Received: 23 August 2016 | Revised: 31 May 2017 | Accepted: 2 June 2017
DOI: 10.1002/gea.21656

RESEARCH ARTICLE

WILEY

Archaeological prospection of the nearshore and intertidal area using ultra-high resolution marine acoustic techniques: Results from a test study on the Belgian coast at Ostend-Raversijde

Tine Missiaen[1] | **Dimitris Evangelinos**[1*] | **Chloe Claerhout**[1†] | **Maikel De Clercq**[1] | **Marnix Pieters**[2] | **Ine Demerre**[2]

[1]Renard Centre of Marine Geology, Department of Geology and Soil Science, Ghent University, Ghent, Belgium

[2]Flemish Heritage Agency (Onroerend Erfgoed), Brussels, Belgium

Correspondence
Tine Missiaen, Flanders Marine Institute (VLIZ)
InnovOcean site, Wandelaarkaai 7 B-8400
Oostende, Belgium
Email: tine.missiaen@vliz.be

[*]Current address: Dimitris Evangelinos, University of Barcelona, Spain

[†]Current address: Chloe Claerhout, ADEDE Search & Recovery, Antwerp, Belgium

Scientific editing by Ian Moffat

Abstract

The coastal site of Ostend-Raversijde in Belgium is known for its archaeological artifacts, mainly from Roman and medieval times. In recent years, detailed geophysical and geotechnical investigations have been carried out here to test the efficiency of these techniques for geoarchaeological prospection of the subtidal and intertidal zone. Very high-resolution 2D subbottom profiling using a parametric echosounder evidenced a highly complex system of paleogullies and tidal channels, some of which can be linked to the medieval peninsula *Testerep* and the drowned settlement of *Walraversijde*. For the first time marine seismic and terrestrial electromagnetic induction (EMI) data were fully integrated in the same intertidal area. The parametric echosounder proved a highly effective tool to map the (partly excavated) peat layers and submerged landscape in high detail, even in extremely shallow water. Using a novel multitransducer parametric echosounder (SES-2000 Quattro), unique 3D imaging of the peat exploitation pattern was possible with unprecedented detail (submeter level). This sets a new standard for shallow water research and opens important new perspectives for geoarchaeological studies in nearshore areas.

KEYWORDS
intertidal geoarchaeology, marine acoustics, peat excavation, ultra-high resolution 3D

1 | INTRODUCTION

Shallow water environments are among the most dynamic elements comprising coastal zones, subject to rapid sedimentary fluxes and a prominent focus for human activities throughout (pre)history. However, these environments often pose major technological problems due to shallow water, fierce wave action, strong currents, and large tidal range. Moreover, nearshore and intertidal areas are often marked by the presence of shallow gas which may severely limit acoustic penetration (e.g., Anderson & Bryant, 1990; Missiaen, Murphy, Loncke, & Henriet, 2002a; Weschenfelder, Correa, Aliotta, Pereira, & De Vasconcellos, 2006; Wilkinson & Murphy, 2009). As a result, these areas are seldom investigated in a structured way, which is unfortunate since such land-sea transition areas are known to be rich in archaeological features (Bates, Bates, & Briant, 2007; Wilkinson & Murphy, 2009). Indeed, recent data show that the vast majority of known submerged prehistoric sites on the continental shelf are found in shallow waters (<10 m) (Flemming et al., 2014). However, these shallow water areas are also an important focus for infrastructure works (mainly related to coastal defense) which forms a major threat to submerged cultural remains (e.g., Dugan, Airoldi, Chapman, Walker, & Schlacher, 2011). It is therefore important to map and record this unique archaeological heritage before large parts of it will indeed be irreversibly lost.

Geophysical investigations, and in particular seismic imaging techniques, are effective tools for obtaining detailed descriptions of the shallow subsurface. Due to its reliability and resolving power, the seismic method is a major investigation tool in marine environmental and geotechnical studies, and increasingly also in archaeological studies (e.g., Fitch, Thomson, & Gaffney, 2005; Grøn, Jørgensen, & Hoffmann, 2007; Missiaen, 2010; Missiaen & Feller, 2008; Quinn, Cooper, & Williams, 2000). With an ever-increasing number of archaeological sites being discovered, the necessity for management and preservation of underwater cultural heritage is recognized internationally (Flemming et al., 2014). It is nowadays well recognized that buried artifacts are often best protected if left alone. Non-intrusive high-resolution techniques capable of locating and identifying archaeological remnants buried in the seabed, possibly also assessing their state of preservation/decay, are therefore becoming increasingly important.

The last decade has seen a significant development in very high resolution seismic acquisition in shallow water environments (e.g., Baradello & Carcione, 2008; Missiaen et al., 2008; Wunderlich, Wendt, & Müller, 2005). Careful attention with regard to source and receiver, geometrical arrangement, and operational conditions is crucial to obtain accurate images of the shallow subsurface (Missiaen, 2005). However, seismic investigations alone are not always able to provide all the answers. Different features, for instance hard layers or fine-grained deposits, may sometimes yield a similar reflectivity and can therefore be easily mistaken (Stevenson et al., 2002). Integrated use of complementary methods is often needed to provide optimal information on sedimentary architecture and buried features, as shown by an extensive geophysical study in The Netherlands at Verdronken Land van Saeftinge, an intertidal marsh area in the Westerschelde estuary (Missiaen, Slob, & Donselaar, 2008).

Recent studies increasingly focus on prehistoric archaeology, in particular the impact of human activities on submerged terrestrial landscapes (e.g., Bates et al., 2013; Hijma, Cohen, Roebroeks, Westerhoff, & Busschers, 2012; Laffert et al., 2006; Westley et al., 2004). The reconstruction of paleolandscapes is not only an important requirement to help understand their archaeological potential (such as submerged or reworked material) but it may also provide key information on human evolution. Sea levels were generally much lower in the Late Pleistocene and early Holocen times, and only reached near-present levels during the later part of the Holocene. Prime targets for seismic studies include relief features such as buried paleochannel systems and associated terrace features. Another good target is organic deposits such as peat layers, since these are good indicators of past coastlines and show a high preservation potential. More knowledge on the evolution of islands and coastal barriers in the past, how they were formed, and how they disappeared, will moreover provide a better grip on future construction works in the nearshore zone and the effects these will have on the present coastline.

In Belgium little attention has been paid to submerged archaeological sites and remnants or submarine landscapes and (pre)historic coastlines. Yet it is this submerged coastal landscape that provides important and exciting windows on prehistoric and historic human activities. In recent years, a number of investigations have been carried out along the Belgian coast in order to test the efficiency of marine seismic techniques for geoarchaeological prospection of nearshore and intertidal areas. The main test area is located at Raversijde, roughly 2 km west of Ostend (Fig. 1). This site is well known for its artifacts and structures dating from prehistoric to medieval times, including a Roman embankment, remnants of a medieval fishing village, and intensive peat and salt exploitation (Pieters, Baeteman, Bastiaens, Bollen, & Clogg, 2013). Most of these archaeological remains were still visible on the intertidal beach up to 1970s but are now buried a few meters below the sand due to extensive beach suppletion works and the construction of groins.

FIGURE 1 Overview map of the study area (background map from Google Earth ©). The red rectangle marks area of seismic investigations (see Figure 2). The black line marks the (presumed) location of the medieval peninsula 'Testerep' and associated gully (modified after Zeebroek et al., 2002). The exact seaward boundary of the peninsula is uncertain [Color figure can be viewed at wileyonlinelibrary.com]

The main goal of the investigations described in this paper was twofold: (1) to map paleochannels, submerged seafloor terraces, and other buried structures in order to gain more insight in the late Holocene evolution of the area (i.e., the last 5000 years), including the drowned medieval peninsula *Testerep*; and (2) to identify small-scale archaeological artifacts and relics of human occupation and/or human activities. The main technique used was very high resolution marine subbottom profiling (applied during high tide), which was complemented by terrestrial electromagnetic induction (EMI) measurements as well as cone penetration tests (CPT) and shallow cores (obtained during low tide). The use of a novel multitransducer parametric echosounder allowed 3D imaging of the subbottom in very high detail (dm resolution), and sets new standards for shallow water geoarchaeological research.

2 | HOLOCENE HISTORY OF THE STUDY AREA

The study area of Ostend-Raversijde is located in the central part of the Belgian coast (Fig. 1). The coastline here consists of a slightly seaward sloping sandy beach (mean slope of about 1.7%), directly bordered by a large dike behind which dunes locally stretch out. The actual coastline has its roots in the Middle Ages, when huge embankment activities were conducted. Shallow sediments are made up of alternating sand, peat, silt, and clay layers that reflect the complex history of the Holocene during which marsh-like environments, sand dunes, and intertidal mud- and sand-flats alternated. Major controlling factors in landscape evolution were changes in sea level rise, paleotopography, accommodation space, and its balance with sediment supply (Baeteman, Beets, & Van Strydonck, 1999; Beets & van der Spek, 2000).

At the onset of the Holocene (*ca.* 11,000 cal. yr B.P.) the Belgian coastline was located roughly 20–30 km offshore (Mathys, 2009). A large dune barrier system protected the coastal plain which consisted of a large (inter)tidal flat environment marked by constantly changing tidal channels, tidal flats, and marshes (Beets & van der Spek, 2000; Mathys, 2009) but also tidal basins such as the IJzer valley (Baeteman et al., 1999). Initial rapid sea level rise (on average 7 m/ky) caused a rapid inland shift, and by 7500 cal. yr B.P. the coastline had reached a position close to the present-day boundary of the coastal plain (Baeteman & Denys, 1997).

As sea level rise started to slow down around 7500–7000 cal. yr B.P. (to an average 2.5 m/ky) the landward shift stopped; moreover, sediment supply now outran the creation of accommodation space by sea-level rise and tidal gullies became rapidly filled (Baeteman et al., 1999). Peat started to develop on former tidal flats which were now out of reach of tidal flooding. Tidal channels shifted rapidly which resulted in an alternation of thin peat layers and tidal flat deposits dated between *ca.* 7800 and 5500 cal. yr B.P. (Baeteman et al., 1999).

Around 5500–5000 cal. yr B.P. sea level rise further slowed to 0.7 m/ky, and due to a lack of accommodation space the shoreline started to prograde. The coastal plain changed into a freshwater marsh and a thick peat layer (so-called “surface peat”) was deposited (Baeteman et al., 1999). Tidal channels filled with silt and served as drainage for the freshwater marsh (Baeteman, 2005). After 3000 cal. yr B.P. peat growth slowed. Tidal channels cutting through the marsh became eroded, most likely by enhanced precipitation run off from the hinterland (due to climate change and deforestation) (Baeteman, 2005). At the fringes of the tidal channels the peat eroded completely, causing drainage and compaction of the peat layer and subsequent lowering of the ground surface. This resulted in a significant vertical accommodation space for tidal waters, and the fresh water marsh was converted to an intertidal area again.

During Roman times the sea was located a few km offshore from today's coastline, sandy dunes protecting the marsh-like hinterland which was crossed by creeks and silted-up gullies with low tidal activity (Baeteman, 2007). The coastal area was intensely exploited for salt and peat, but permanent habitation at that time seems unlikely (Thoen, 1978). With the increasing influence of the sea (also enhanced by local subsidence of the land related to peat excavation) and retreat of Roman troops around A.D. 300, salt and peat production largely ended. During early medieval times gradual reclamation of the area started and dikes were built (Tys, 2013). Together with artificial drainage and renewed peat digging, this resulted in lowering of the land surface, creating large areas vulnerable to flooding (Vos & Van Heeringen, 1997).

During the Middle Ages, the study area was part of a marsh-like peninsula (so-called *Testerep*), separated from the mainland by a large E-W oriented tidal gully (so-called *Testerep*-gully) (Zeebroek, Tys, Pieters, & Baeteman, 2002) (Fig. 1). In the 13th century, the fishing settlement of *Walraversijde* was established on the peninsula, close to a local tidal gully or so-called *Yde* (hence the name) (Tys & Pieters, 2009). Drainage works and peat exploitation lowered the land, and as a result large parts of *Testerep* were flooded after fierce winter storms in the late 13th and early 14th centuries, also partly destroying *Walraversijde*. The village was definitely abandoned in the 15th century and relocated behind a new dike (so-called *Graaf Jans dike*, see Fig. 2) (Tys & Pieters, 2009).

3 | ARCHAEOLOGICAL ARTIFACTS

Since the late 19th century, many archaeological traces and structures have been documented in the study area (Pieters et al., 2010). Prehistoric artifacts include a large number of flints ranging from 13,000 cal. yr B.P. (final Paleolithic) to 4000 cal. yr B.P. (early Bronze period) (Chocqueel, 1950; De Bie, 2013). One of the marked findings involves a wooden paddle discovered in the surface peat layer, dated between 6300 and 2635 cal. yr B.P. (Baeteman, 2007; Pieters et al., 2013). Roman artifacts include pottery and refuse pits but also numerous remnants of peat and salt exploitation (Pieters et al., 2010; Thoen, 1978). In the 1930s and 1940s, remnants of houses (bricks and wood) were documented on various locations of the beach at Raversijde. The remnants were dated to the early 14th century and can most likely be linked to the drowned fishing village of *Walraversijde* (Chocqueel, 1950). Other medieval artifacts found on the beach include coins and ceramics (Pieters et al., 2013).

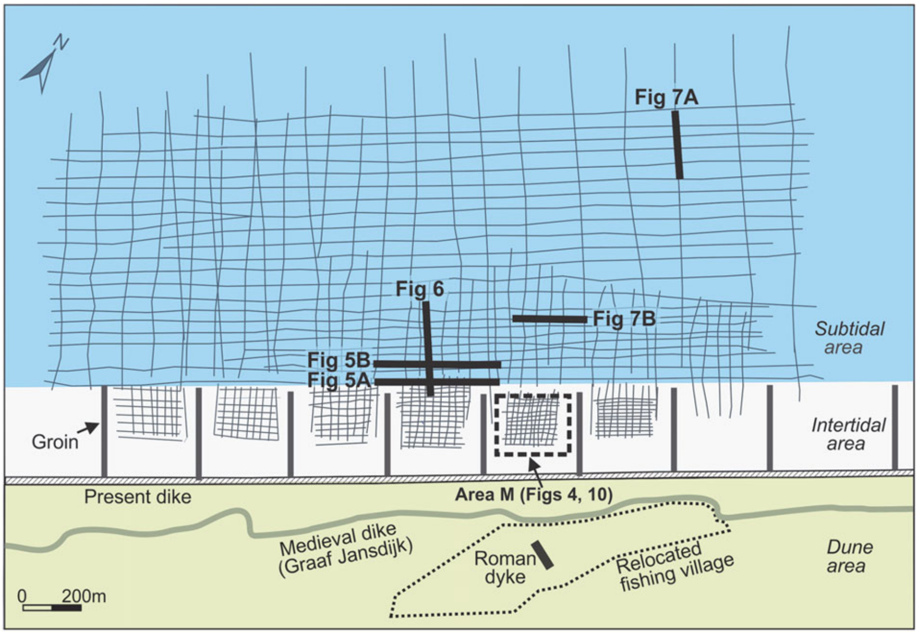

FIGURE 2 Overview map of the seismic network (thin black lines) recorded at Raversijde. Groins are marked by thick gray lines. The black dashed rectangle marks intertidal zone M with detailed 2D/3D seismic measurements and ground-truth data (see Figures 4 and 10). The short black line marks the Roman dike fragment found inland. The black dashed line behind the medieval dike marks the extension of the relocated fishing village [Color figure can be viewed at wileyonlinelibrary.com]

Large-scale archaeological investigations were conducted between 1992 and 2005 behind the *Graaf Jans dike* where remnants of the re-located fishing settlement were discovered (see Fig. 2) (Pieters et al., 2013). Remnants of a Roman dike (2nd century A.D.) were also detected, roughly 12 m wide and 1 m high and with a total length of 110 m (Pieters, 1993). The dike is built of stacked clay blocks, reinforced on its western side by peat slabs. Its orientation, roughly perpendicular to the coastline, suggests that it most likely embanked a tidal gully stretching far inland. Similar stacked clay and peat blocks were found on the beach in the 1970s (Pieters et al., 2010, 2013). Unfortunately, the exact location remains unknown, so any link with the Roman dike is therefore speculative.

3.1 | Salt and peat exploitation

Artifacts related to salt and peat exploitation activities, discovered on the beach at Raversijde, include remnants of extraction pits and trench system (Fig. 3). The saltpans were occasionally lined by small wooden poles (5–10 cm diameter). In order to extract salt, an intricate drainage system of trenches was constructed to guide seawater via trenches through a number of shallow basins (saltpans) where the water slowly evaporated, leaving behind a thick layer of salt. In order to boil the latter into salt blocks (so-called ‘’briquetage”) a lot of fuel was needed, and it seems most likely that peat was used as fuel for salt ovens, although it may also have been used as source of salt since this peat had a high salt content (van den Broeke, 1996). Radiocarbon dating of one of the wooden structures related with salt production indicated an age going back to the 1st century A.D. (Thoen, 1978).

Roman peat extraction pits found behind the present dunes at Raversijde indicate that a peat layer, often a few cm thick, was left intact at the bottom of the pit, most likely to prevent groundwater from entering and/or mixing of organic material with mineral material during the extraction (Pieters et al., 2013). The fact that the pits were not filled with waste (i.e., immediately after digging) but instead filled with tidal sediments indicates the absence, at least locally, of an area in agricultural use (Pieters, 1993). It is believed that these Roman peat extraction pits did not affect the pattern of newly formed tidal channels, unlike the case in Zeeland where channels often followed the courses of Roman artificial drainage (Baeteman, 2007; Vos & van Heeringen, 1997).

Investigations in the polder area of Raversijde indicate that peat (where not excavated) generally occurs between −0.2 and +1.6 m TAW (Belgian water level reference level "Tweede Algemene Waterpassing”), with a thickness ranging from 0.2 to 1.6 m. The top of the peat often shows clear evidence of erosion. Vertical cracks reaching the underlying sediments suggest a phase of total desiccation (Pieters, Baeteman, Demiddele, & Ervynck, 1998). Radiocarbon dating of the top of the peat yielded ages between 2207 and 2744 cal. yr B.P. (Baeteman, 2007). The peat is covered by a thin clayey deposit (<0.5 m) and a thick sequence of clay and sand (Pieters et al., 2013).

In the late 1970s, groins were constructed at regular intervals along the Belgian coast to protect the beaches from erosion. This resulted in sand accretion, further enhanced by additional sand suppletion works on the beaches. As a result, archaeological features are now buried beneath a sand cover of at least 0.5–1 m thick, locally more. In recent years, the beach of Raversijde is also used for controlled explosions of old munitions (from WW1 and WW2) found on nearby beaches. This forms a major threat to archaeological remains, and most likely these controlled explosions are the main cause for large round pits observed on old aerial photographs (see Fig. 3 bottom).

FIGURE 3 Top: Remnants of peat digging exposed on the beach of Raversijde around 1970. Bottom: Aerial photo of the beach at Raversijde around 1970 showing different patterns of peat extraction. The large circular pits are likely related to the impact of explosions (Photos E. Cools) [Color figure can be viewed at wileyonlinelibrary.com]

4 | DATA ACQUISITION AND PROCESSING

4.1 | 2D seismic data

Notwithstanding recent sand accretion, marine investigations in most of the intertidal area were still possible due to large variation of the local tide (4–5 m). A number of high-resolution 2D marine seismic surveys were conducted between 2007 and 2014 at Raversijde. Recorded data included a large-scale network in the subtidal nearshore area (up to 1.2 km from the shore, line spacing 50–100 m, water depth 4–10 m) and a number of smaller scale networks in intertidal zones between groins (line spacing ~20 m, water depth $\leq$4 m) (see Fig. 2). It was hoped that these data could provide more insight into the distribution of nearshore paleogullies and possible remnants of ancient coastal defense structures. A detailed seismic survey with 5–10 m line spacing (Fig. 4, left) was carried out in one of the intertidal areas (area M, for location see Fig. 2) where peat exploitation was expected based on old photographs.

2D seismic surveys were conducted with the SES-2000 parametric echosounder (PES) (1). In recent years, this source has been used successfully in a wide range of geotechnical, environmental, and archaeological studies (e.g., Missiaen & Feller, 2008; Missiaen, Demerre, & Verrijken, 2012; Missiaen & Noppe, 2010; Zeebroek et al., 2009). The source simultaneously transmits two signals of slightly different high frequencies (typically 100 and 110 kHz) at high sound pressures; non-linear interactions generate new frequencies in the water, one of them being the difference frequency (between 6 and 14 kHz), which has a bandwidth similar to the primary frequency signal (100 kHz) but whose low frequency allows penetration into the seafloor. The directivity of the difference frequency has virtually no side lobes during transmission (Wunderlich et al., 2005). Penetration depth below the seafloor can reach up to a few tens of meters in soft (mud rich) sediments, whereas in sandier sediments it is often limited to 5–10 m (Missiaen & Noppe, 2010; Missiaen et al., 2012).

Notwithstanding the small transducer size (~20 × 20 cm), the PES allows transmission of narrow beams with short pulse length at low frequencies. This does not only result in a high vertical and horizontal resolution (cm/dm range), but also increases the signal-to-noise ratio for detection of weak reflectors (Wunderlich et al., 2005). The narrow beam width ($\pm 1.8°$, independent of frequency) allows detection of small buried structures, whereas the short pulse length (0.07–1 ms) allows to work in very shallow water (<1 m) (Wunderlich & Müller, 2003). Contrary to conventional echosounders, which often record only the envelope of the acoustic signal, the full waveform is also recorded here. This allows detection of phase inversions (negative peaks in the reflectivity series), typical for the presence of peat and wood buried in fine-grained sediments (Bull, Quinn, & Dix, 1998; Plets, Dix, Bastos, & Best, 2007; Quinn, Bull, & Dix, 1997). However, it should be noted that a negative reflection coefficient can also be a sign of gas accumulation (Judd & Hovland, 1992).

For the intertidal surveys a catamaran vessel with small draft was used. The echosounder was attached onto an iron pole fastened to the side of the ship. The fast pulse rate (up to 40 pulses/s), combined with low vessel speed (2–3 knots), resulted in high lateral coverage (data points every 5–10 cm in the inline direction). A motion sensor was used to filter out wave movement. Positioning was done using a DGPS antenna with an overall accuracy of 1–5 m. The echosounder was operated with a low frequency ranging between 8 and 12 kHz and pulse length of 100 μs, which resulted in a vertical resolution of 5–10 cm. Data processing was straightforward and included band pass filtering, stacking (where needed), smoothing, and time variable gain. Tidal correction was a crucial step and involved tide data obtained from a nearby tidal gauge at Ostend and interpolated for the survey area. All seismic data were corrected to a common level (TAW). Time to depth conversion was done using a sound velocity of 1550 m/s.

4.2 | 3D Seismic Data

Data acquisition as described above results in a 2-dimensional image of the subseafloor. Through data interpolation a pseudo-3D image can be constructed that may allow adequate imaging of large-scale features (10–100 m in size) but which is insufficient for small archaeological artifacts or structures ($\leq$1 m range). The latter can only be imaged correctly using true 3-dimensional imaging. Such very high

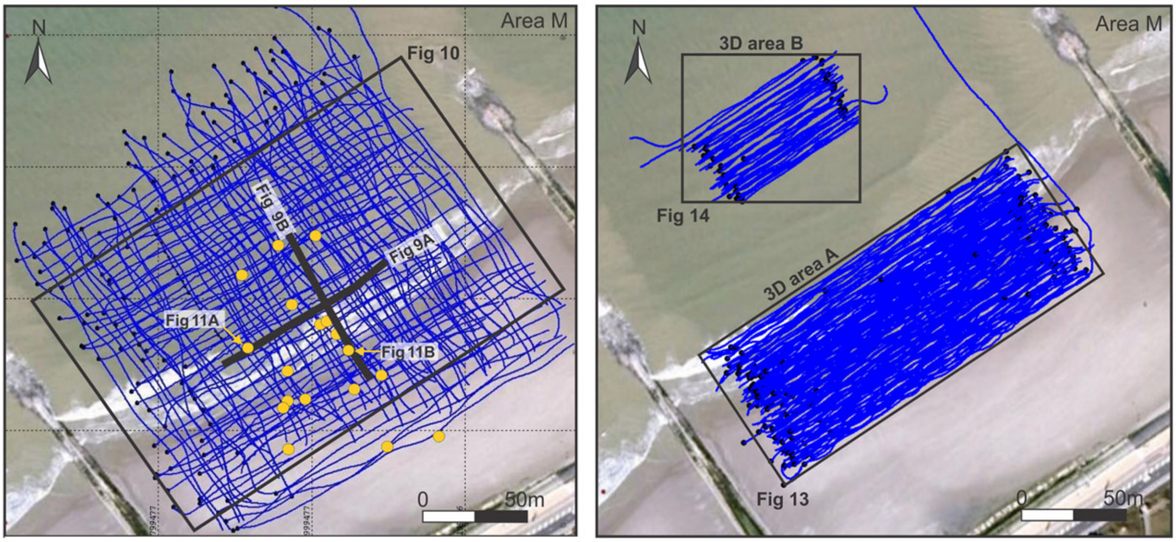

FIGURE 4 Detailed seismic networks recorded in the intertidal zone M (for location see Figure 2). Left: dense 2D network recorded in 2012 with the parametric echosounder SES-2000. Thick black lines mark the seismic profiles shown in Figure 9. Yellow circles indicate core and CPT locations. Yellow arrows mark the two CPT/cores shown in Figure 11. Right: 3D networks recorded in 2015 with the multitransducer parametric echosounder SES-2000 *Quattro* [Color figure can be viewed at wileyonlinelibrary.com]

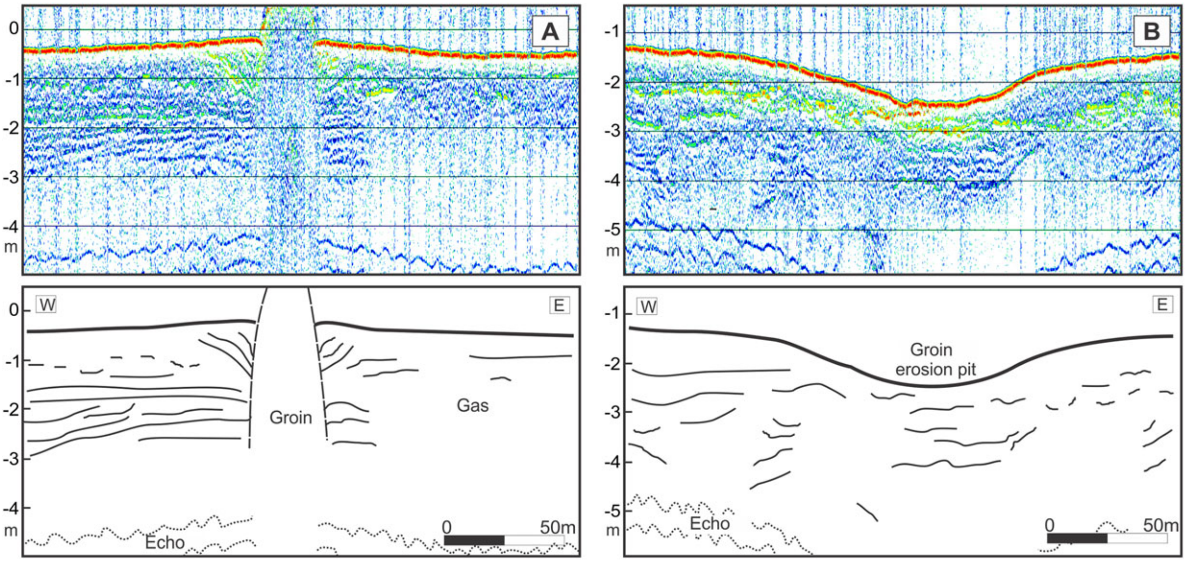

FIGURE 5 Seismic profiles and interpreted line-drawings from the subtidal area showing (A) a breakwater construction (groin) and (B) associated erosion pit. For location of the profiles see Figure 2. Depth in meters TAW [Color figure can be viewed at wileyonlinelibrary.com]

resolution true 3D seismic imaging however is a complex operation, not only with regard to the data acquisition but also the often intensive and time-consuming data processing (e.g., Gutowski et al., 2008; Marsset, Missiaen, Noble, Versteeg, & Henriet, 1998; Missiaen, Versteeg, & Henriet, 2002b; Müller et al., 2009). Moreover, in extremely shallow areas (<3 m water depth) application of VHR 3D seismics is problematic due to physical constraints placed on sampling and positioning accuracy (Missiaen, 2005).

In recent years, a novel multitransducer parametric echosounder system was developed (SES-2000 *Quattro)* specifically designed for 3D seismic applications with very high data density in very shallow water. The system consists of four individual transducers fixed in a line array (1). Total width of the array is 1 m (25 cm spacing between transducers), which implies a line spacing of ~1 m to achieve full coverage. Fix mounted transducers largely simplify volume rendering (3D) processing, since time-consuming migration and beam forming processing are no longer required. Together with the relatively simple acquisition (no complex floating platform) it makes this system particularly fit for rapid, cost-efficient 3D site surveys in shallow water (<15 m). An additional advantage is the flexible configuration of the individual transducers, which also allows for a 2D single beam set-up (e.g., four transducers configured into a quadrangle and acting as a single transducer), resulting in higher energy and deeper penetration, or a pseudo-3D dual beam set-up (two transducers combined as a single transducer), which will also increase the energy level and has an intermediate data density (maximum water depth ~20 m).

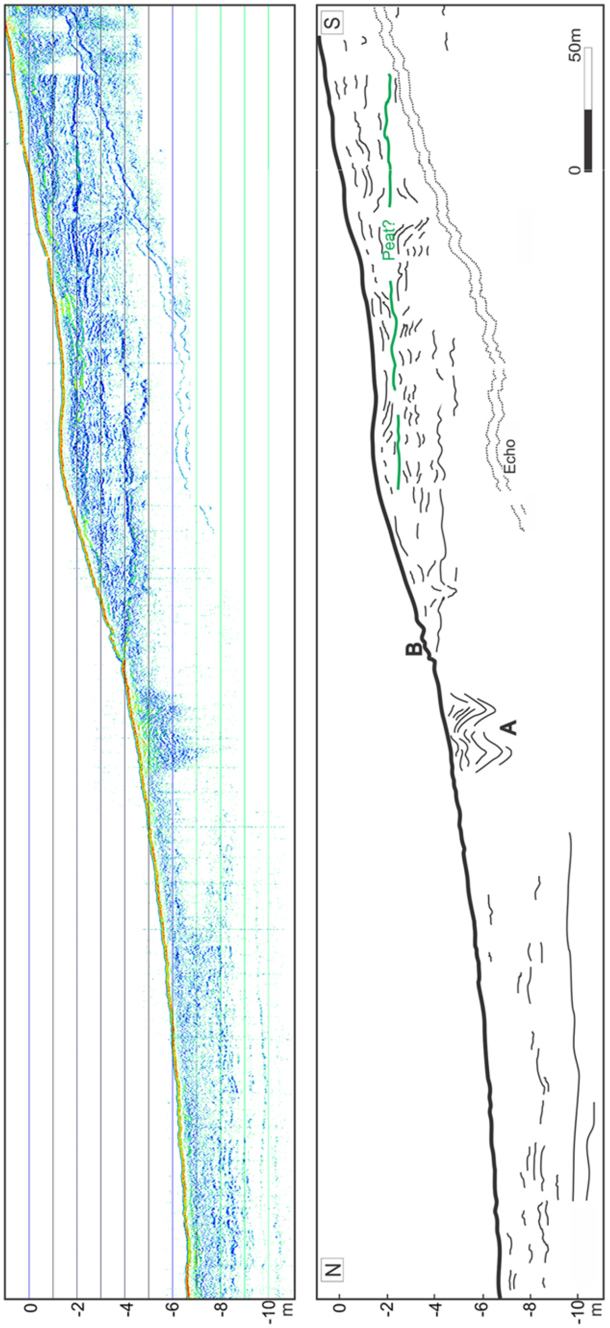

FIGURE 6 Seismic profile and interpreted line-drawing from the subtidal area showing the step-like form in the seafloor topography creating a distinct terrace. The foot of the terrace is marked by a shallow paleogully (locally two intertwining gullies) oriented parallel to the shore (A), and small irregularities on the seabed (B). The depth of the green reflector suggests a thin peat layer. For location of the profile see Figure 2. Depth in meters TAW [Color figure can be viewed at wileyonlinelibrary.com]

In May 2015, a test survey was conducted with the multitransducer parametric echosounder (in 3D line array set-up) in intertidal zone M at Raversijde (see Fig. 2). A line spacing of 1 m or less was envisaged but this was difficult due to currents and waves, and therefore it was decided to record two separate networks over the same area (during two consecutive days) and afterwards merge the two data sets. Total survey time involved was 6 to 7 hours. The multitransducer system was operated with a low frequency of 10 kHz and pulse length of 100 μs, with a resulting vertical layer to layer resolution of 10 cm. A recording window of 7 meters was used and each of the individual transducers was operated with ~ 17 pings per second. Simultaneously recorded multibeam data allowed to map the seafloor in high detail and detect possible exposed features.

Ultra-high resolution 3D data modeling requires highly accurate navigation and positioning. Therefore, a state-of-the-art motion sensor (Octans) with high update rate (50 Hz) was used in combination with RTK positioning which allowed cm accuracy (x,y,z) with an update rate of 10 Hz. Transducer, motion sensor, and GPS antenna offsets were known with centimeter precision. During offline data processing, positional offsets were corrected by using the RTK data and true heading sensor data. Two data volumes were recorded in intertidal zone M (Fig. 4, right): a larger volume (3D area A) of roughly 200 × 80 m in the nearshore part, and a smaller volume (3D area B) of roughly 100 × 60 m slightly more offshore. Thanks to the high line coverage, a cell size of 25 × 20 × 1 cm was possible, although still some small gaps small gaps remained within the acquired data set as can be seen in Figure 4.

4.3 | Additional ground-truth data (cores, CPT, EMI)

In 2012, an EMI test survey was conducted on the beach at low tide in intertidal zone M (Fig. 2) (Delefortrie et al., 2014). Previous studies have shown the suitability of the EMI method for the detection of peat excavation in polder areas (e.g., De Smedt et al., 2013; Verhegge, Missiaen, & Crombé, 2016). For the measurements at Raversijde, a Dualem-21S sensor was used with three different coil sizes (depth penetration of the different coils, respectively, 0.5, 1, and 3 m). The sensor was dragged over the beach by a four-wheel all terrain vehicle. Main goal of this survey was to corroborate the presence/absence of peat in the shallow subsoil (as peat is known to increase the conductivity). An important step in the EMI data processing was to filter out the variation in salinity and/or groundwater level in the intertidal zone. More details and information on this EMI survey are discussed in the paper by Delefortrie et al. (2014).

Ground-truth for the geophysical data was provided by shallow hand cores, using a combination of conventional augering devices (e.g., pulse) and a so-called "van der Staay" suction corer especially designed for water-logged sandy sediments (Wallinga & van der Staay, 1999). In all, 16 short cores were obtained, with depths varying between 1.5 and 3.5 m (average depth ±2 m). Coring on the intertidal beach proved very difficult and time consuming, due to the variable lithology (dense peat and clay layers interfingering with water saturated sand). As a result, the quality of the core samples was often poor. No dating was done on the core samples.

Electrical CPT were conducted at 13 locations (average depth 10 m). The (partially overlapping) location of cores and CPTs is shown in Figure 4, left. The CPT probe measured cone tip resistance (qc) and sleeve friction (fs). Both are related to soil type and moisture content, and the ratio of sleeve friction and cone resistance (friction ratio Rf) can be used to classify the soil (Lunne, Robertson, & Powell, 1997). In general, CPT logs allow good distinction

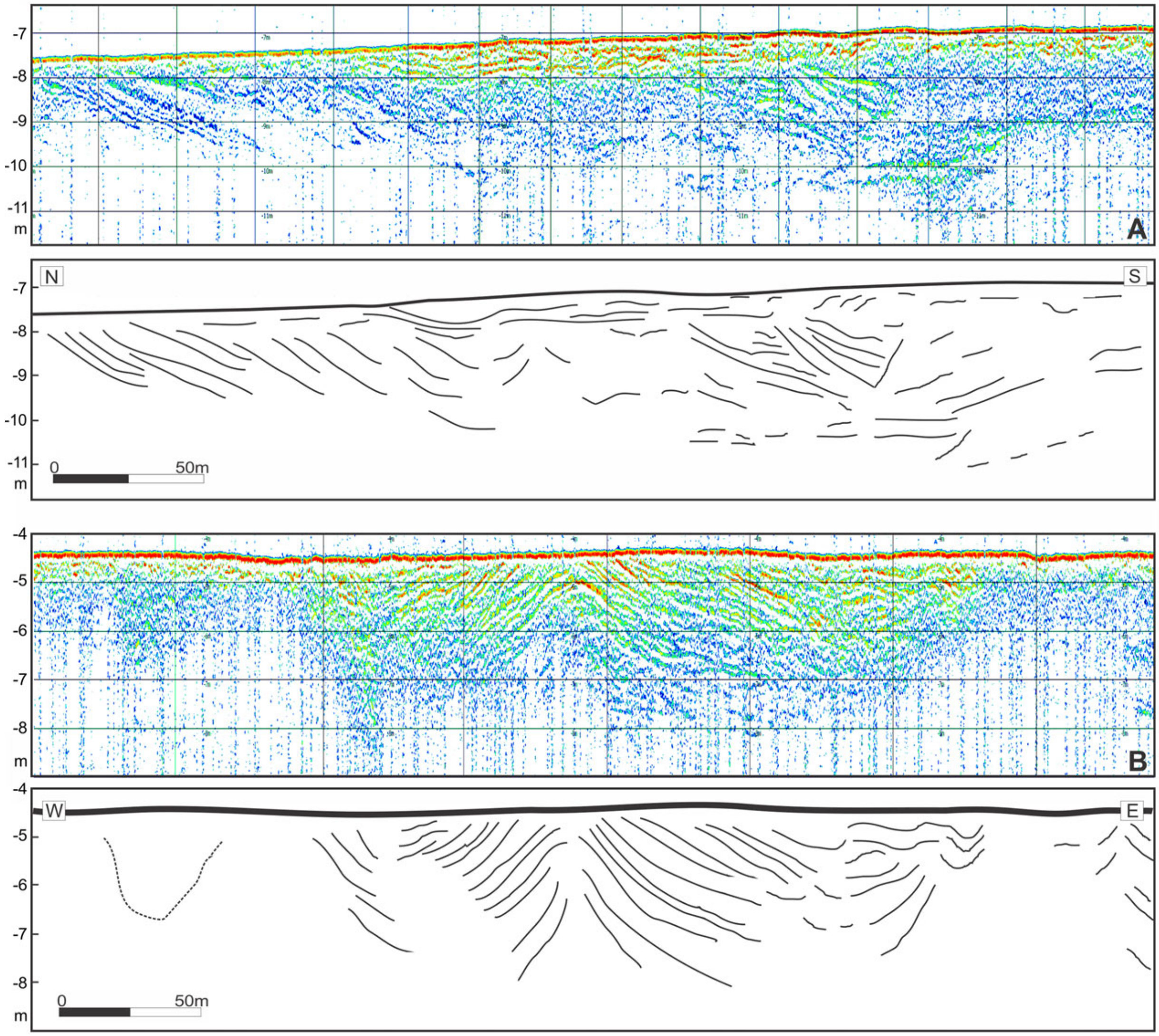

FIGURE 7 Two seismic profiles and interpreted line-drawings from the subtidal area illustrating the complex pattern of paleochannels. For location of the profiles see Figure 2. Depth in meters TAW [Color figure can be viewed at wileyonlinelibrary.com]

between sand, clay, and peat deposits (Missiaen, Verhegge, Heirman, & Crombé, 2015).

5 | RESULTS AND DISCUSSION

5.1 | Seafloor topography

On the whole, the seafloor topography is relatively smooth, except for the groins which stand out clearly on the most nearshore subtidal seismic lines (Fig. 5A). The groins are surrounded by wide erosion pits of over 1 m deep which extend up to 100 m away on the seaward side, indicating strong scouring effects (Fig. 5B). Minor erosion and accumulation effects are also observed directly alongside the groins (Fig. 5A).

The seafloor topography shows a gentle slope that is marked by a clear step-like form in the nearshore part (Fig. 6). The downslope part of the terrace is occasionally marked by small irregularities in the seabed (Fig. 6B). The latter are located slightly landward of the outcropping reflector that marks the base of the terrace. The top of the terrace locally shows a slight dip that is most likely related to scouring effects near the groins. The recent sediment cover that was deposited after construction of the groins is clearly observed on the seismic data. At the foot of the seafloor terrace a shallow, recent paleochannel can be observed that runs parallel to the shore. The channel locally consists of two intertwined channels (clearly visible on Fig. 6). The depth of the green reflector (at −2.2 m TAW) suggests that we may be dealing with a thin peat layer, also observed in core 4/CPT8 (see Fig. 11 left).

It is tempting to link the seafloor terrace to construction of the groins. However, the seismic data suggest a different (and likely much older) origin, although it cannot be excluded that the groins have increased the relief (amplitude) of the terrace. The seafloor terrace seems more likely related to the medieval peninsula of *Testerep*, and as such represents the shoreface of the former coastal barrier. The channel running at the foot of the terrace (Fig. 6A) may indicate a tidal gully bounding the seaward edge of the peninsula. Indeed, it is known that islands are often marked by strong tidal currents that "encircle" the island (Pingree & Maddock, 1979). On a number of seismic profiles, marked seafloor irregularities (Fig. 6B) can be observed slightly above

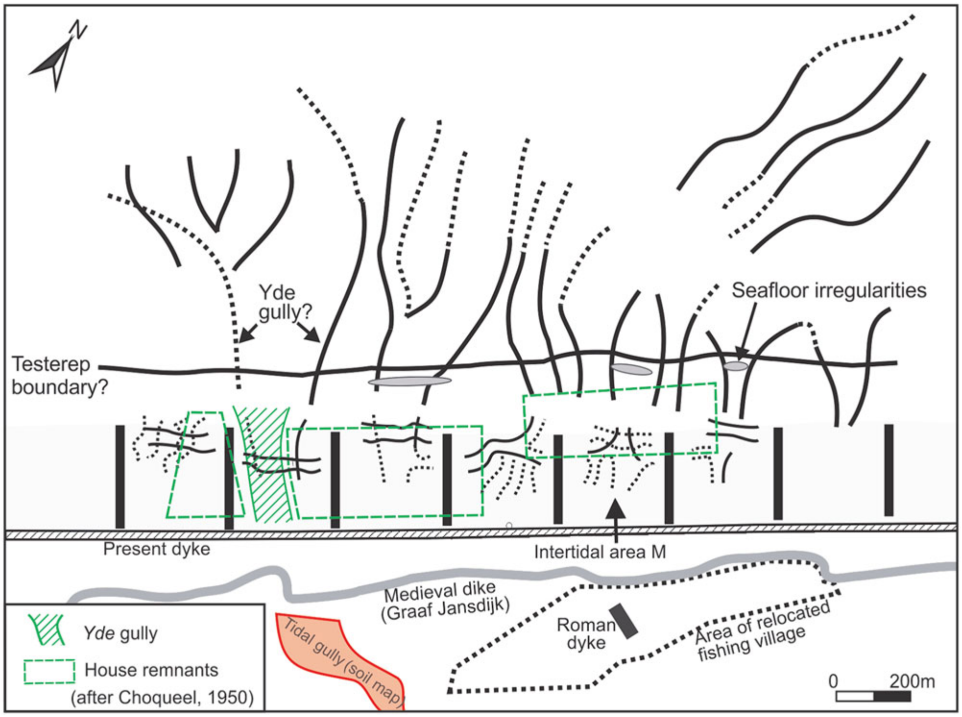

FIGURE 8 Overview map of the main buried paleochannels identified on the seismic data in the subtidal and intertidal area (tentative map). The tidal gully running parallel to the shore indicates the possible seaward boundary of the drowned *Testerep* peninsula. Light gray areas mark irregularities observed on the seafloor. Green dashed rectangles mark areas where remnants of medieval houses were found on the beach (modified after Chocqueel, 1950). The green striped area marks the location of the *Yde* gully proposed by Choqueel (1950). The red line marks the location of a tidal gully identified on the soil map [Color figure can be viewed at wileyonlinelibrary.com]

the foot of the terrace, suggesting some relation to the *Testerep* peninsula (e.g., possible remnants of former dikes?).

Until now the *Testerep* peninsula had only been proposed based on (soil) studies in the polder area, specifically focused on the inland *Testerep* gully (e.g., Ameryckx, 1956, 1959). The seaward extension of the peninsula still remained very uncertain. The parametric echosounder data from Raversijde present the first geophysical proof of the medieval coastline and the drowned peninsula of *Testerep*.

5.2 | Buried tidal channels

The 2D seismic data allowed to identify a complex pattern of paleochannels, marked by numerous overlapping and interfingering channels, with younger gullies overlying older gullies at different angles (Fig. 7). Due to the high spatial variability of the paleochannels and relatively large profile spacing in the subtidal area (roughly between 25 and 100 m), it was not always possible to fully map the course of the channels. The seismic data were furthermore locally hampered by shallow gas which limited the penetration of the acoustic signal. The gas is believed to be of biogenic origin, produced by bacterial degradation of organic matter, most likely related to organic-rich layers (Missiaen et al., 2002a).

Figure 8 shows a (tentative) reconstruction of the main paleochannels observed on the seismic data. Most channels in the subtidal zone are oriented roughly perpendicular to the coast. Farther offshore they seem to disperse and fan out. Toward the west two large tidal channels stand out clearly. The westernmost channel can only be identified clearly on its eastern flank, shallow gas masking the western extent of the channel. The tidal channel indicated on the soil map from the coastal area (marked in red on Fig. 8) most likely presents its landward continuation. The location of this channel, combined with earlier archaeological observations on the beach (Chocqueel, 1950) (marked in green on Fig. 6), suggests that we may be dealing with the *Yde* gully that once bordered the settlement of *Walraversijde*.

Also in the intertidal zones between the groins, a large number of buried paleochannels were observed, but local gas and a strong, shallow seafloor echo (multiple) severely hindered the data interpretation here. In the deeper part of the intertidal area, some of the observed paleochannels seem to be running parallel to the shore. The channels, often cutting through the peat, could possibly be related to one or more retreating stages of the *Testerep* peninsula. Despite the high level of detail in the 2D parametric echosounder data so far, no clear remnants of the Roman dike were identified. This is not so surprising in view of the material that was used (stacked clay and peat blocks) which may not easily have survived marine erosion. The tidal gully associated with the Roman dike seems a more probable "target." It is not unlikely that the latter can be linked to one of the buried paleochannels identified in (or near) intertidal area M (Fig. 8).

5.3 | Peat/salt exploitation remnants

2D seismic data from the intertidal zones were often marked by strong reflectors in the nearshore part, roughly 1–2 m below the seafloor

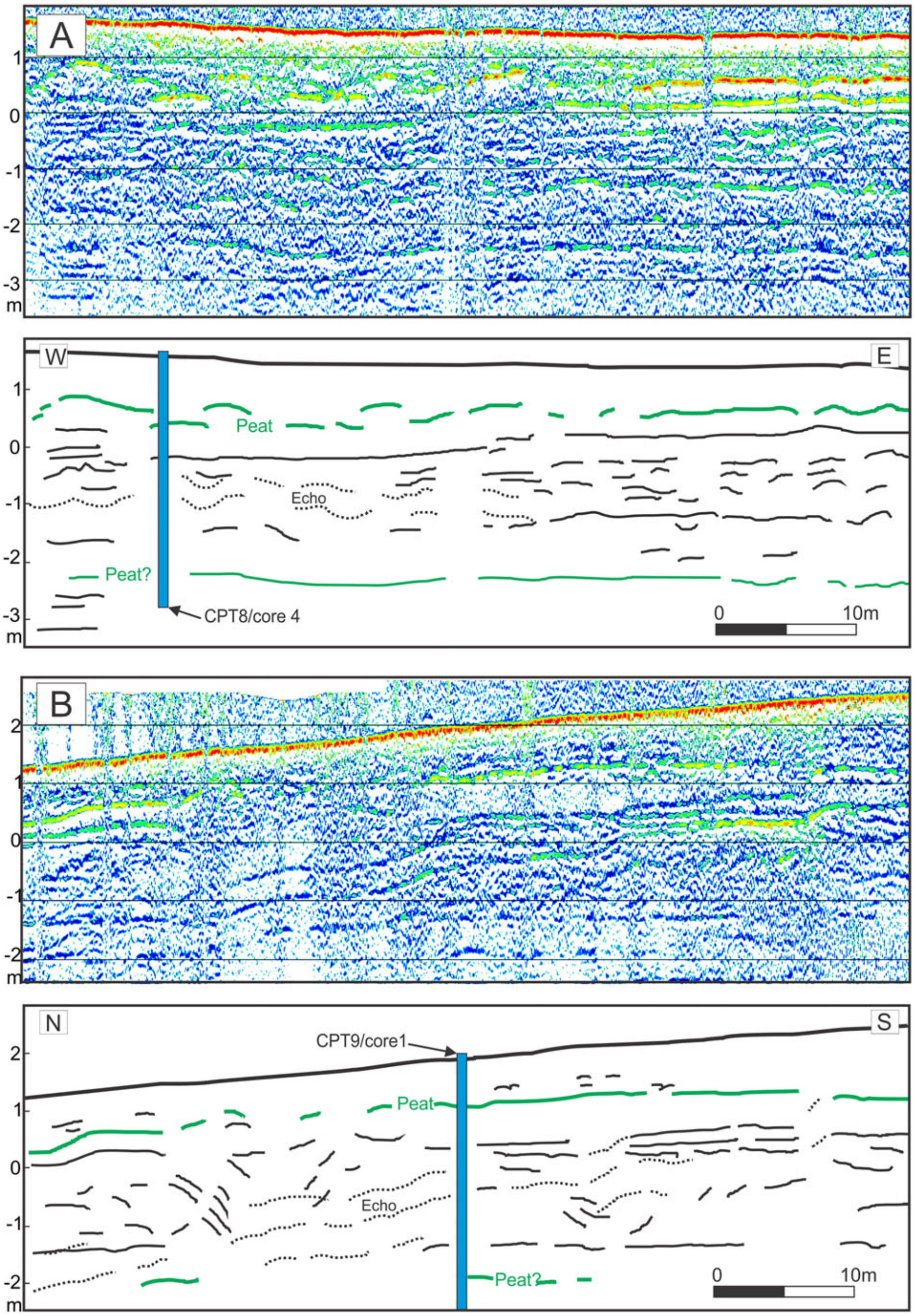

FIGURE 9 Seismic profiles and interpreted line-drawings from the intertidal zone M showing interrupted peat layers (for location see Figure 4). CPTs and corresponding cores shown in Figure 11 are marked in blue. Depth in meters TAW [Color figure can be viewed at wileyonlinelibrary.com]

(Fig. 9A). Their irregular form, marked by sudden interruptions and an uneven topography, suggests an anthropogenic origin possibly related to peat exploitation. The depth of the reflectors, between 0 and 1 m TAW, correlates well with the surface peat layer observed nearby behind the dunes (Pieters et al., 2013). The dense 2D seismic network in intertidal zone M allowed us to map the distribution of these interrupted shallow reflectors. The results correlate extremely well with the results from EMI measurements obtained here during low tide (Fig. 10). The distinct high conductivity zone (marked in white) observed close to the dike perfectly “mirrors” the interrupted reflectors (marked in orange). Since peat is known to exhibit a high conductivity (due to the high salt water content), this supported the interpretation of peat excavation.

Peat excavation was further confirmed by the CPT logs and core data from intertidal zone M (Fig. 11; for location see Figs. 4 and 10). CPT 8/core 1 (Fig. 11, right) is located in the main high conductivity zone. The high friction ratio (Rf) observed between −0.2 and 0.8 m TAW indicates a thick peat layer which is confirmed by the core. The top of the peat can be linked to a strong, shallow reflector on the seismic data (marked in green on Fig. 9B). The latter correlates well with the high conductivity zone on the EMI data (see Fig. 11). The peaty clay layer at the bottom of the core could not be identified on the CPT log,

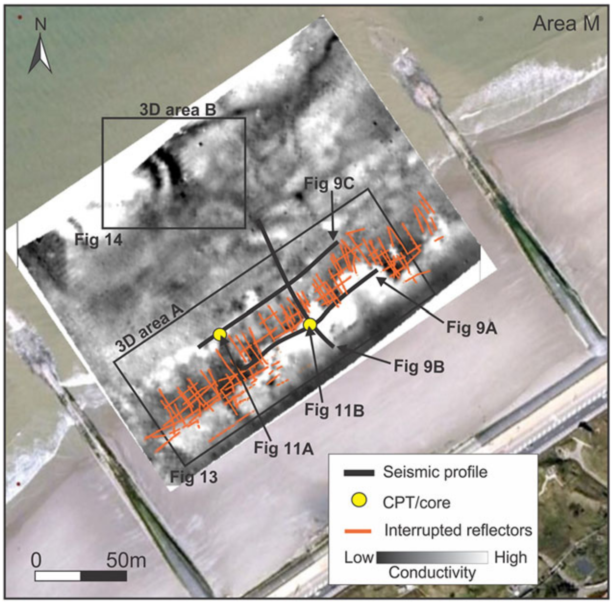

FIGURE 10 Comparison between 2D marine seismic data and terrestrial electromagnetic induction (EMI) data obtained in intertidal zone M (for location see Figure 2) (background projection Google Earth map ©). EMI data after Delefortrie et al., 2014. Thin orange lines indicate interruptions in the shallow seismic reflectors. The latter exactly "mirror" the high conductivity area (in white) on the EMI plot. Thick black lines mark the seismic profiles shown in Figure 10. Yellow dots mark the CPT/cores shown in Figure 11 [Color figure can be viewed at wileyonlinelibrary.com]

most likely a result of insufficient lithological difference with the overlying clay sequence.

CPT 8/core 4 (Fig. 11, left) is located slightly farther offshore, in a zone marked by alternating high and low conductivity (see Fig. 10). The CPT log indicates a thick upper peat layer and a thin peat layer roughly 3 m below; both are confirmed by the core. The upper peat corresponds well with the interrupted strong reflector on Figure 10 A indicating a complex peat extraction zone. The thin, deeper peat layer can likely be linked to the reflector at roughly −2.5 m TAW. Analysis of the full seismic signal near core 4 indicated a large negative reflection for the upper peat layer (Fig. 12). The negative peak for the bottom peat layer was less distinct, possibly due to a decrease in density difference with the surrounding deposits. Remarkably, also the thin peat intercalation just beneath the upper peat layer showed up on the reflection series. The sand and clay sequence observed in the core is barely detected on the CPT log, likely due to insufficient lithological differences. A number of irregular reflectors are observed on the seismic data (Fig. 9A) that could be related to these sand and clay deposits, but a clear identification is hindered by the seafloor multiple.

Not all the CPT logs and related cores display good agreement. This could be due to several reasons, such as (1) the very high lateral and vertical variability of the sediments, where even <1 m between core and CPT location may give different results, (2) erroneous depths due to the compaction of peat in the core, or (3) the presence of very thin peat layers (<10 cm) which may not show up clearly in the CPT log. In general, the CPT logs and cores show less presence of peat farther offshore. This could be due to paleochannels that have largely eroded the peat.

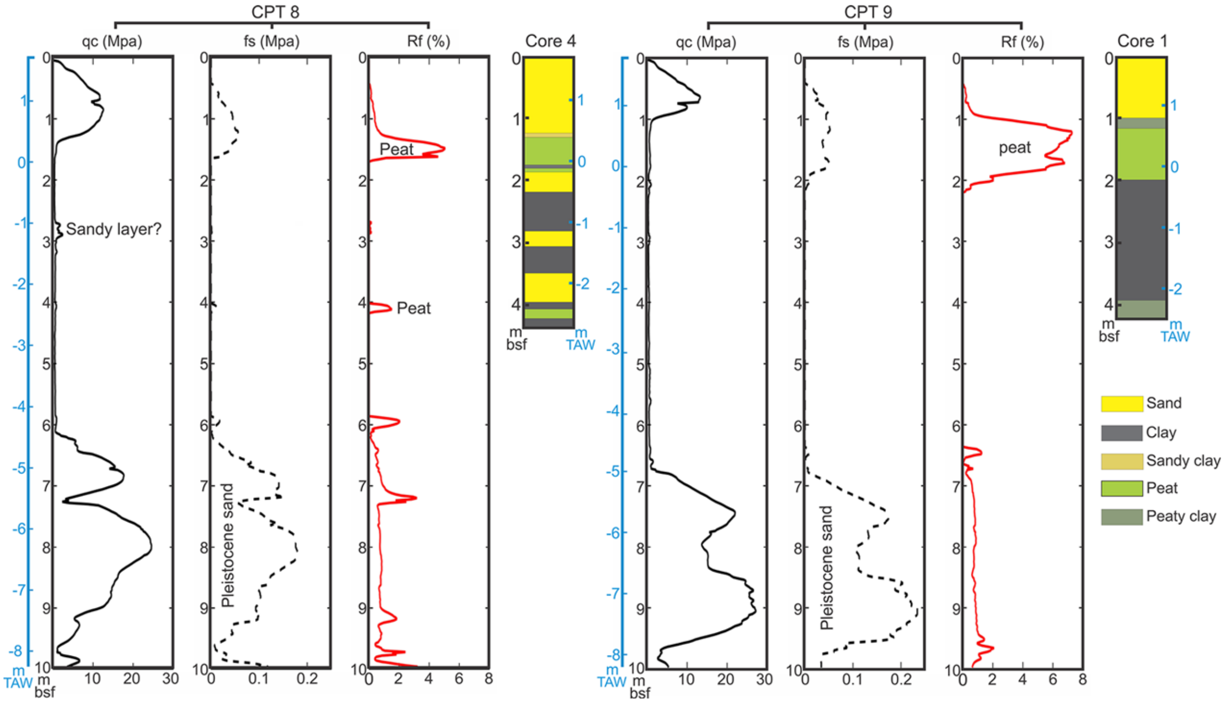

FIGURE 11 Two CPT logs and their corresponding shallow hand cores obtained in the nearshore part of intertidal zone M (for location see Figures 4 and 10). Peat layers in the cores correspond well with the CPT logs (high friction ratio Rf). The marked increase in cone resistance (qc) and sleeve friction (fs) in the lower part of the CPT logs indicates hard sandy deposits, possibly Pleistocene sand. Depth in meters below seafloor (bsf) (black) and meters TAW (blue) [Color figure can be viewed at wileyonlinelibrary.com]

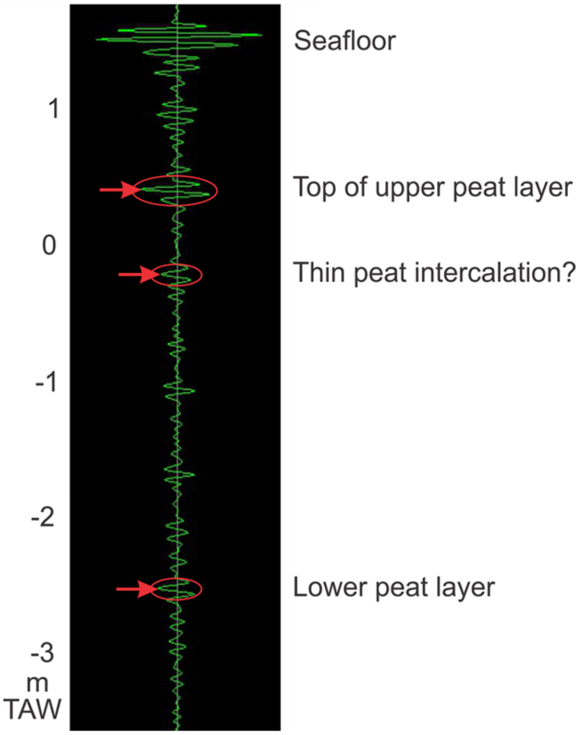

FIGURE 12 Seismic trace near CPT8/core 4 (see Figure 11). Red arrows mark negative peaks in the reflection series. The large negative peak roughly 1 m below the seafloor corresponds with the top of the thick upper peat layer. The two smaller negative peaks below are likely linked to thin peat layers [Color figure can be viewed at wileyonlinelibrary.com]

5.4 | 3D Seismic Data

Notwithstanding the high density of 2D seismic data in intertidal zone M, it was still very difficult to get a coherent image of the peat exploitation. This only became possible when 3D data were obtained with the multitransducer parametric echosounder. In order to allow optimal visualization, the uniform lattice was visualized in 3D with a volume renderer using an opacity and color map transfer function. Clipping planes were applied to visualize buried sections and time slices below the sediment floor. The results are striking. For the first time, a detailed image was obtained of the different peat and/or salt excavation features (Fig. 13). This was a direct result of the extremely small grid cell size (25 × 25 × 1 cm) of the 3D data volume which allowed to observe even the smallest details.

No exposed features were observed on the seafloor in the recorded areas, both on the seismic and multibeam data. The high complexity of the subseabed morphology was already visible when seismic sections of neighboring transducers within the array were compared. Horizontal depth slices across the volume of 3D area A revealed numerous artificial subsurface features (Fig. 13). Dimensions of the subsurface features varied between 1 m and up to 50 m length. The peat layer distribution was recognizable by a distinct amplitude level of the acoustical signals.

On the depth slices in Figure 13, we can clearly observe an appearing and disappearing pattern including peat strips, rectangular and circular pits, long (often diagonal) trenches, and small parallel ridges. Fine meandering features are likely due to small tidal gullies. Most of the circular features (with diameter ranging between 5 and 15 m) can likely be linked to controlled explosions of WW1 and WW2 ordnance. The observed features agree extremely well with old photographs taken before construction of the groins (Fig. 13, right). Unfortunately, exact georeferencing of the photographs remains difficult due to spectroscopic distortion and a lack of identification points. No clear indications were found of wooden poles lining the excavation pits. Most likely their thickness (<10 cm) is beyond the resolution of the 3D data.

Figure 14 shows a horizontal depth slice through the smaller volume of 3D area B located slightly farther offshore. Though the resolution is noticeably less than in area A (due to larger gaps in the line spacing, see Fig. 4), there seem to be no peat excavation features present here. Instead a marked paleochannel is observed which cuts sharply through a thin peat layer. The feature agrees well with the EMI data in Figure 10.

6 | CONCLUSIONS

The study area at Ostend-Raversijde is marked by a high level of heterogeneity and lateral variability in the shallow subsurface, typical of high-energy tidal flat areas. Very high resolution 2D subbottom data, obtained with a parametric echosounder, have allowed mapping of the complex pattern of buried paleogullies, not only in the subtidal area but also in the extremely shallow intertidal zone. Due to the local presence of gas in the sediments and relative wide profile spacing (50–100 m in the subtidal area), and the often unpredictable course of the channels, it was not always possible to exactly follow and map all the channels. Still the high level of detail in the 2D seismic data led to a few important new discoveries. For the first time geophysical proof is presented for the drowned medieval peninsula of *Testerep* and the *Yde* gully that bordered the fishing village of *Walraversijde*.

In the intertidal area the chaotic pattern of interrupted shallow seismic reflectors suggested human interference related to peat digging. This was confirmed by EMI measurements and additional CPTs and shallow cores obtained on the intertidal beach at low tide. Peat layers barely 10 cm thick could still be recognized on the seismic data (as negative peaks in the reflection series). Notwithstanding the high resolution of the parametric echosounder profiles, the 2D data did not permit us to fully map the complex excavation pattern. This was only possible through 3D investigations using a novel multitransducer parametric echosounder and applying a line spacing of 1 m. This finally allowed us to image the peat exploitation pattern in the highest detail (e.g., rectangular and circular pits, long trenches, small parallel ridges). The observed features agree completely with old aerial photographs of outcropping peat on the beach.

The presented research at Ostend-Raversijde is unique in more than one way. First, it is one of the first studies carried out in an intertidal area integrating marine and terrestrial geophysical data with geotechnical data. This was possible due to the high tidal variations that allowed us to obtain marine data very close to shore and land data relatively far offshore on the beach. The results also show that parametric echosounder data are a highly effective tool to map buried

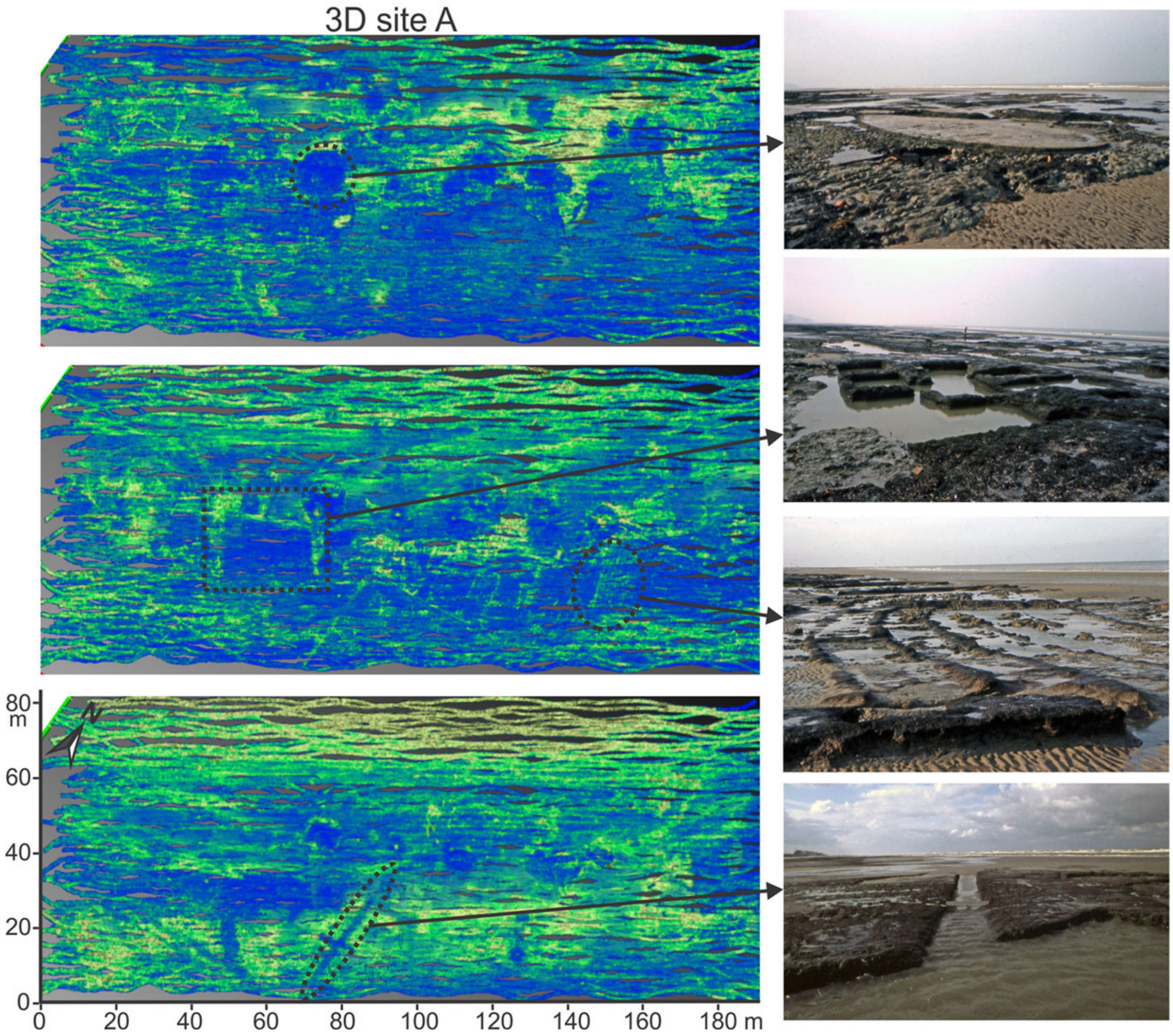

FIGURE 13 Horizontal depth slices (~30 cm interval) through 3D area A (for location see Figures 4 and 10). On the right, old photographs from excavated peat exposed on the beach (before the construction of groins) that show a striking resemblance to the features observed on the depth slices (Photos E. Cools) [Color figure can be viewed at wileyonlinelibrary.com]

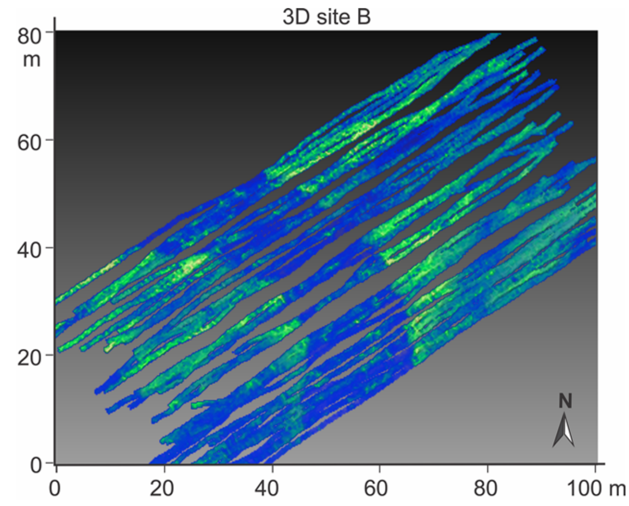

FIGURE 14 Horizontal depth slice through 3D area B (for location see Figures 4 and 10). The curved feature can be linked to a paleochannel cutting through the peat layer [Color figure can be viewed at wileyonlinelibrary.com]

peat layers and submerged landscapes in high detail, even in extremely shallow water. Secondly, this is the first study to present ultra-high resolution 3D seismic images of buried archaeological features with unprecedented detail (sub-meter level). With this, the novel multi-transducer parametric echosounder system sets a new standard for shallow water research and opens important perspectives for geoarchaeological studies in nearshore areas.

Thus far, no indications have been found of the actual drowned medieval settlement or the Roman dike. This may be (partly) due to insufficient lateral resolution of the 2D data. New investigations with the multitransducer parametric echosounder are planned at Raversijde in the near future that will hopefully allow us to identify buried house remnants and/or former coastal defense structures.

ACKNOWLEDGMENTS

Funding of the presented research was obtained through various national (IWT-SBO “SeArch”) and international (EU Interreg “Atlas of the 2 Seas” and “Arch-Manche”) research projects. Jens Lowag from

Innomar is kindly acknowledged for his help in processing of the multi-transducer data. The captain and crew of the Last Freedom and Hydro I are kindly acknowledged. Special thanks to Samuel Deleu and Kris Vanparys from Flemish Hydrography for their logistic support with the 3D measurements. The authors would like to thank the two anonymous reviewers for their valuable comments.

ORCID

Tine Missiaen http://orcid.org/0000-0002-8519-5737

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

How to cite this article: Missiaen T, Evangelinos D, Claerhout C, et al. Archaeological prospection of the nearshore and intertidal area using ultra-high resolution marine acoustic techniques: results from a test study on the Belgian coast at Ostend-Raversijde. *Geoarchaeology*. 2017;1–15. https://doi.org/10.1002/gea.21656