

The potential of seismic imaging in marine archaeological site investigations

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Introduction

Over the last decades marine acoustic techniques have become a successful investigation tool in archaeological studies, often focused on nearshore areas. The most commonly applied techniques involve side-scan sonar and multibeam systems, aimed to identify archaeological artefacts lying on the seabed. However, the main disadvantage of those techniques is that they cannot penetrate the subsurface. The marine seismic method, due to its penetration capacity, allows the detection and imaging of submerged archaeological objects. The steady development towards very high and ultra-high resolutions² has made the seismic technique a major asset in site-specific archaeological research.

One of the major applications concerns the study of (buried) wooden shipwrecks. Since the late eighties there has been a sharp increase in research of archaeological shipwrecks using marine seismic techniques³. With an ever-increasing number of wrecks and other marine archaeological structures being discovered, the necessity for management and preservation of underwater cultural heritage becomes increasingly important. Furthermore it is nowadays well recognized that buried artefacts are often best protected if left *in situ*⁴. Non-intrusive high-resolution acoustic techniques capable of locating and identifying wooden materials buried in the seabed, possibly also assessing their state of preservation or decay, are therefore becoming increasingly important.

The most recent international developments in marine archaeological studies increasingly focus on prehistoric archaeology, in particular the impact of human activities on submerged terrestrial landscapes⁵. Although undoubtedly many of these terrestrial sites may have been eroded or destroyed by rising sea levels, their existence and importance is nowadays generally accepted.

The reconstruction of the paleo-landscapes is not only an important requirement to help understand their archaeological potential, such as submerged or re-worked material from older deposits, but it may also provide key information on the human evolution. Seismic techniques form an ideal tool to image these buried paleo-landscapes.

In Belgium, little attention has so far been paid to the potential of seismic techniques for marine archaeological studies – in stark contrast to The Netherlands and the UK where this research has gained considerable interest over the last years. Up to now, the main archaeological research on the Belgian Continental Shelf (BCS) has been focused on exposed shipwrecks, for example on the Vlakte van de Raan ('t Vliegend Hert, Zeebrugge-site)⁶. An important challenge, however, lies in the detection and imaging of buried objects (such as shipwrecks or dykes) and the study of inundated terrestrial sites. Sea-levels were generally much lower in late Pleistocene and early Holocene times and only reached near-present levels during the later part of the Holocene. The identification of buried tidal channel, dunes, lagoons, river valleys, reclaimed areas, etc should allow a better understanding of the archaeological potential of the BCS, including the different processes involved in reworking of archaeological artefacts.

Three different seismic case-studies will be discussed in this paper. The first case-study involves seismic imaging of a buried 17th-century shipwreck in the Dutch Wadden Sea. The second case-study is located offshore Raversijde (Ostend, Belgium), and focuses on the possible remains of Roman dykes and salt and/or peat exploitation and the distribution of prehistoric tidal gullies. The third case-study finally focuses on an exposed shipwreck on the Buiten Ratel sandbank.

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² Resolution is the ability to separate two features that are very close together.

³ Bull *et al.* 1998; Quinn *et al.* 1997 & 2000.

⁴ Garaballo & Scovazzi (eds) 2003.

⁵ Lafferty *et al.* 2006; Westley *et al.* 2004.

⁶ Zeebroek *et al.* 2006.

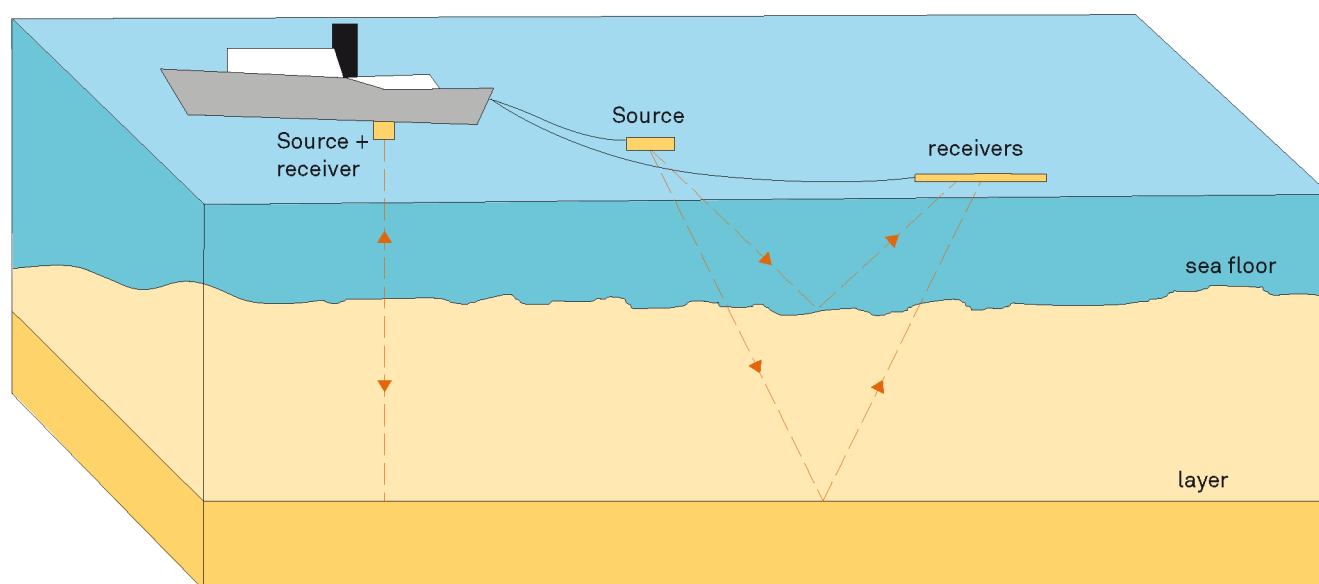


FIG. 1 Schematic diagram showing the principle of marine seismic imaging. A seismic source emits a sound pulse that is reflected against the sea floor and deeper layers; the reflected signals are recorded by a towed receiver. As the boat moves continuously, this results in a vertical image across the seabed along the ship's trajectory.

Schematisch diagram van het principe van mariene seismische beeldvorming. Een akoestische bron zendt een geluidsgolf uit die weerkaatst wordt op de zeebodem en de onderliggende lagen. Het gereflecteerde signaal wordt opgenomen door een ontvanger. Doordat het meetschip zich continu verplaatst, wordt op die manier een verticale doorsnede van de ondergrond bekomen langs het traject van de boot.

1 Marine seismic imaging

In marine seismic imaging an acoustic source and receivers are towed behind a ship. The source emits an acoustic pulse that travels through the water and is reflected from the seabed and subsequent layers of the subsoil (fig. 1). The reflected energy intensity depends on the different densities of the seabed and sub-seafloor layers, the denser (i.e. harder) the seabed or layer the stronger the reflected signal. The reflected signal then travels back through the water to the receiver (fig. 1). The received signals are recorded, and as the ship constantly moves this will result in a vertical cross section through the seabed. So-called reflectors on the seismic image mark the boundary between two distinct subsurface layers.

In order to image the shallow subsurface with the highest possible detail (and to allow the detection of small buried objects) a high vertical resolution is needed. This implies the use of high-frequency acoustic (seismic) sources, such as boomers⁷ and echosounders⁸. Boomer sources have a frequency ranging between 2 and 5 kHz, and offer a good compromise between resolution (20–50 cm) and penetration (tens of meters up to hundred m or more). Echosounder sources are generally marked by a higher frequency (4 to 10 kHz), resulting in an increased resolution (10–20 cm) but often also a decrease in penetration depth⁹.

The ability to image buried wooden objects, such as wooden shipwrecks, will highly depend on the type of wood and the level of decay, the density of the surrounding sediment and the depth of the artefact. Studies in the UK have shown that oak and pine artefacts are acoustically detectable in a wide range of marine sediments, with sandy sediments generally giving a better contrast than sand-silt-clay mixtures¹⁰. Increasing wood degradation, caused by bacteria, woodborers and (to a lesser extent) fungi, will often yield a better image. Burial in marine sediments, however, may limit the progression of degradation due to a limited oxygen supply. Wooden artefacts exposed on the sea floor are usually well detected, but once the wood is heavily degraded seismic detection can become very difficult¹¹.

The ability to image archaeological artefacts will also depend on the size and orientation of the object. Acoustic reflections from a shipwreck will mainly be caused by long boards. To allow detection the wavelength of the seismic signal should therefore not be much bigger than the size of the wooden boards. In our case, working with acoustic signal frequencies well over 3 kHz this should not be a problem¹². The sediments surrounding a shipwreck are also often marked by scour features. In time these scour features may become filled in and buried. In some cases the di-

⁷ Electromagnetically driven sound source where a capacitor bank is discharged through a flat coil. Eddy currents are generated in aluminium plates beneath the coil, causing rapid repulsion of the plates and the creation of a shock wave.

⁸ Type of sound source where a pulse is generated by passage of an electrical impulse through a piezoelectric crystal. The crystal is physically deformed, generating a pressure wave. The transmitting transducer also acts as a receiving transducer.

⁹ Missiaen 2008.

¹⁰ Arnott *et al.* 2005.

¹¹ Arnott *et al.* 2005.

¹² Frequencies ≥ 3 kHz will yield a wavelength ≤ 0.5 m (for $V = 1500$ m/s).

mensions of the scour features (often much larger than the wreck itself) may make them more easily recognized on seismic profiles. In the extreme case of a completely degraded wreck, no longer detectable by seismic imaging, or excavation of the wreck, the scour pits may form the only remaining evidence of the wreck site.

2 Case study 1: Seismic imaging of a buried wooden shipwreck, Wadden Sea

In July 2003 a seismic survey was carried out over a buried wooden shipwreck ('Scheurrak SOR') in the Dutch Wadden Sea, 25 km NE of Den Helder. The wreck is roughly 25 m long and dates presumably from the late 16th century¹³. From 1989 to 1997 the wreck has been excavated by divers of the RACM (The Netherlands) - at that time the wreck was largely exposed on the sea floor (fig. 2). Results showed that the wreck had been broken lengthwise (the starboard side had broken off the hull of the ship)¹⁴. Since then, sedimentation has resulted in complete burial of the wreck under a thin layer of fine sandy silt. The sea floor in the wreck area is relatively flat, locally marked by large ripples and sand waves. The water depth varies between 6.5 and 8 m below MLLWL (mean lowest low water level at spring tide).

In the framework of the IMAGO project (acronym for "Innovatief Meten aan Gezonken Objecten") a dense network of 62

seismic profiles was recorded over the wreck site (fig. 3: left). Multibeam data, recorded simultaneously with the seismic data, indicate that the wreck is completely buried. On these multibeam data we can also clearly observe the short poles, an external measuring grid placed by divers to mark the wreck area (fig. 3: right). Both 2D and 3D seismic data were recorded, the latter using an inflatable receiver array which was towed behind the vessel. The seismic source consisted of a 3.5 kHz echosounder. Average length of the seismic profiles was 200-250 m with a line spacing of roughly 7 m. Strong side currents made it not always possible to steer exactly along straight lines, as can be seen on fig. 3: left. Positioning was done using a short-range DGPS¹⁵ system based on RTK¹⁶ positioning which allowed to record real-time (x, y, z) positions each second with cm accuracy.

The quality of the seismic images was generally quite good, although locally some data were marked by poor penetration which was likely due to the presence of small amounts of gas bubbles in the sediments. Fig. 4 shows an example of a 2D seismic profile and interpreted line-drawing across the buried wreck site (the location of the profile is shown in fig. 3). The profile crosses the wreck more or less obliquely and the wreck stands out clearly on the seismic image. Some deeper reflections observed on the left are most likely caused by the irregular edge of the westernmost wreck piece. The large diffraction (marked in red on fig. 4)

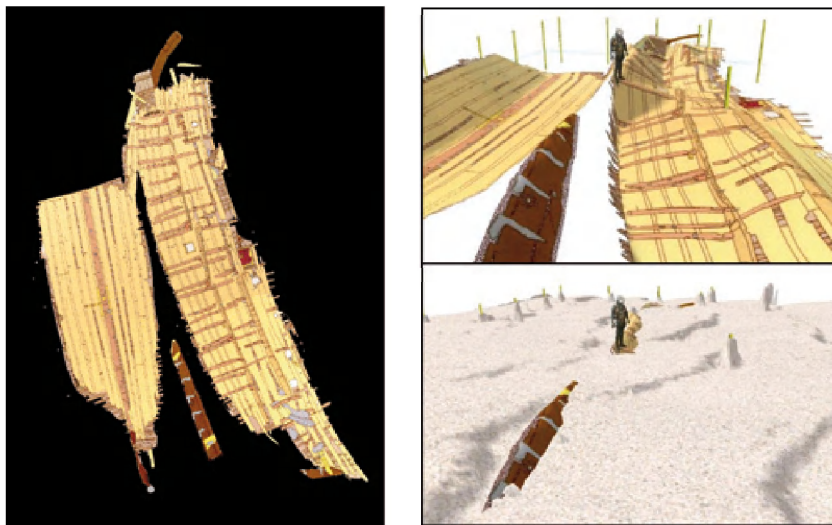


FIG. 2 Schematic views of the shipwreck 'Scheurrak SOR' in the Wadden Sea, based on archaeological excavations. Left: Top view of the wreck that has been broken in two large pieces. Right top: 3D model of the wreck based on drawings and the multibeam data. The green poles were put in as an external measuring grid during excavation (the diver marks the scale). Right bottom: same 3D model of the sea floor based on multibeam data. The partly exposed rudder can be seen on the foreground. Spikes are due to the partly exposed poles. Courtesy RACM (left picture) and RACM/RWS (right pictures).

Illustraties van het scheepswrak 'Scheurrak SOR' in de Waddenzee gebaseerd op archeologische opgravingen. Links: Bovenaanzicht van het wrak dat in twee grote stukken is gebroken. Rechtsboven: 3D model van het wrak, gebaseerd op de tekeningen en de multibeam data. De gele meetpaaltjes markeren de wraksite (de duiker dient als schaalmodel). Rechtsonder: hetzelfde 3D model maar met invulling van de zeebodem zoals gezien door multibeam data. Op de voorgrond is het gedeeltelijk uitstekende roer duidelijk te zien. De scherpe spikes in de multibeam data zijn veroorzaakt door uitstekende paaltjes. Met dank aan RACM (linkerfiguur) en RACM/RWS (rechterfiguren).

¹³ Manders 2000.

¹⁴ Rijkswaterstaat 2003.

¹⁵ Differential Global Positioning System.

¹⁶ Real-Time Kinematic- positioning technique based on the use of carrier phase measurements of the GPS signals where a single reference station

provides the real-time corrections resulting in a centimetre level of accuracy.

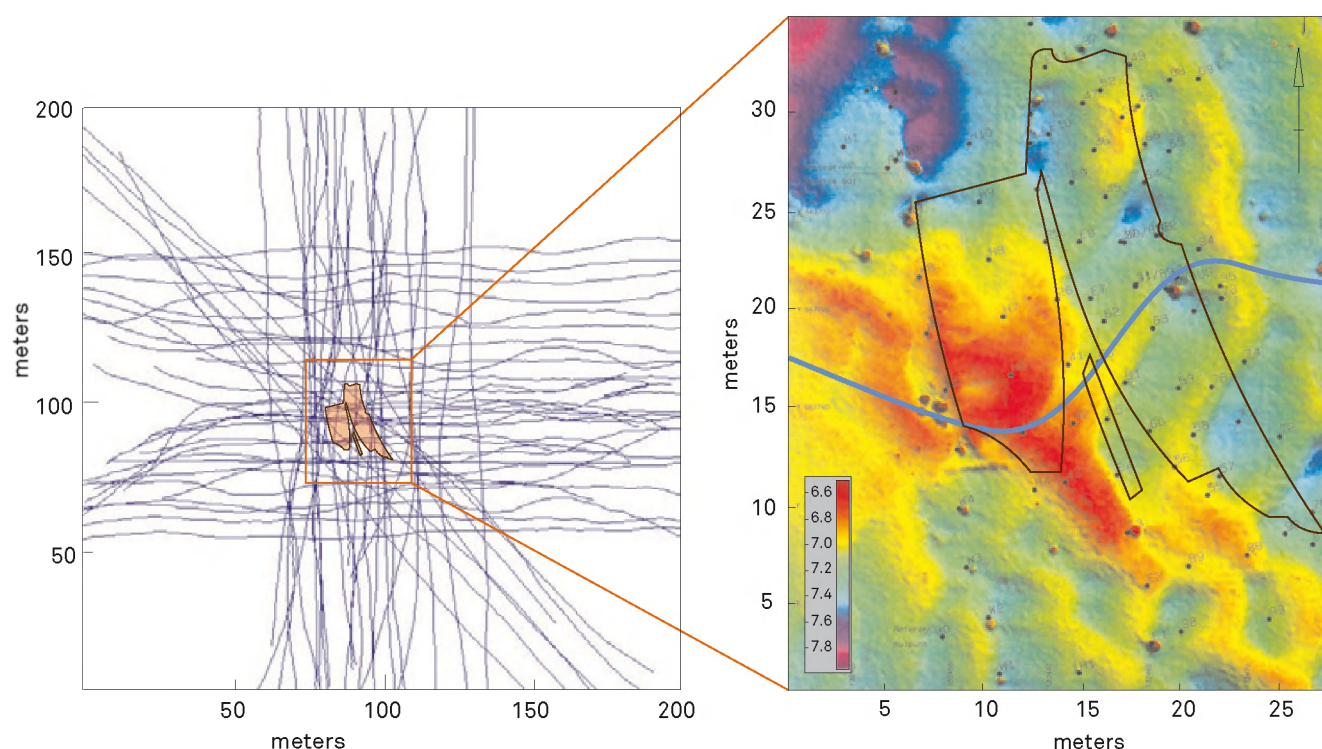


FIG. 3 Left: Seismic network (thin blue lines) recorded over the wreck site in the Wadden Sea. Black lines = wreck contours (recorded in excavation when the wreck was still exposed). Right: Multibeam recording over the buried wreck. The wreck is now completely covered by sediments. Black lines = wreck contours. Red dots = short poles used by divers in 1990 to use as an external measuring grid. Thick blue line = location of the seismic profile shown in fig. 4. Courtesy RWS.

Links: Overzicht van het seismische netwerk (dunne blauwe lijnen) dat werd opgenomen over de wraksite in de Waddenzee. Zwarte lijnen = contouren van het wrak, zoals waargenomen tijdens de opgravingen (toen het wrak nog vrij lag). Rechts: Multibeam opname over de wraksite. Het wrak ligt volledig begraven onder een laag sediment. Zwarte lijnen = contouren van het wrak. Rode stippen = uitstekende paaltjes die de site markeren. Dikke blauwe lijn = locatie van het seismische profiel besproken in fig. 4. Met dank aan RWS.

at a depth of 12 milliseconds (ms) below the sea floor is possibly related to the ship's rudder (see also fig. 2). The data indicate that the deepest part of the wreck is covered by roughly 1.5 to 2 m of sediment. The sea floor surrounding the wreck is locally marked by sand waves with an amplitude of 50–70 cm and length up to 5 m. The seismic reflectors related to the wreck are marked by a slight phase inversion¹⁷, which indicates a moderate state of decay of the wood. Due to the highly variable data quality (attributed to shallow gas), it was not possible to obtain a reliable 3D map of the wreck outline.

3 Case study 2: Seismic investigations off Raversijde

The Provincial Domain of Walraversijde, between Ostend and Middelkerke, has been the focus of a large-scale archaeological research project set up by the Flemish Heritage Institute (VIOE) and the province of West-Flanders. The main archaeological findings include the remnants of a Late Medieval settlement, both on the beach (see fig. 5: left) and more inland in the dune

area¹⁸. Due to severe coastal erosion the first settlement, dating from the late 13th century, was lost to the sea and relocated behind a dyke in the early 15th century.

In September 2005 part of a buried Roman dyke was discovered in Walraversijde. The dyke is over 11 m wide and a little over 1 m high, and has a total length of at least 110 m¹⁹. The dyke is mainly built of stacked clay blocks, on its western side reinforced with peat (fig. 5: right). The dyke is oriented roughly perpendicular to the present coastline, which suggests that its purpose was most likely to embank a tidal gully that stretched further inland²⁰. In the 70's traces of the Roman dyke have been found on the beach of Raversijde²¹.

Soil studies on land have indicated a highly complex Holocene history²². Locally, the coastal landscape has been heavily influenced by peat exploitation. This human impact is in some cases thought to be the origin of relief inversion. Peat-digging started already in Roman times and was revived in Late Medieval times (15–16th century). Various peat-digging pits have been described

¹⁷ A phase shift of 180° of the signal waveform.

¹⁸ Pieters 1992.

¹⁹ Pieters *et al.* 2006.

²⁰ Pieters *et al.* 2006.

²¹ Pieters 2007.

²² Pieters *et al.* 1998.

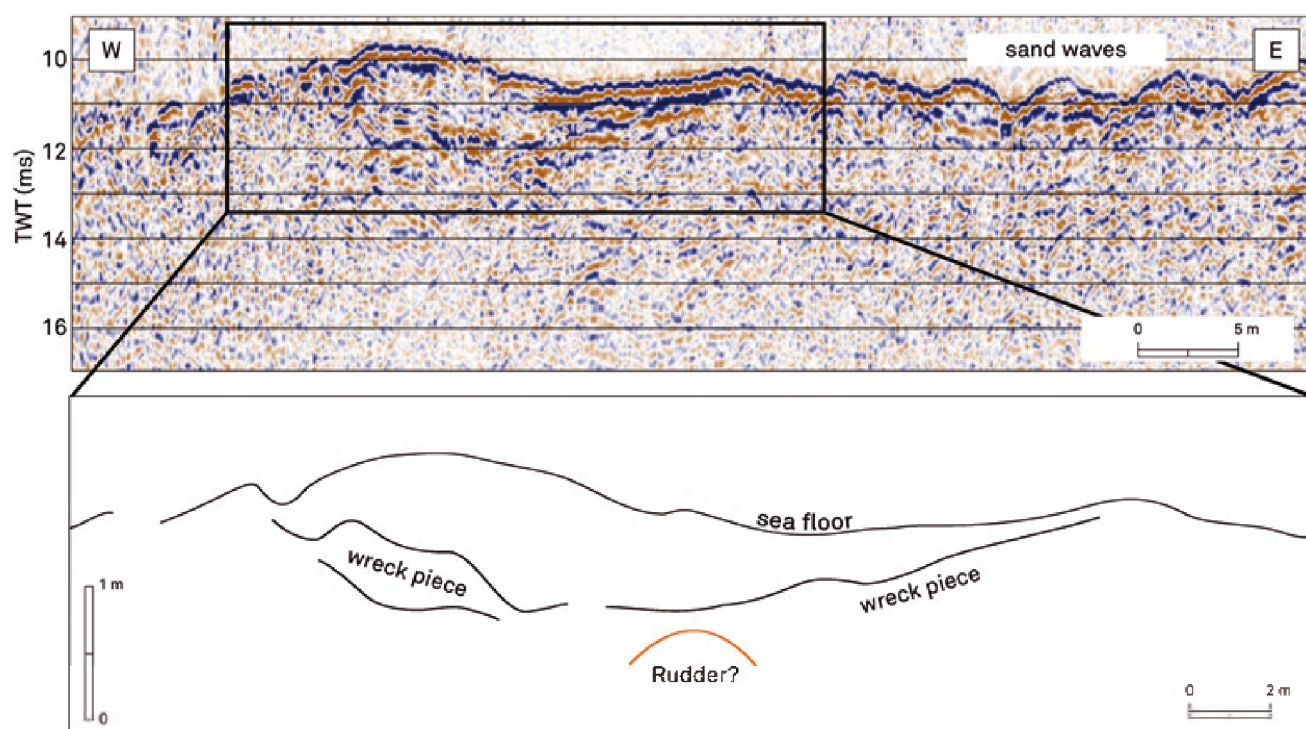


FIG. 4 Example of a 2D seismic profile (top) and interpreted line-drawing (bottom) across the wreck site in the Wadden Sea (for location of the profile see fig. 3). Depth below the water surface in milliseconds two-way traveltime ($2 \text{ ms} = 1.5 \text{ m}$). The profile crosses the wreck more or less obliquely and the wreck outline is clearly observed. The large diffraction at the bottom is possibly related to the ship's rudder.

Voorbeeld van een tweedimensionale verticale akoestische doorsnede (boven) en geïnterpreteerde lijntekening (onder) over het wrak in de Waddenzee (voor de locatie van het profiel zie fig. 3 rechts). Diepte onder het wateroppervlak in milliseconden ($2 \text{ ms} = 1.5 \text{ m}$). Het profiel kruist het wrak min of meer dwars en de contouren van het bedolven wrak zijn duidelijk te zien. De in het oog springende diffractie onderaan komt mogelijk overeen met het roer.



FIG. 5 Left: Ground-plan of a late medieval house on the beach of Raversijde (After Chocqueel 1950). Right: Excavation of the Roman dyke in Walraversijde. The dyke is made up of carefully stacked clay blocks. Wedge-like peat sods (dark colour) were used to reinforce the western side of the dyke, in the forefront a horizontal cross-section of the same peat sods. The latter clearly indicate three successive reinforcement phases of the dyke.

Links: Plattegrond van een laatmiddeleeuws huis op het strand van Raversijde (naar Chocqueel 1950). Rechts: Opgraving van de Romeinse dijk in Walraversijde. De dijk is opgebouwd uit zorgvuldig gestapelde kleizoden. Wigvormige veenblokken (donkerbruine kleur) werden aangebracht ter versterking van de westkant van de dijk; op de voorgrond een basisdoorsnede van dezelfde veenblokken. Deze laatste wijzen duidelijk op drie opeenvolgende 'bewapeningen' van de dijk.

in the area of Walraversijde, some of these pits have a diameter of over 14 m²³.

In October 2007 a marine seismic reconnaissance survey was carried out offshore Raversijde. The scientific goal of this survey was multifold: (1) localisation and identification of fossil (prehistoric) tidal gullies; (2) detection of the old Roman dyke that was discovered nearby on land; (3) detection of old coastline and/or coastal defense features; and (4) detection of possible artefacts (including peat excavation) of the deserted late medieval village Walraversijde. This should eventually lead to a better understanding of the complex late-Holocene evolution and the human impact on this part of the Belgian coastal region.

During the seismic survey a parametric echosounder source was used. The latter emits two sound signals with a different frequency (100 kHz and 8–12 kHz)²⁴. Whereas the high-frequency signal allows a very detailed image of the sea floor, the lower-frequency signal gives a detailed image of underlying structure. The echosounder was attached on a long iron pole fastened to the side of the ship (fig. 6). A motion sensor was used to filter out any movement caused by wave action. The fast pulse rate (25 pulses per second) and the low vessel speed (3–4 knots) resulted in a high lateral coverage (one data point every 5 to 10 cm). Positioning was done using a DGPS antenna with an accuracy of ± 1 m.

In total 37 seismic profiles were recorded (22 profiles parallel to the shore, 15 profiles perpendicular to the shore) (fig. 7). The length of the profiles varies between 1.9 and 2.3 km, with a spacing of 100–200 m. A few short profiles were recorded at high tide in between the groynes and as close to the beach as possible. The quality of the seismic images is generally very good. The profiles nearest to the shore are marked by a large number of shallow reflectors and show a high level of detail in the sub-seafloor structure and stratification. Further out towards the open sea the quality of the images decreases. This is most likely due to an increase in biogenic gas in the shallow sediments which will absorb the seismic energy²⁵. The sloping sea floor towards the shore is marked by a step-like form, creating distinct terraces.

Figs. 8 to 10 show some examples of recorded seismic profiles and the interpreted line-drawings. The length and depth scale are respectively indicated below and left of the profile (depth conversion was done using a constant velocity of 1550 m/s). On the whole, a large number of fossil tidal channels were observed on the seismic profiles. In most cases the gullies were best seen on the N-S oriented profiles and on the nearshore E-W oriented profiles (up to 1 km from the shore). Due to the high spatial variability of the shallow sediments and the large profile spacing it was not always possible to accurately track the channel pattern, especially the minor gullies. Further offshore the seismic profiles were marked by less penetration but still various shallow parallel reflectors, in some cases sharply interrupted by shallow gas, could still be identified just below the sea floor.

No clear indications were found of the Roman dyke. But the chance is real that such a dyke (and also other old dykes) has been largely eroded by the strong floods and tidal currents that mark this coastal area. A marked, more recent tidal gully could be observed clearly on all N-S oriented seismic profiles. The gully runs roughly parallel to the shoreline (yellow line on fig. 7). The latter seems to indicate that most likely it represents an artefact of an old coastal defense feature built to dam a creek or tidal gully. The orientation of this gully, more or less perpendicular to the Roman dyke, seems to suggest that there is no link between the two. The exact age of this more recent gully is not known.

Seismic profile A (fig. 8)

This profile is oriented NW-SE, perpendicular to the shore. The water depth ranges from 9 m in the NW to 5 m in the SE. Except for a shallowing towards the shore the sea floor does not show any marked morphological features. In a few places the sea floor reflector is interrupted; this is due to some minor technical malfunction of the acoustic equipment. We can clearly identify different fossil tidal channels (marked by striped black lines). The age of these channels is not known due to a lack of core data, but a possible relation to the so-called Walraeve's Yde gully is not unlikely. Although the profile crosses the presumed continuation of the Roman dyke, no clear traces of the latter were observed. The most recent tidal gully, marked in yellow, is likely a remnant of an old coastal defense feature (yellow line on fig. 7).

Seismic profile B (fig. 9)

This profile is oriented SW-NE, parallel to the shore. It is located roughly 1.2 km from the shore in a water depth of roughly 9.5 m. Although the acoustic penetration seems to be locally decreasing we can still clearly observe a large fossil tidal channel (marked by the striped black line). The parallel infilling structure inside the gully also stands out visibly. Again, the age of the channel is not known. On the left of the profile, towards the west, an object can be seen protruding from the sea floor. Below the object the acoustic image disappears completely. Possibly we are dealing with a small shipwreck. The seabed near the wreck shows a marked depression, probably caused by scouring (from tidal currents) around the wreck.

Seismic profile C (fig. 10)

This profile is oriented SW-NE, parallel to the shore and within the low-tide mark. Although the water is very shallow (roughly 2.5 m deep), the seafloor echo is not a prominent feature, which indicates soft upper sediments. Various horizontal, parallel reflectors can be observed down to a depth of 4 m below the seabed. There are no indications of fossil tidal channels. The most striking features are a number of strong, short and often jagged reflectors in the upper 1–1.5 meters (marked by thick black arrows). Their shallow depth and rugged form suggest a man-made origin, possibly related to artefacts from the fishing village Walraversijde or extensive peat-exploitation. Due to the large profile spacing it is not possible to map the exact distribution of these shallow reflectors.



FIG. 6 Left: Parametric echosounder attached to a pole on the side of the ship. During measurements at sea the echosounder is lowered 20–30 cm below the water surface. Right: Fishing vessel used for the seismic survey off Raversijde.

Links: Parametrische echosounder bron vastgemaakt aan een paal aan de zijkant van het meetschip. Tijdens de metingen wordt de echosounder neergelaten tot zo'n 20–30 cm onder het wateroppervlak. Rechts: Het meetschip dat werd gebruikt voor de seismische survey voor de kust van Raversijde.

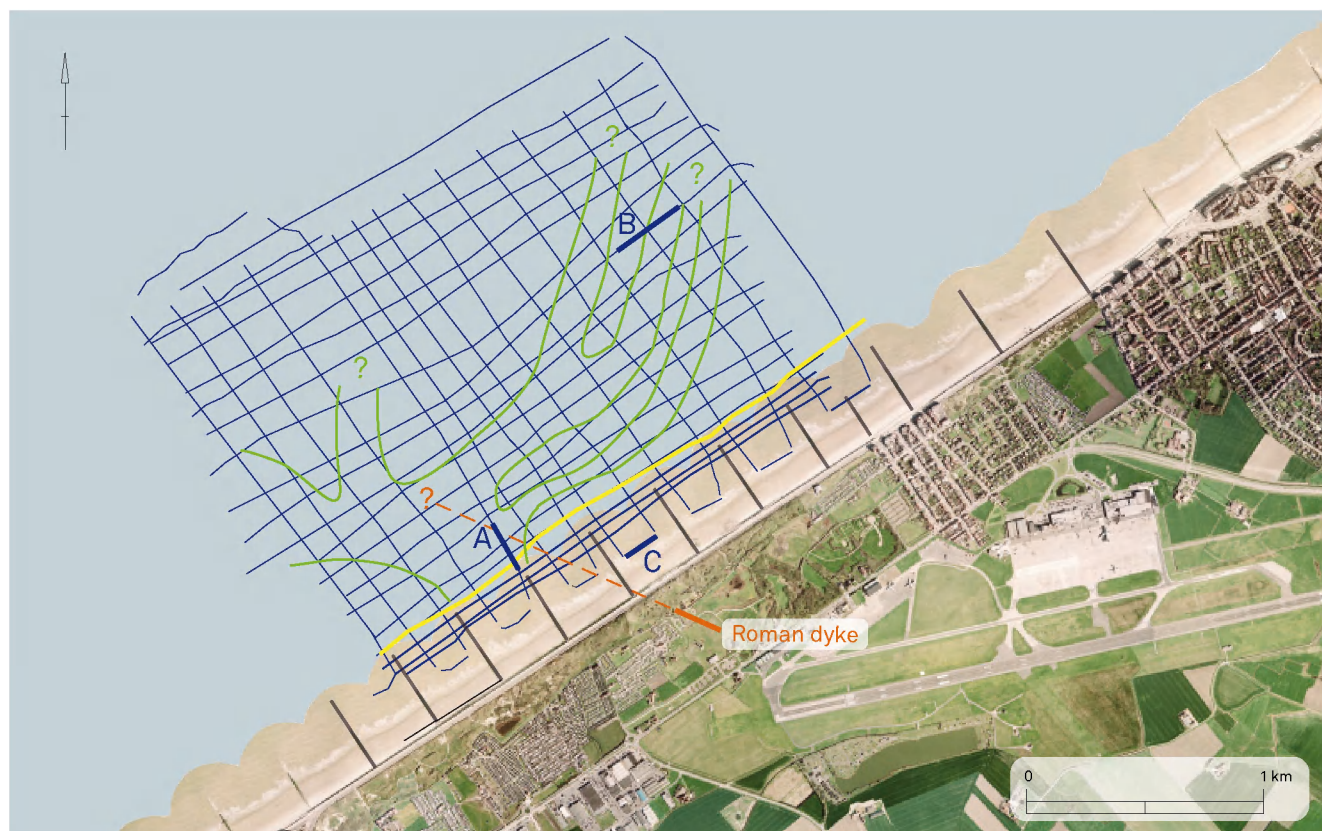


FIG. 7 Seismic network (thin blue lines) recorded offshore Raversijde (background map Google Earth™ image). Thick blue lines = location of profiles A–C shown in figs. 8 to 10. Red line = location of the Roman dyke on land; the striped thin red line marks its presumed continuation at sea. Yellow line = recent tidal gully discussed in fig. 9. Green lines = various prehistoric tidal gullies. Black lines = groynes. *Overzicht van het seismische netwerk (dunne blauwe lijnen) dat werd opgenomen voor de kust van Raversijde (achtergrondkaart Google Earth™ afbeelding). Dikke blauwe lijnen = locatie van profielen A–C besproken in fig. 8 t.e.m. 10. Rode lijn = ligging van de Romeinse dijk op land; de gestreepte dunne rode lijn is een mogelijke voortzetting van de dijk op zee. Gele lijn = recente getijdengul, besproken in fig. 9. Groene lijnen = overige (oude) getijdengulen. Zwarte lijnen = strandhoofden.*

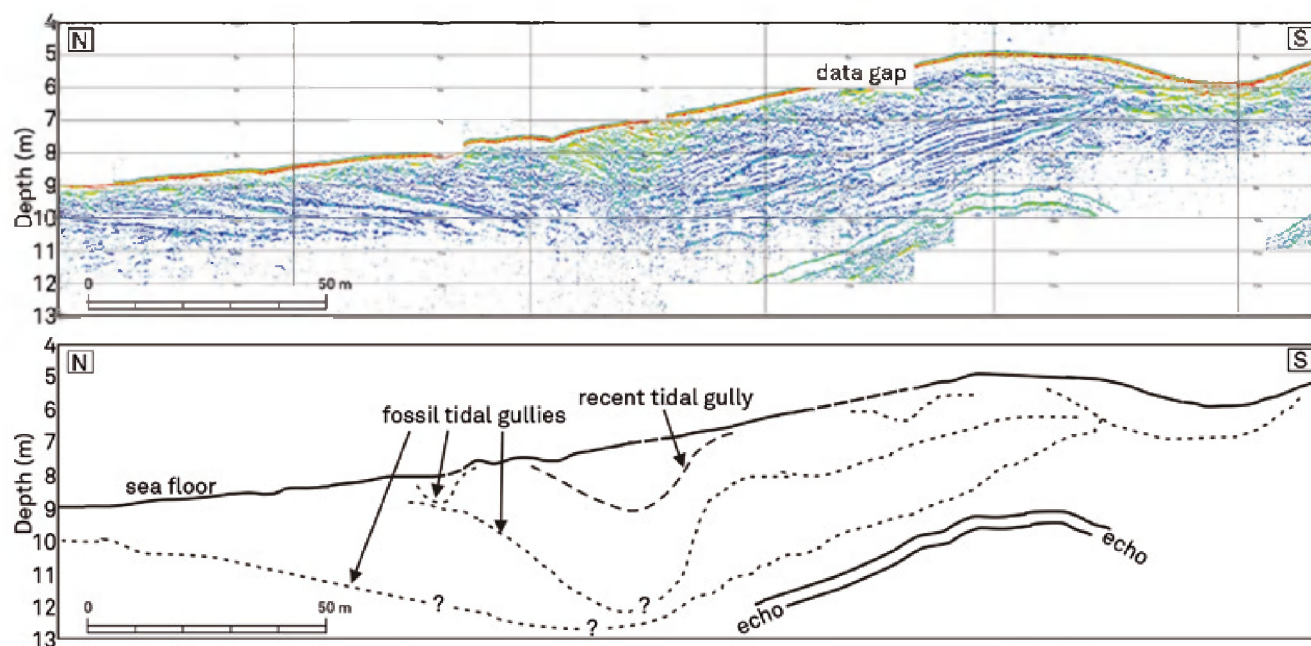


FIG. 8 Seismic profile A offshore Raversijde (for location see fig. 7). The interpreted line-drawing is shown below. Depth below the water surface is in meters. For description of the profile see text.

Seismisch profiel A voor de kust van Raversijde (voor de locatie van het profiel zie fig. 7). De geïnterpreteerde lijntekening wordt daaronder getoond. Diepte onder het wateroppervlak in meter. Een gedetailleerde bespreking van het profiel wordt gegeven in de tekst.

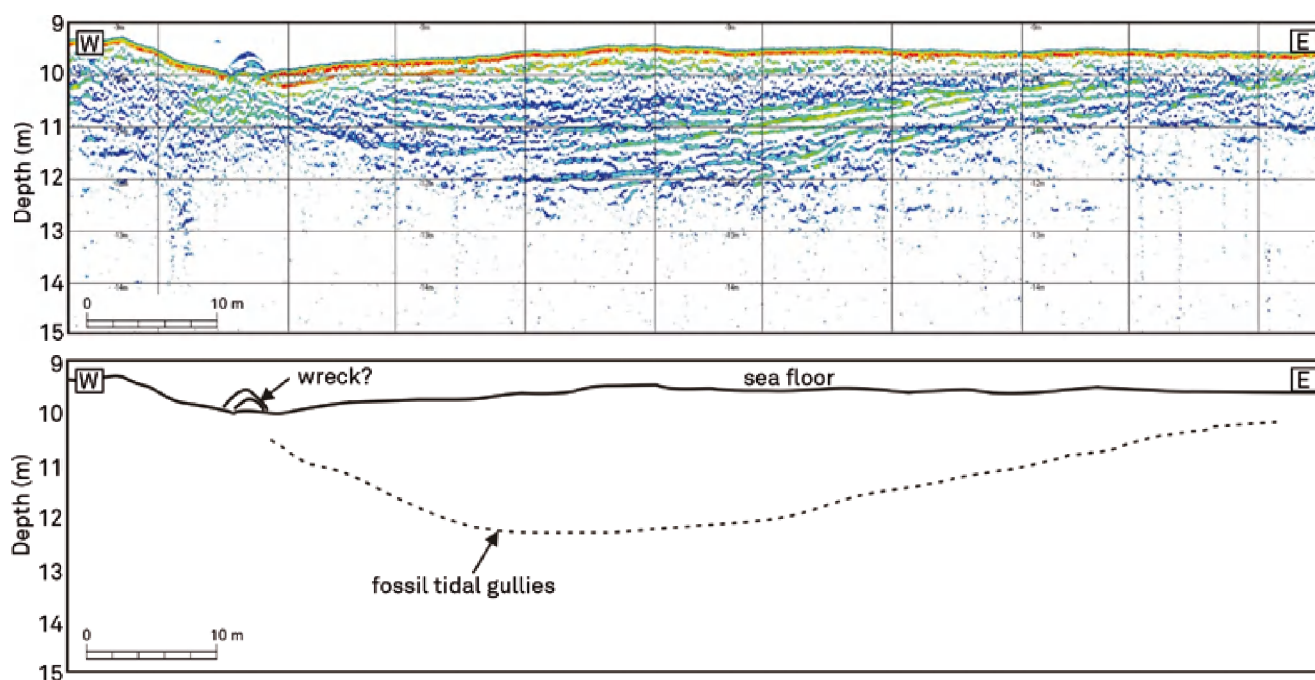


FIG. 9 Seismic profile B offshore Raversijde (for location see fig. 7). The interpreted line-drawing is shown below. Depth below the water surface is in meters. For description of the profile see text.

Seismisch profiel B voor de kust van Raversijde (voor de locatie van het profiel zie fig. 7). De geïnterpreteerde lijntekening wordt daaronder getoond. Diepte onder het wateroppervlak in meter. Een gedetailleerde bespreking van het profiel wordt gegeven in de tekst.

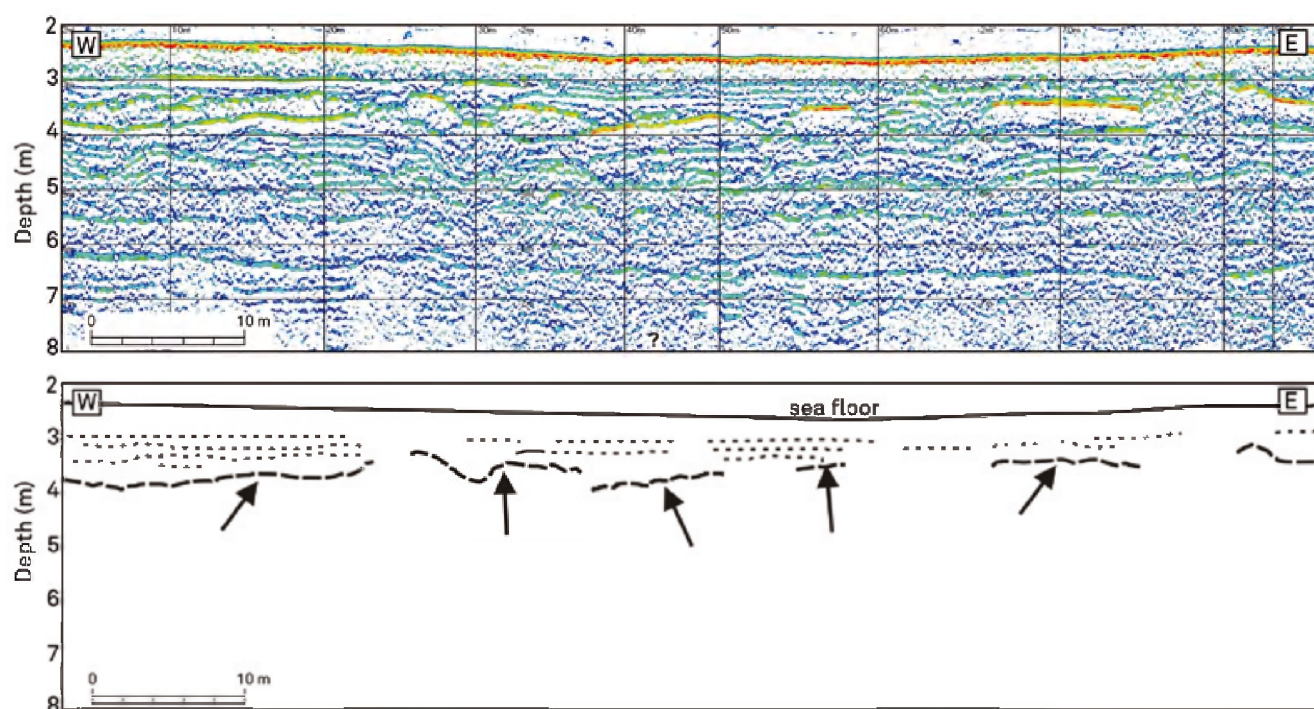


FIG. 10 Seismic profile C offshore Raversijde (for location see fig. 7). The interpreted line-drawing is shown below. Depth below the water surface is in meters. For description of the profile see text.

Seismisch profiel C voor de kust van Raversijde (voor de locatie van het profiel zie fig. 7). De geïnterpreteerde lijntekening wordt daaronder getoond. Diepte onder het wateroppervlak in meter. Een gedetailleerde bespreking van het profiel wordt gegeven in de tekst.

4 Case study 3: Seismic imaging of an exposed shipwreck, Buiten Ratel sandbank

The third example involves an 18th-century wooden shipwreck on the Buiten Ratel sandbank, 9 miles (16.5 km) offshore from Nieuwpoort. The wreck, which has a length of roughly 18 m, was examined extensively by divers between 1996 and 2005. Artefacts recovered from the shipwreck, including ceramics, weapons, tools, utensils, clocks and wood, bear a large resemblance to objects recovered from 18th-century VOC-ships (Verenigde Oost-Indische Compagnie - Dutch East India Company)²⁶. Up to now the identity of the shipwreck remains unknown. In 2007 a multibeam survey was carried out over the wreck site by the Flemish Hydrography (Vlaamse Hydrografische Dienst²⁷). The multibeam image shows that the wreck has been broken in two pieces; the partly exposed anchor is clearly visible (fig. 11).

In October 2007 a seismic survey was carried out over the Buiten Ratel shipwreck. During the survey a parametric echosounder source was used, combined with a motion sensor. More information on the seismic source is given in section 3 and in Zeebroek *et al.* (this volume). Positioning was done using a DGPS antenna with an accuracy of roughly 1 m. In total 44 short profiles were recorded, crossing the wreck at different angles (fig. 12). The length of the profiles ranges between 500 and 1000 m. Due to strong tidal currents it was not always possible to sail straight lines.

Figs. 13 to 15 show a few examples of seismic profiles recorded over the Buiten Ratel wreck. The upper and middle pictures respectively show the low-frequency (10 kHz) and high-frequency (100 kHz) seismic image, the lower picture shows an interpreted line-drawing. In general the wreck outline (thin red-yellow line) is observed more sharply on the high-frequency data. The low-frequency data are marked by deeper penetration into the sediments and therefore allow identification of buried objects.

On the seismic images we can clearly distinguish the wreck outline (bright red or yellow reflectors) and the sediment cover that spreads over the wreck surface (blue or blue-green reflectors). The wreck is entirely covered by sediments. The thickness of this sediment cover ranges from a few cm up to 50 cm or more. The low amplitudes of the sediment cover, compared with the high-amplitude seafloor reflection, suggests that we are dealing with relatively soft cover sediments (e.g. increased silt and/or mud content) in contrast to the surrounding sandy sea floor.

Although the different wreck parts stand out sharply on various profiles (e.g. fig. 14), the distinction is not always clear when we only look at the sediment cover. Most likely local sedimentation, induced by tidal currents, has partly silted up the gap between the wreck parts. The height of the wreck above the floor is in general no more than 1 m. The depth of the bottom of the wreck remains unknown because the acoustic signals cannot penetrate

²⁶ Zeebroek *et al.* 2010 (this volume).

²⁷ Vlaamse Hydrografie, Afdeling Kust van het Agentschap Maritieme Dienstverlening en Kust (MDK), Vrijhavenstraat 3, 8400 Oostende.

through the wreck. Only a few minor buried objects were observed near or (partly) under the wreck on the seismic profiles. But possibly this gives a distorted view of the actual situation – the chance to identify such objects is relatively small taking into account the large spacing between the profiles.

Seismic profile 18 (fig. 13)

This profile is oriented roughly N-S. The wreck contours on the seismic image are quite disturbed, most likely due to side reflections caused by curved or protruding parts of the wreck. The sediment cover is less than half a meter. The different wreck parts, well observed on the multibeam image, do not stand out clearly. Probably this is due to the fact that the profile mainly crosses over the northern edge of the eastern wreck part (see fig. 12: right). On the low-frequency profile (fig. 13: top) a buried object can be observed, most likely a small detached wreck piece. The thin blue lines on the low-frequency image (fig. 13: top) are probably due to acoustic noise related to the equipment.

Seismic profile 42 (fig. 14)

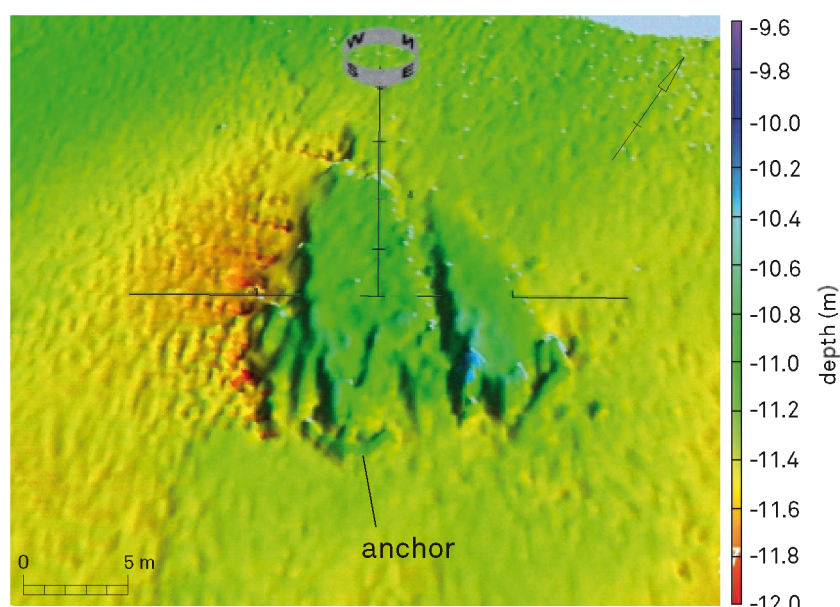
This profile is oriented SW-NE and crosses both wreck parts. The wreck is covered by a thin layer of sediments, no more than a few dm thick. The different wreck parts can be clearly distinguished. No additional buried objects were observed near or underneath the wreck. The thin vertical lines on the low-frequency image (fig. 14: top) are probably due to acoustic noise related to the equipment.

Seismic profile 30 (fig. 15)

This profile is oriented W-E and only crosses the western wreck part. The surface of the wreck is quite irregular, and there is a clear difference in height between the two wreck parts. The seismic image agrees well with the multibeam data. The wreck is covered by a thin sediment layer no more than a few decimetres thick. The weak reflector below the sea floor most likely marks a small buried wreck piece. The wavy blue lines in the water column of the low-frequency image (fig. 15: top) are most likely related to fish.

FIG. II Multibeam image acquired in 2007 over the Buiten Ratel wreck site (Flemish Hydrography). The two large wreck pieces can be clearly observed.

Multibeam afbeelding uit 2007 van het wrak van de Buiten Ratel (Vlaamse Hydrografische Dienst). Twee grote wrakstukken zijn duidelijk zichtbaar.



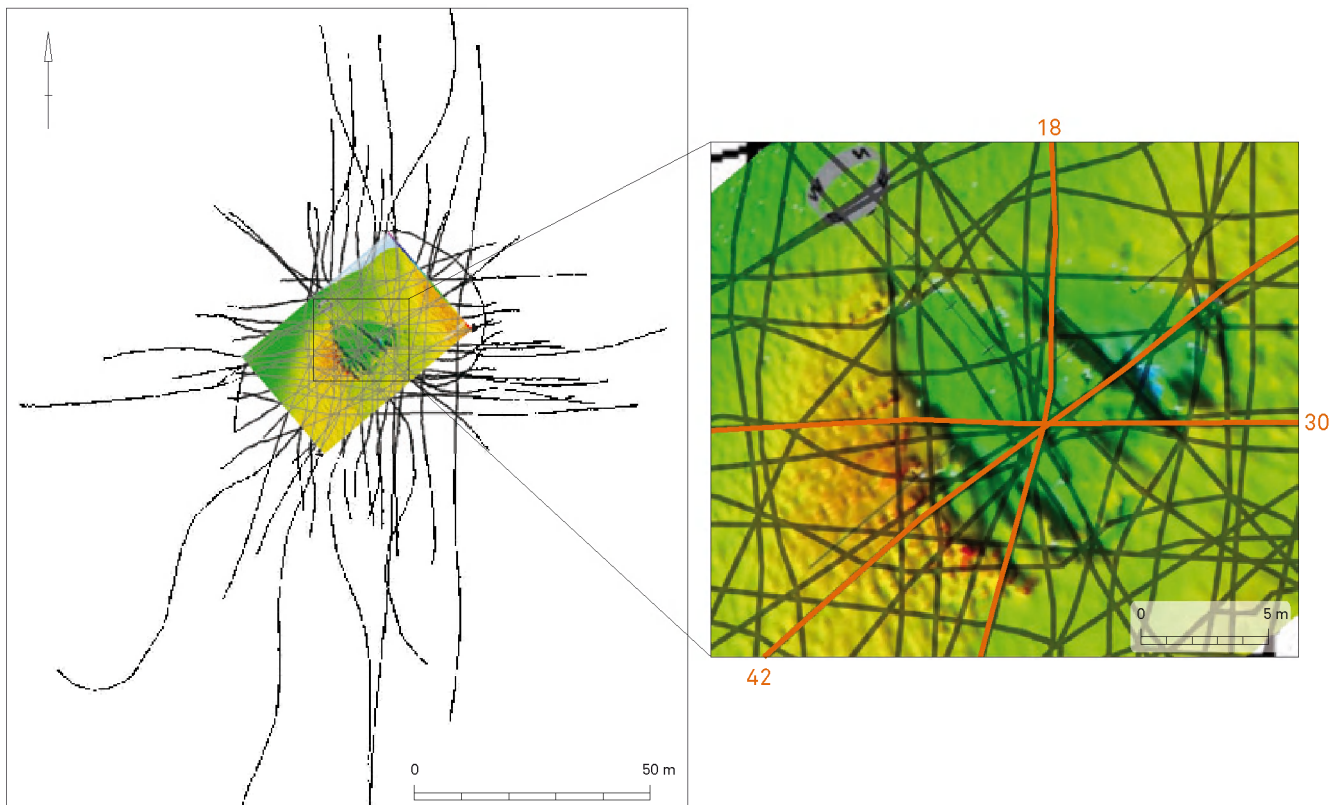


FIG. 12 Left: Seismic network recorded over the wreck site on the Buiten Ratel sandbank, plotted against a multibeam background (Flemish Hydrography). Right: Close-up of the multibeam image and seismic network. Thick orange lines mark the location of seismic profiles 18, 42 and 30 shown in figs. 13 to 15.

Links: Overzicht van het seismische netwerk dat werd opgenomen over het wrak op de Buiten Ratel-zandbank, geprojecteerd op een multibeam achtergrondkaart (Vlaamse Hydrografische Dienst). Rechts: Close-up van het seismisch netwerk en multibeam kaart. Dikke oranje lijnen markeren de locatie van profielen 18, 42 en 30 besproken in fig. 13 t.e.m. 15.

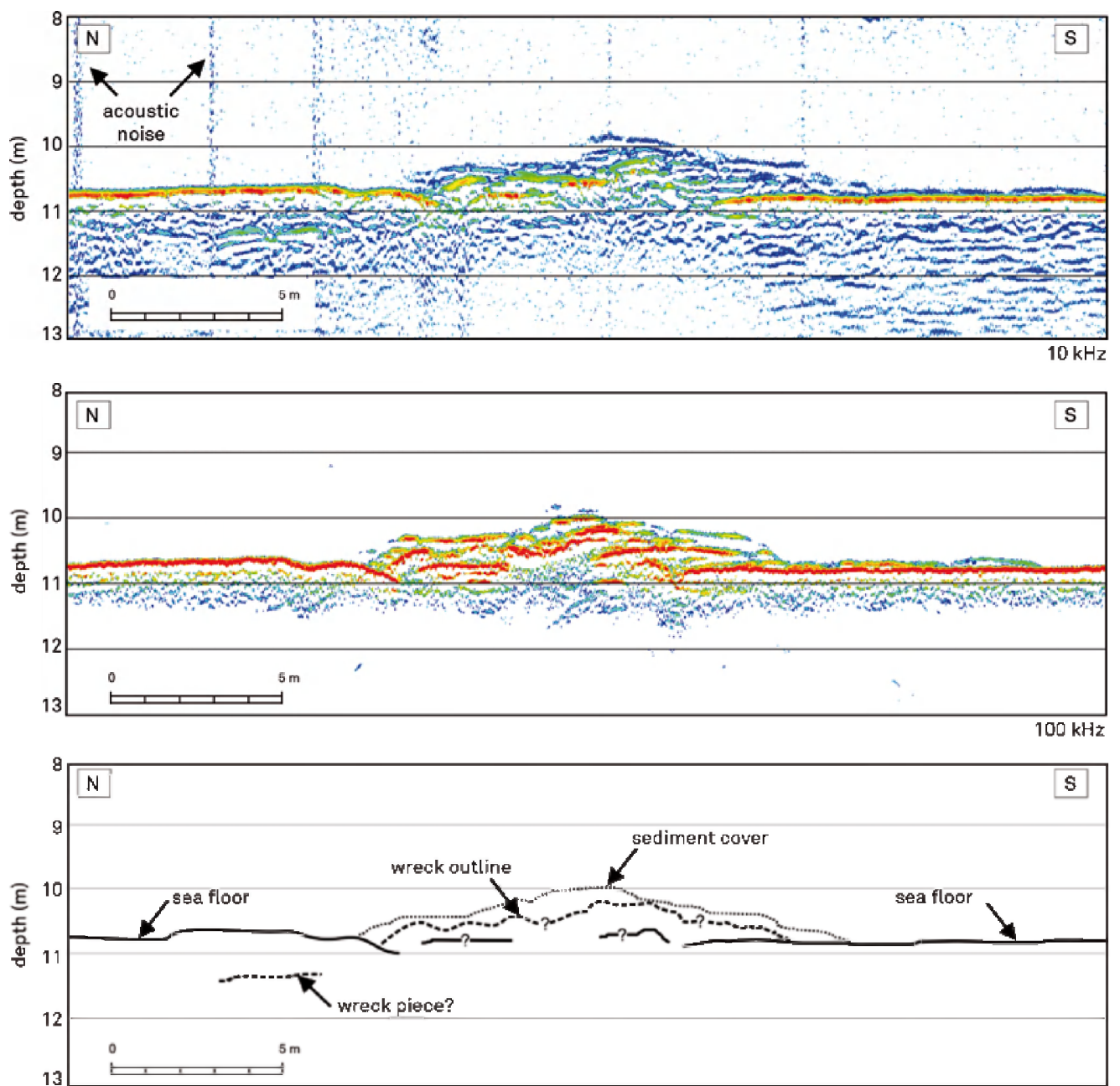


FIG. 13 Seismic profile 18 over the Buiten Ratel wreck site (for location see fig. 12). Top: Low-frequency image (10 kHz). Middle: High-frequency image (100 kHz). Bottom: Interpreted line-drawing. Depth below the water surface is in meters. For the description of the profile, see text.

Seismisch profiel 18 over het wrak op de Buiten Ratel zandbank (voor de locatie van het profiel zie fig. 12). Boven: Laagfrequent beeld (10 kHz). Midden: Hoogfrequent beeld (100 kHz). Onder: Geïnterpreteerde lijntekening. Diepte onder het wateroppervlak in meter. Een gedetailleerde bespreking van het profiel wordt gegeven in de tekst.

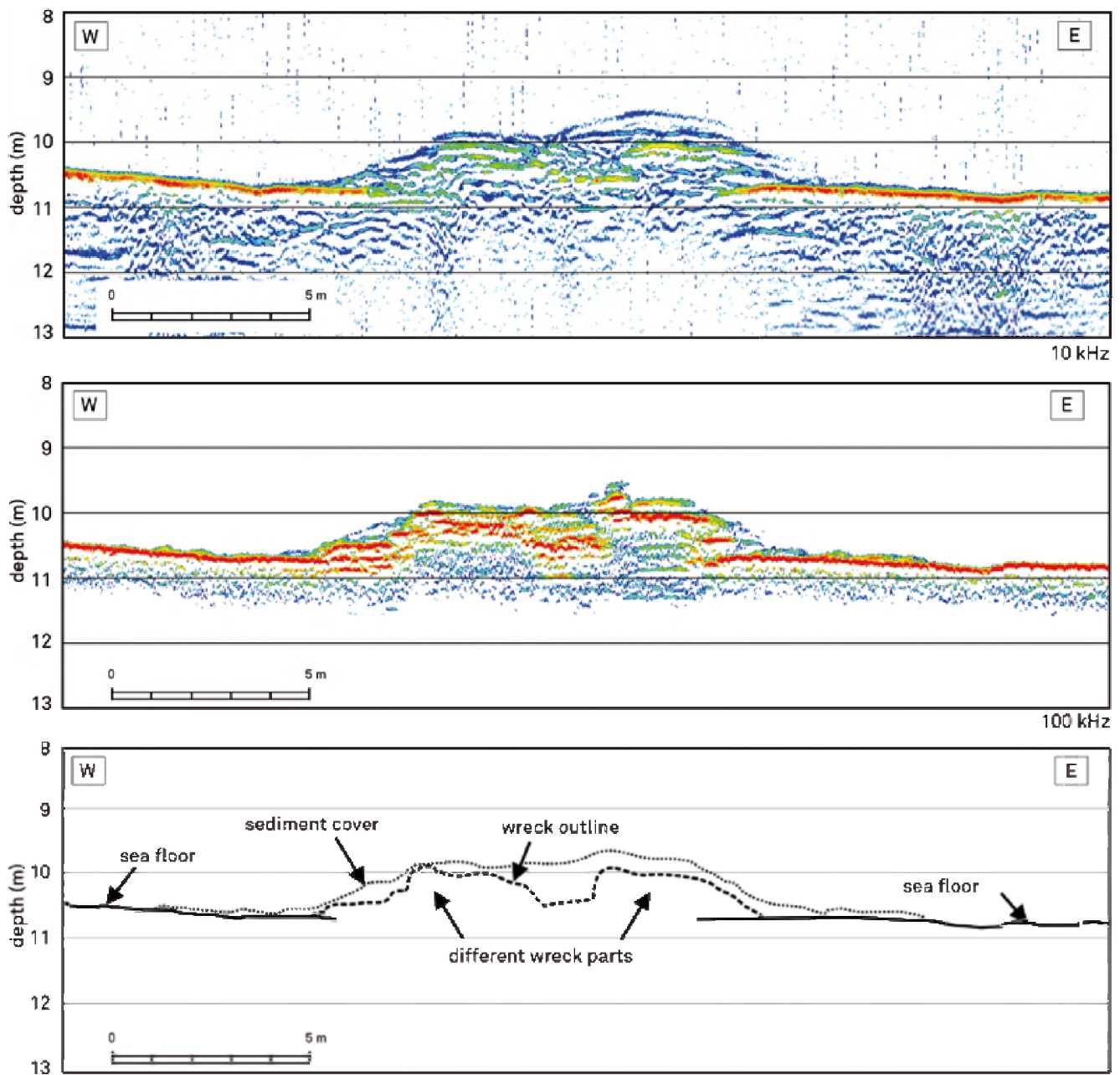


FIG. 14 Seismic profile 42 over the Buiten Ratel wreck site (for location see fig. 12). Top: Low-frequency image (10 kHz). Middle: High-frequency image (100 kHz). Bottom: Interpreted line-drawing. Depth below the water surface in meters. For description of the profile see text.

Seismisch profiel 42 over het wrak op de Buiten Ratel zandbank (voor de locatie van het profiel zie fig. 12). Boven: Laagfrequent beeld (10 KHz). Midden: Hoogfrequent beeld (100 KHz). Onder: Geïnterpreteerde lijntekening. Diepte onder het wateroppervlak in meter. Een gedetailleerde bespreking van het profiel wordt gegeven in de tekst.

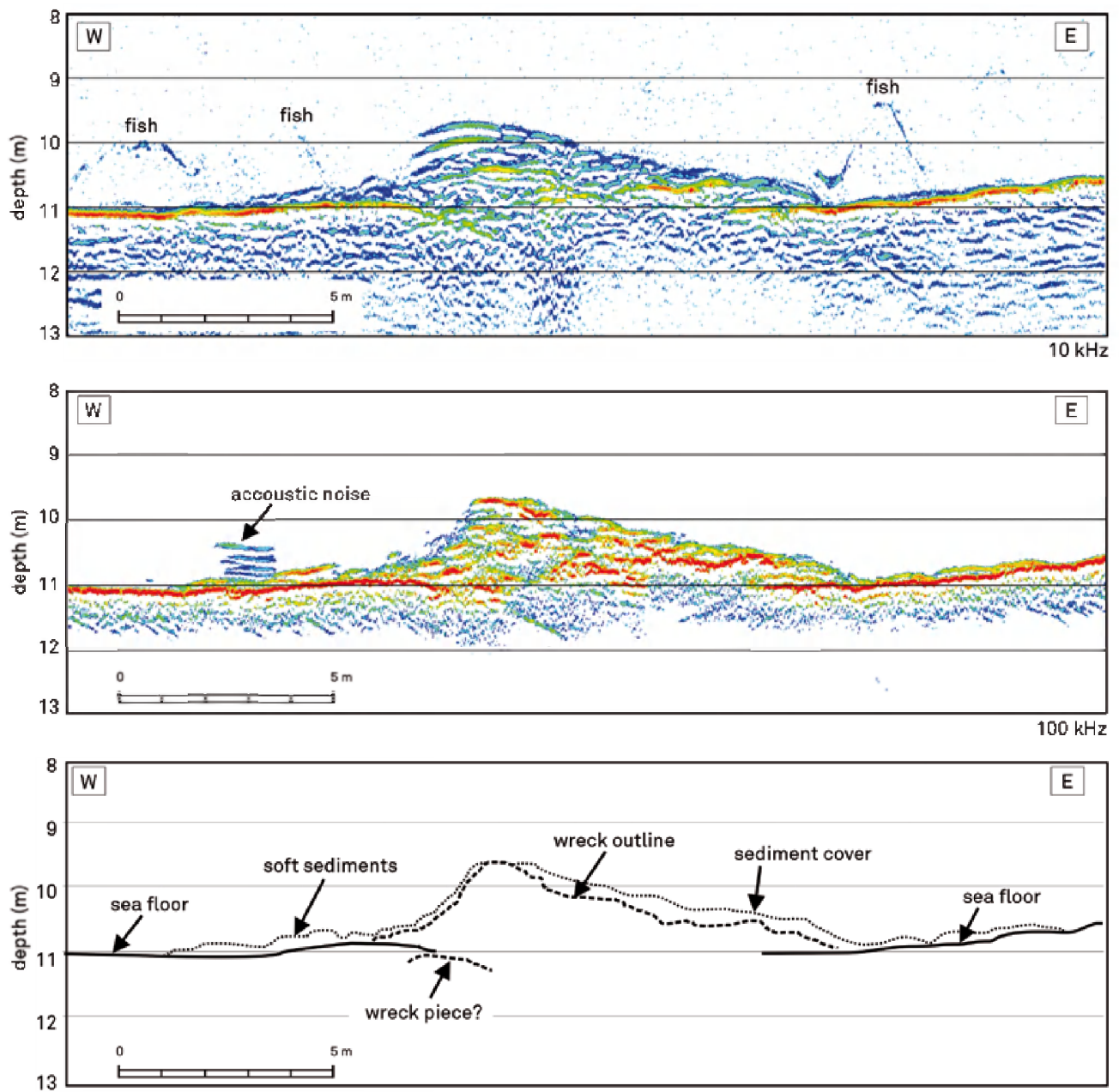


FIG. 15 Seismic profile 30 over the Buiten Ratel wreck site (for location see fig. 12). Top: Low-frequency image (10 kHz). Middle: High-frequency image (100 kHz). Bottom: Interpreted line-drawing. Depth below the water surface in meters. For description of the profile see text.

Seismisch profiel 30 over het wrak op de Buiten Ratel zandbank (voor de locatie van het profiel, zie fig. 12). Boven: Laagfrequent beeld (10 kHz). Midden: Hoogfrequent beeld (100 kHz). Onder: Geïnterpreteerde lijntekening. Diepte onder het wateroppervlak in meter. Een gedetailleerde bespreking van het profiel wordt gegeven in de tekst.

Summary and conclusions

The use of marine seismic techniques for archaeological studies is illustrated by three different case studies. A first case study involved a buried wooden shipwreck in the Dutch Wadden Sea. Although the acoustic visibility of buried wooden objects will depend on various factors (a.o. related to the wood and the surrounding sediment), clear detection is mostly possible. In our case the different wreck parts, covered by roughly 2 m of sediment, stood out markedly on the seismic profiles. The images confirm the existing information regarding shape and setting of the wreck. The seismic data furthermore suggest a moderate state of decay of the wood.

The second case study focused on the nearshore zone off the coast of Raversijde. The seismic data allowed to identify a large number of fossil tidal channels. A more recent tidal gully, oriented roughly parallel to the shoreline, can most likely be linked to an old coastal defense feature. The exact age of this gully is not known. No offshore remnants were found of the Roman dyke discovered behind the dunes in Walraversijde. The seismic profiles nearest to the beach show the indication of a large number of man-made features, possibly related to the fishing village or peat-exploitation.

The last case study involved an exposed 18th-century wooden shipwreck on the Buiten Ratel sandbank. The wreck has been broken up in two large pieces. The different wreck pieces are clearly distinguished on the seismic data. Recent sedimentation, possibly induced by tidal currents, has resulted in a thin cover of relatively soft sediments. The latter has also partly silted up the gap between the two wreck parts. The wreck sticks out less than 1 m above the sea floor. A few small buried objects were observed near and under the wreck; most likely these can be linked to detached wreck pieces.

The results from the different case studies clearly demonstrate the potential of very high resolution seismic imaging for marine archaeological site investigations, in particular buried objects. The challenge of these often shallow marine environments calls on advances in technology, together with a certain pragmatism and creativity. Careful survey design is needed using lightweight equipment and small, shallow draft boats. A high spatial survey accuracy, preferably in 3 dimensions, is essential. Line spacing should be adapted to the size and specifications of the site. For example in the Raversijde study a closer line spacing (in the order of meters or tens of meters) should allow to get a closer grip on the full extent and exact distribution of the fossil gully system and its possible relation to ancient coastal defence features. Detailed imaging of buried archaeological objects requires an even higher grid density. If the location of the object is known this generally does not pose a major problem. The big challenge, however, is to find objects of which we do not know they are there.

It is likely that no single technique will provide all the answers. The inventive use of complementary methods, for instance merging marine seismic acquisition with ground-truth coring and other geophysical measurements (e.g. electric or electromagnetic methods, land-based seismics) is likely the best strategy.

In the Raversijde study such added ground-truth data, taken on the beach at low tide, should result in improved detection and identification of the man-made features that were observed on the marine seismic data. Recent studies in the *Verdronken land van Saeftinge* have shown that such integrated approach is indispensable for a better understanding on the shallow sedimentary environment, and its archaeological potential²⁸. This opens new perspectives for the use of geophysical techniques in marine archaeological site surveys.

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The captain and crews of the 'Westergat' and 'Last Freedom' are gratefully acknowledged. The author would furthermore like to thank Wim Versteeg, Koen De Rycker, Arne Bayens, Remco Romijn and Seger van den Brenk for their assistance during the data acquisition. The Wadden Sea survey was carried out in the framework of the IMAGO project ('Innovatief Meten aan Gezonken Objecten') in collaboration with TNO-TPD, The Netherlands.

Samenvatting

Het potentieel van seismische beeldvorming in marien archeologisch onderzoek

Seismische beeldvormingstechnieken worden de laatste jaren met groeiend succes toegepast in marien archeologisch onderzoek, onder andere voor scheepswrakken en bedolven paleo-landschappen. Vreemd genoeg werd hieraan in België tot nu toe bijna geen aandacht besteed. Een eerste voorzichtige stap werd gezet met twee verkennende surveys voor de kust van Raversijde en bij een scheepswrak op de Buiten Ratel zandbank. Aan de hand van deze twee voorbeelden én een eerdere studie van een begraven houten scheepswrak in de Waddenzee (Nederland) illustreren we het potentieel van marien seismische metingen voor archeologische studies.

Bij seismische metingen wordt met behulp van gereflecteerde geluidsgolven een beeld gevormd van de structuur van de ondergrond. Daartoe worden een akoestische bron en één of meerdere ontvangers achter een schip gesleept. De bron zendt geluidsgolven uit die weerkaatst worden op de zeebodem en de onderliggende lagen. Deze gereflecteerde signalen worden opgevangen door de ontvangers. Doordat het meetschip zich constant verplaatst wordt op die manier een verticale doorsnede van de zeebodem bekomen, langs het traject van het schip.

Het onderzoek op de Waddenzee, uitgevoerd in 2003 in het kader van het IMAGO-project, betrof een bedolven 16de-eeuws houten scheepswrak. Het wrak ligt begraven onder een sedimentlaag van maximum 2 meter dik, en is uiteengevallen in twee delen. Beide wrakdelen zijn duidelijk waarneembaar op de seismische beelden. De vorm en ligging van de wrakdelen bevestigen eerdere informatie van duikers (in de jaren 90 van de 20ste eeuw) toen het wrak nog gedeeltelijk aan de oppervlakte lag. De seismische data lijken te wijzen op een niet al te verregaande staat van ontbinding van het hout.

Op de seismische profielen voor de kust van Raversijde valt de aanwezigheid op van een aantal fossiele getijdengeulen. Door de grote afstand tussen de seismische lijnen (100 tot 200 m) is het niet steeds mogelijk om het precieze verloop van deze geulen te volgen. Duidelijke sporen van de Romeinse dijk, die aan land werd teruggevonden, zijn niet te zien. Opmerkelijk is echter een kleine subrecente getijdengeul die parallel loopt met de huidige kustlijn en die waarschijnlijk duidt op een oude kustverdediging. De grillige vorm van de ondiepe seismische data dicht bij het strand suggereert een antropogene oorsprong. Mogelijk hebben we te maken met restanten van het eerste vissersdorp Walraversijde.

De seismische survey op de Buiten Ratel zandbank toont duidelijk aan dat het wrak begraven ligt onder een variabele sedimentlaag van een paar cm tot ruim een halve meter dik. Het wrak steekt niet meer dan 1 meter uit boven de zeebodem. De bovenkant van het wrak is vaak grillig, met een duidelijk hoogteverschil tussen beide wrakdelen. Op sommige plaatsen zijn de

wrakdelen gedeeltelijk aan elkaar gesedimenteerd. Een paar begraven objecten (mogelijk afgebroken wrakdelen) werden waargenomen vlakbij het wrak.

De resultaten van deze drie verschillende casestudy's tonen duidelijk het nut aan van seismische opnames voor archeologisch onderzoek. Het vaak ondiepe water vergt een nauwkeurige planning, met gebruik van kleine bootjes en licht materiaal, en een lijnspatiëring die is aangepast aan de specificaties van elke vindplaats. Ondanks de veelbelovende resultaten kan één enkele techniek uiteraard nooit alle antwoorden leveren. Het inventieve gebruik van complementaire methodes is waarschijnlijk de beste strategie. Mariene seismiek kan bijvoorbeeld gecombineerd worden met ondiepe boringen of met andere geofysische metingen, zowel op zee als aan land. Dat laatste is bijvoorbeeld van toepassing op Raversijde. Dit opent nieuwe perspectieven voor de ontwikkeling en het gebruik van seismische technieken voor marien archeologisch onderzoek.

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