entrance to the harbour basin. The two wrecks laying at this entrance (the previously known and excavated wreck P3 and the latest discovered wreck P5) were dated to the 12th and 13th century and the stratigraphic arrangement suggested that both wrecks did not sink later than in the 1340s (Popek 2020). Currently, a vast number of wooden artefacts are visible above seabed (wooden poles, etc.), but others are fully buried below the sediments.

Fig. 2: Line array of four parametric transducers mounted on a small survey vessel. The transducer array has a length of 1 m

3 Methods

3.1 Data acquisition

A parametric sub-bottom profiler dataset was acquired during two surveys, one conducted in December 2018 (two days), the other one in March 2019 (three days), using the Innomar SES-2000 quattro system, bow mounted on a small survey boat (Fig. 2). The parametric acoustical system consisted of a transceiver unit and four transducers, arranged in a linear array. Each transducer had an active size of 155 mm by 155 mm and the distance between two transducer centre-points was 250 mm. Parametric systems produce two slightly different primary frequencies which generate new secondary frequencies (the sum and difference of the primary frequencies), which are received and analysed (Wunderlich et al. 2005). The Innomar system used in this study transmits primary frequencies around a centre frequency of 100 kHz, which generate secondary frequencies between 5 and 15 kHz. The half-power beam width (5 degrees at –3 dB) is very narrow and valid for both, the primary and the secondary frequency of 10 kHz used during acquisition. Due to the narrow sound beam the acoustical footprints of the individual transducers did not overlap significantly at the given water depth range of 1 m to 3 m (Fig. 3). Multiple transducers of the line array were used during reception to focus the energy of the echo signals. The transmitted pulse length was 100 µs and the pulse rate was circa 19 s^{-1} for each transducer. Positioning was realised with a dual-antenna differential GPS receiver utilising cellular network broadcasted correction data for the recording of centimetre accurate sounding positions, water level variations during the survey and true heading of the transducer array. A motion sensor was used for the recording of heave, roll and pitch motions of the transducer array. The site was divided into several regions of interest and covered by parallel survey lines at 1-m spacing (Fig. 1). Based on the intermittent transmission for the individual transducers, the ping rate and the survey speed, a data density of circa 10 cm per sounding was achieved along track. The average data density across track is 25 cm depending on the navigational offsets from the planned lines but for a single profile the coherent sounding distance is always 25 cm. Every survey line provided four seismic sections with a spacing of 25 cm. A survey speed of around 1.5 m/s to 2 m/s was used and about 700 short lines were acquired during 35 hours of survey with a total coverage of circa 0.13 km^2 (less than three hours per hectare). At the time of writing this case study, the Innomar system has been extended into a version with six transducers which can be arranged into a wider line array with an adjustable transducer spacing and advanced processing for an increased efficiency providing a swath width of up to 250 cm without compromising sounding density along the array.

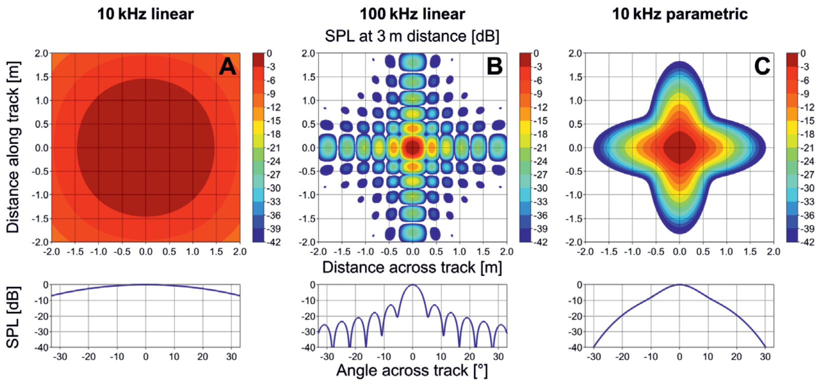

Fig. 3: Comparison of sound pressure levels (SPL) for equally sized transducers at a distance of 3 m, transmitting 10 kHz linear (A), 100 kHz linear (B) and 10 kHz parametric (C). The upper series shows the SPL distribution (acoustical footprint) in dB for an area of 2.0 m by 2.0 m. The lower series shows the SPL level in dB across the transducer centre for an angular range of ±30 degrees. Note the significant difference in footprint size between (A) and (C), as well as the lack of side lobes for (C)

3.2 Data processing

All sub-bottom acoustic records were band pass filtered (5 to 15 kHz) and the seismic sections were depth converted with a constant acoustic velocity of 1500 m/s. Static corrections of the water level variations were applied using the differential GPS data. Sounding positions were corrected for GPS antenna offsets including roll and pitch related deviations from vertical incident angles of the sound beam. Corrections of the heave were applied using the direct heave and roll measurements from the motion sensor. The signal-to-noise ratio was optimised by the application of digital filters in the time domain and a threshold table. An envelope function was applied prior to 3D processing and visualisation. Due to separate soundings per transducer with very narrow sound beams and an almost vertical incident angle towards the seafloor, the amount of diffraction was small and no extensive migration processing was required. Although the system acquires full waveform data, the processing of this dataset did not include processing in the frequency domain, the analysis of phase information or any seismic inversion techniques to determine sediment or material properties.

Due to the navigational constraints of the man-steered boat all combined soundings for a surveyed region resulted in a spatially irregular dataset and needed to be transformed and gridded into uniform lattices. For this, a grid cell size of 12.5 × 12.5 × 1 cm^3 was chosen and the system's resolution enabled the creation of time slices at 1-cm separation. The inverse distance to a power weighted average interpolation method was used as the main gridding method. Some data gaps remained within the seismic cubes even after interpolation due to occasionally significant deviations of the surveyed profiles from the planned lines. The uni-

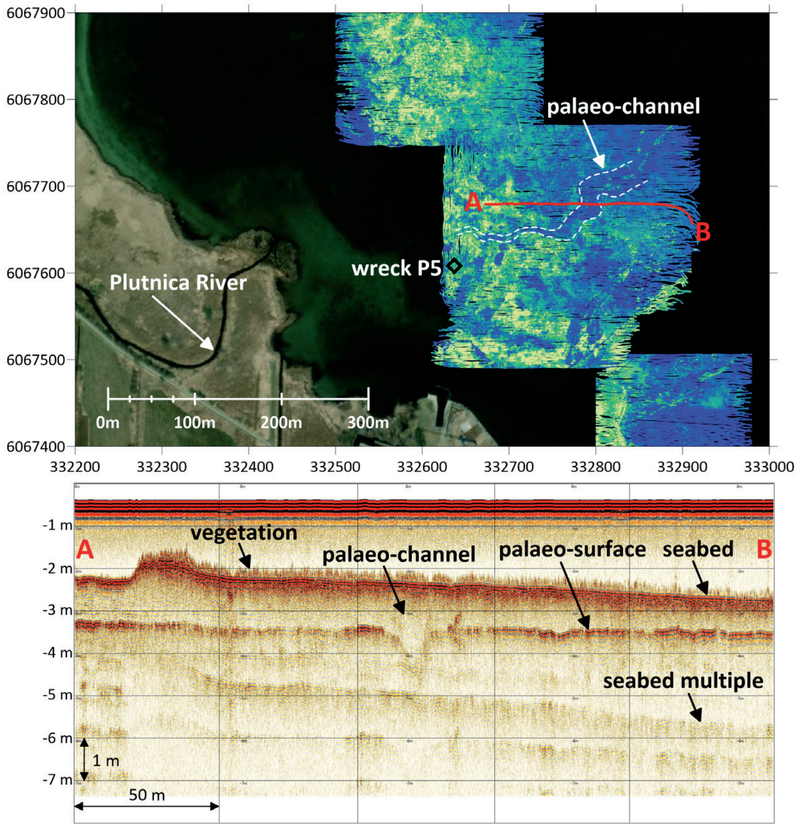

Fig. 4: Time slice from a depth of 330 cm below chart datum obtained from the combined 3D volume of all seismic sections acquired. This depth is the approximate level of a significant palaeo-surface present in the entire survey area. The seismic section (A–B) shows the seabed (with a 20 cm thick vegetation cover) and the palaeo-surface at about 1 m below seabed. The palaeo-channel cutting through the palaeo-surface is about 15 m wide at this location. The interpreted course of the palaeo-channel has been marked on the map

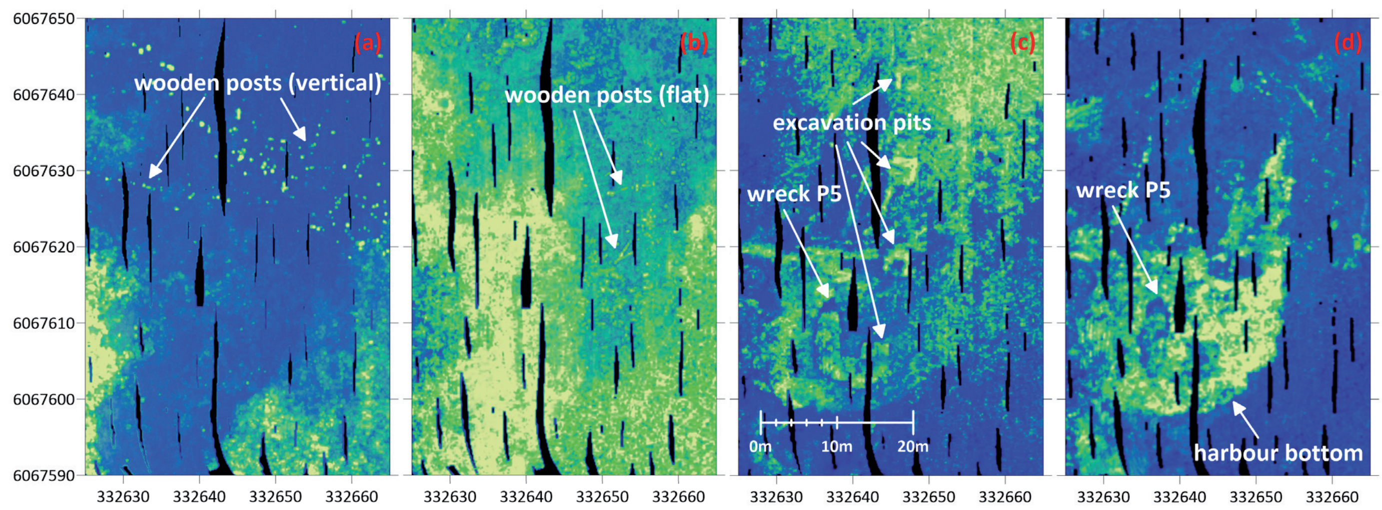

Fig. 5: Series of four time slices around the location of wreck P5 with increasing depths of 140 cm (a), 190 cm (b), 230 cm (c) and 260 cm (d) below chart datum. Subset (a) shows wooden posts standing vertically above seabed, subset (b) shows a few wooden posts laying on the seabed, subset (c) shows the outline of the buried wreck P5 (i.e. shadow from acoustical blanking) and some old excavation pits from the 1990s, subset (d) shows the outline of the buried wreck P5 at the depth level of the top of the harbour sediments

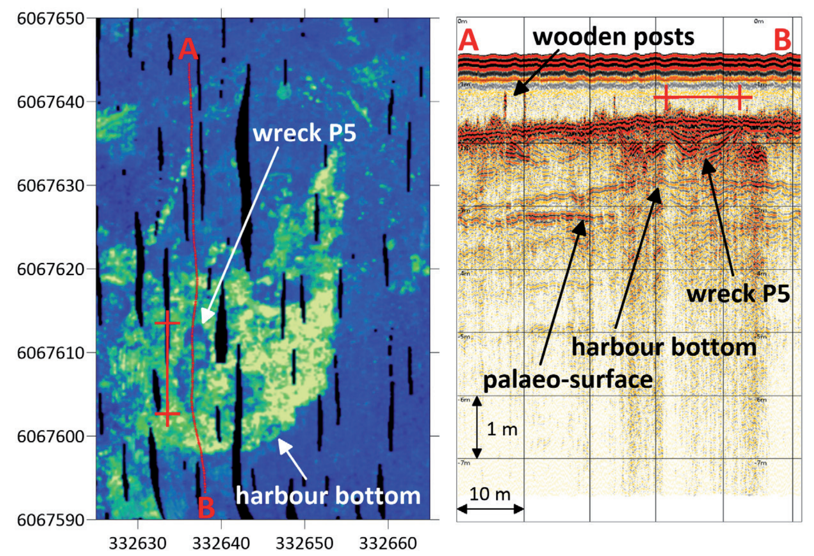

Fig. 6: Time slice around wreck P5 at 260 cm below chart datum at the depth of the top of the harbour sediments and vertical seismic section (A–B) through the wreck location (NS profile). Note the wooden posts, the layered sediment infill at the inner part of the wreck and the circa 50 cm thick harbour sediments deposited on top of the prominent palaeo-surface

form lattices were visualised in 3D with a volume renderer using an opacity and colour map transfer function. Clipping planes were applied to visualise and export time slices below the sediment floor (Fig. 4, Fig. 5 and Fig. 6). Such time slices were easily geo-referenced and imported into GIS packages to pick artefacts and outline structures or to combine them with other geo-spatial datasets, such as multibeam grids or underwater photogrammetry (Pydyn et al. 2021).

4 Results and discussion

The parametric acoustic profiling resulted in sediment penetration of up to 3 m, but typically around 2 m below the seabed. Due to the selected dominant frequency of 10 kHz and a bandwidth of circa 10 kHz, a vertical layer-to-layer resolution of better than 10 cm was achieved.

The bathymetry of the surveyed area showed varying depths between 1.5 and 2.5 m below chart datum, a dredged channel reached a depth of slightly more than 3 m. Some prominent irregularly formed ridges protrude the seabed surface NE of the dredged channel (Fig. 1). These outcropping structures were interpreted as marshlimnic sediments, consisting of peat and calcareous gyttja (Szymczak et al. 2014). Otherwise, fine sands dominate the bottom sediments of the bay in this area. About one to two metres below seabed a significant high amplitude reflector could be traced throughout the entire survey area and forms a significant palaeo-surface. It is interpreted as the Holocene transgression boundary (Littorina transgression), where the formerly freshwater lake and wetland surface was flooded and transformed into a shallow marine bay (Kramarska et al. 1995). The palaeo-surface reflector is generally flat, occasionally cut by channel features (Fig. 4) with various depths down to one metre below this surface as well as circular and irregular depressions of varying size and depth. Some of the circular depressions can be associated with ground water discharge processes as previously identified in the wider area of the Bay of Puck (Matziak et al. 2024), others may resemble small water filled hollows in the formerly wetland environment (Fig. 7). One prominent channel feature can be traced through the entire survey area in SW to NE direction and forms a meandering palaeo-channel. Some high amplitude reflections are recognisable within the sediments about 30 cm above this approximately

10 m (SW) to 25 m (NE) wide channel feature, following its course. Those two related features can clearly be interpreted as the palaeo-channel of the local Plutnica river (Fig. 4). The sediments above the interpreted palaeo-surface are interpreted as sandy sediments, occasionally silty and gas bearing, which is caused by the decay of organic materials transported into the bay by fluvial processes. Also, numerous and sometimes highly structured and complex features are recognisable within the sediment layer above the palaeo-surface. There is ongoing work to relate those features to their archaeological significance or to geological and depositional sources, such as buried fragments of peat. At the heritage site numerous vertical wooden poles, flat laying wooden poles, stones and other elevated features are recognisable above the seabed (Fig. 5).

On the western side of the survey area where Phase III of the medieval harbour is located, a shipwreck was identified just below the seafloor (Fig. 5). The shape of the wreck with a dimension of circa 10 m × 3 m is clearly seen in the horizontal time slices. A seismic section in NS direction through the wreck location from bow to stern (Fig. 6) indicates that the top of the wreck corpus corresponds with the seabed reflector. Therefore, the wreck shape itself is caused by acoustical blanking from wooden pieces at seabed level where high amplitudes are merged with the strong echoes of the seabed. The inside of the wreck is filled with some layered sediments. The time slice in Fig. 6 is at the same level as a distinct acoustical reflector which is circa 50 cm above the consistent palaeo-surface of the area. This high reflector is interpreted as the top of sediments which fill the previous harbour basin. The distinct outline of the harbour basin is recognisable (Fig. 6).

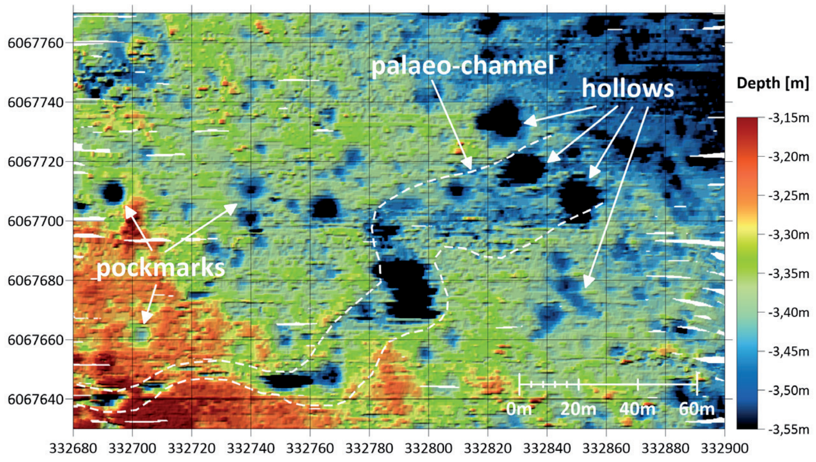

Fig. 7: Regional colour coded height map of the digitised palaeo-surface showing some distinct circular depressions, interpreted as pockmarks caused by groundwater discharge, whereas other irregular depressions are interpreted as formerly water-filled hollows in the pre-transgressional wetland environment. The palaeo-channel of the Plutnica river is clearly recognisable in the palaeo-surface

5 Conclusions

The arrangement of multiple transducers in a fixed linear array resulted in a dense and coherent dataset with good coverage, not achievable by normal line-per-line surveys with single-transducer systems. The use of a parametric sub-bottom profiler allowed to survey in water depths as shallow as one metre and image the sub-seabed morphology in high detail. A buried shipwreck could clearly be identified in the dataset. The lateral extent of the early-medieval harbour of Puck could clearly be outlined from the differences in the acoustical impedance of the sub-seabed sediments. The palaeo-channel of the local Plutnica river was detected and could be traced across the entire survey area covered. Some additional buried features were detected, and further archaeological work is required to assess their relationship to the different phases of the Puck harbour development. The Innomar quattro system with its parametric acoustic technology proved a valuable instrument for the high-resolution 3D imaging of buried archaeological artefacts and mapping palaeo-landscape features. //

Acknowledgements

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