CASE STUDY 3L – OSTEND RAVERSIJDE, BELGIUM.

Case Study Area: Ostend/Raversijde

Main geomorphological types: Beaches, Dunes

Main coastal change processes: Natural erosion, Human induced

Primary Resources used: Archaeological/Palaeoenvironmental Data

Summary: The Ostend-Raversijde study area, located on the central Belgian coast, is known for its numerous archeological traces and remnants, often found in the intertidal zone but all buried now due to sand accretion. The technological challenges posed by the land-sea transition zone made this an excellent test-case.

Recommendations: The results of this case study demonstrate that a clever combination of marine and terrestrial geophysical and geotechnical techniques forms a valuable tool for the evaluation of archaeological remnants and the reconstruction of buried palaeo-landscapes. This opens important perspectives for long-scale coastal change studies, especially in view of the current and future coastal defense plans

Coastal managers face an ongoing battle to moderate impacts from the sea in the face of a changing climate and pressures from human use of the coastal zone. The challenges that lie ahead are forecast to increase while resources are being forced to go further.

This case study report is part of the technical report on the Arch-Manche project, which quantifies the value of under-used coastal indicators that can be applied as tools to inform long term patterns of coastal change. In addition, it provides instruments to communicate past change effectively, model areas under threat and interpret progressive coastal trends.

Ostend/Raversijde is one of two Belgium case study areas for the Arch-Manche project. This case study report introduces the study area and why it was chosen as part of the project, the results of the archaeological and palaeoenvironmental study are then presented. The analysis of these results and the potential for demonstrating the scale and rate of coastal change are then presented. For further details about the project methodology see Section 2.

Within the study area the archaeological and palaeoenvironmental resource has been researched, ranked and analysed along with a small number of historical maps. The extents of the detailed study areas are shown in Figure 3L1 below.

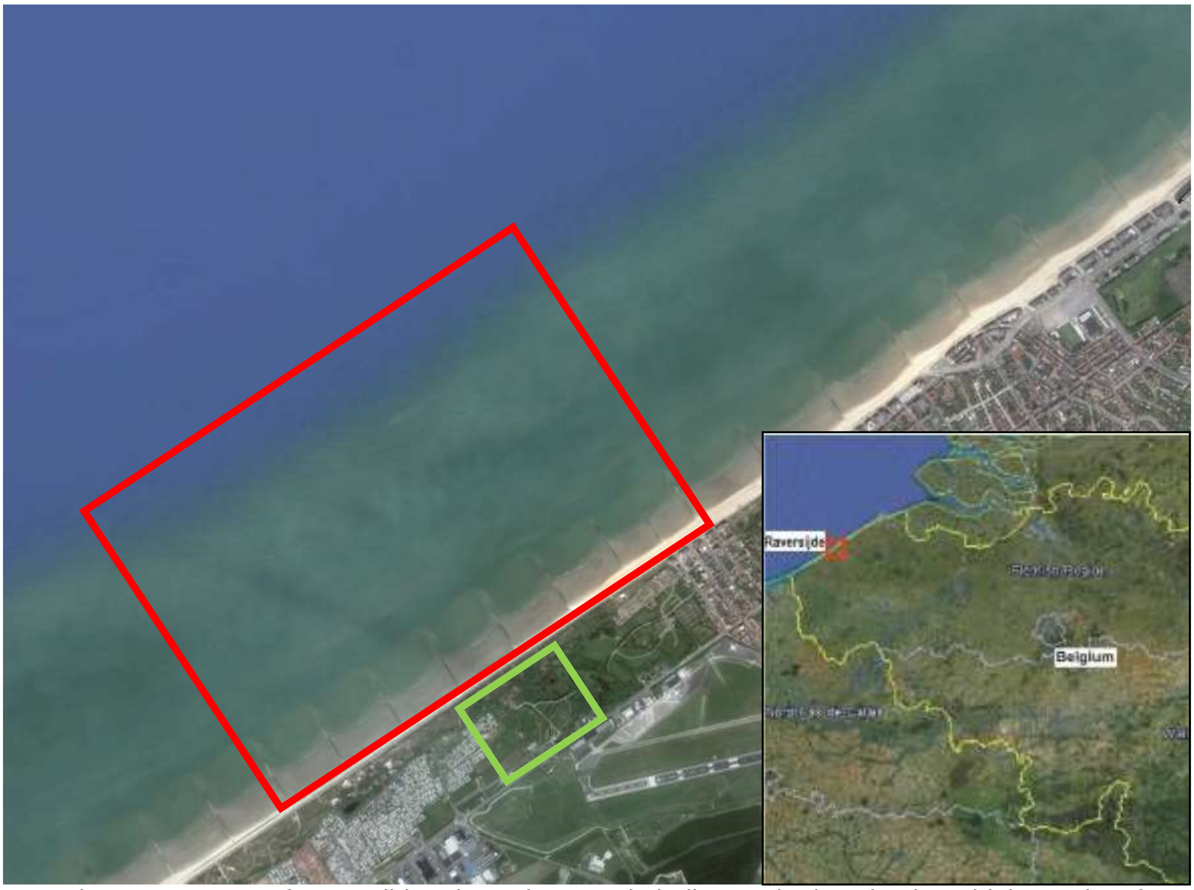

Figure 3L1: Area of Raversijde. The red rectangle indicates the location intertidal test site of Raversijde (red rectangle). The green rectangle marks the archaeological site inland, where many investigations have carried out since 90's (Google Earth).

3L.1 Introduction to the Ostend/Raversijde Study Area

The Ostend-Raversijde study area is located in the central Belgian coastal region, between Ostend and Middelkerke (Figure 3L1). The Belgian coast is largely marked by a rigid coastline, consisting of a small strip of beaches, directly bordered by human reinforcements, sometimes intersected by dune sections. This rigid coastline only came into existence after the Early Middle Ages, due to human embankment activities. In the Holocene pre-medieval period, the coastline was characterized by barrier beaches with tidal flats extending landward. The present beach of Raversijde is a low lying, slightly seaward sloping intertidal area. Since the 19th century, many archeological traces and structures have been found, almost all being located in the intertidal zone (Demerre et al., 2013). This archaeological importance, and the fact that such an intertidal zone poses major technological challenges (combining both marine and land survey techniques), makes this an excellent test-case for the evaluation of these techniques for efficient palaeogeographical landscape reconstructions in the Belgian coastal area.

3L.1.1 Geomorphological evolution

This section outlines the key geological and geomorphological features and processes of the study area. These factors have a significant impact on the on-going changes to the coastline and associated sites, deposits and features preserved related to the archaeological and heritage resource.

Pre-Holocene evolution of the Ostend Valley

The pre-Holocene evolution of the Belgian coastal plain is highly intertwined with 4 major palaeovalleys: the IJzer, Ostend, Coastal and Flemish valley. An overview map of these valley systems and the surrounding top-Pleistocene (i.e pre-Quaternary or top-Paleogene) surface of the Belgian continental shelf and coastal area is shown in Figure 3L2. The Ostend-Raversijde site is located at the edge of the Ostend Valley, which was connected to the Flemish Valley through the Coastal valley (Mathys, 2009; De Clercq et al., 2013). The Ostend valley itself was formed during the Saale ice age (ca. 352.000 - 130.000 yrs BP). At that time the North Sea was dry land and large rivers incised the landscape. Gradually, river sediments were deposited in the valley. When temperatures started to rise at the end of the Saale ice age, the permafrost melted and the river started to incise even further. During the warmer Eem period (ca. 130,000 - 116,000 yrs BP) sea level rose again and the Ostend valley transformed into a tidally influenced estuarine area. It is then that it obtained its typical funnel shape (Figure 3L2).

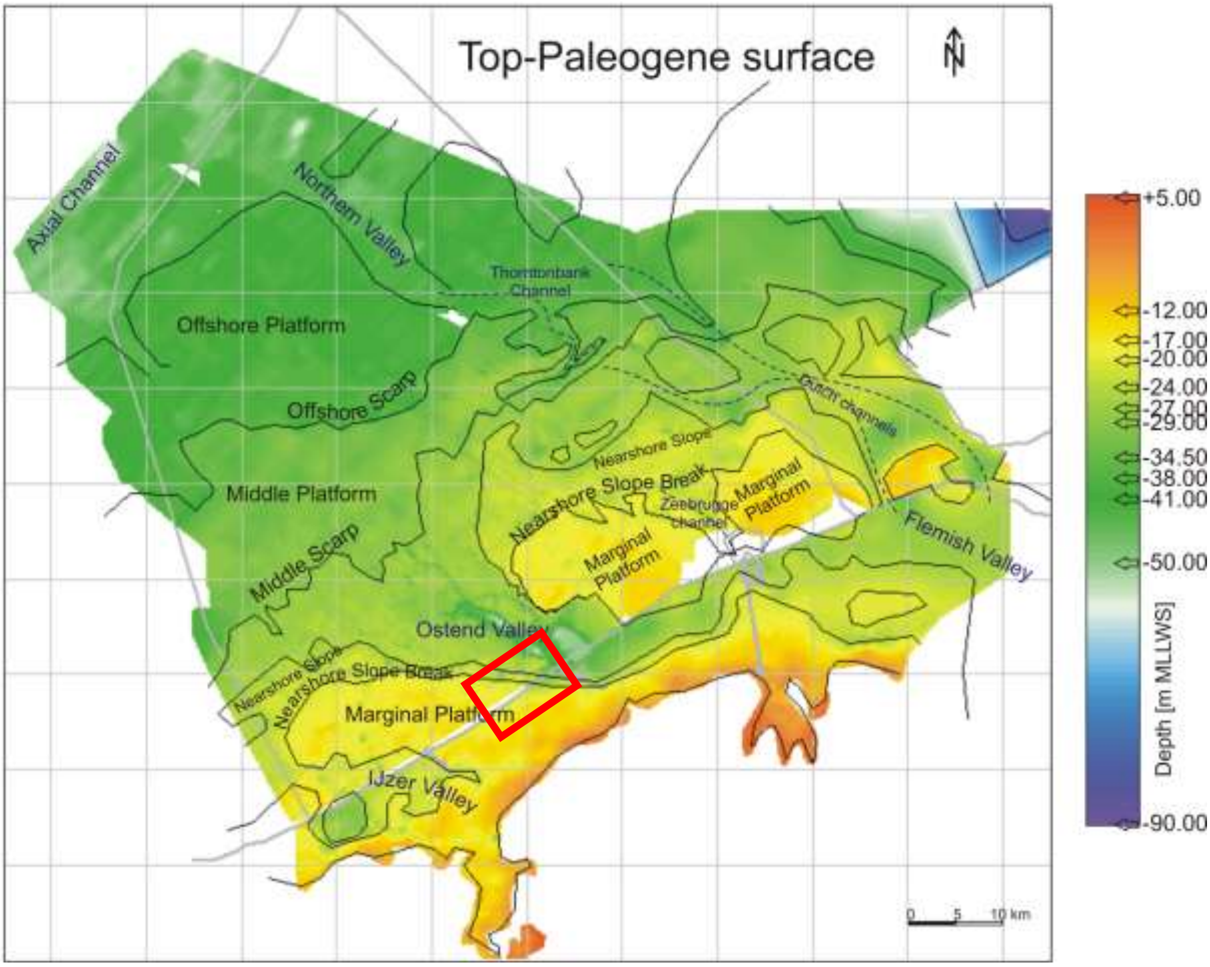

Figure 3L2: Pre-Quaternary (top-Paleogene) topography of the Belgian continental shelf and coastal plain, and its four valley systems (Ostend, IJzer, Coastal and Flemish valley). The Ostend Valley has a typical funnel-shape (De Clercq et al., 2013; Mathys, 2009).

During the following ice age, the Weichsel (116.000 – 11.700 yrs BP), sea level dropped and the North Sea became dry land again, and the Ostend valley was transformed into a river valley again. Incision, however, was less profound than in the Saale period. Due to the dry conditions, large dune complexes were formed. One of these dune complexes (*Maldegem-Stekene*) separated the Ostend valley from the Flemish valley, causing the end of river activity in the Ostend valley (Mathys, 2009).

Holocene evolution of the study area

The shallow sediments of the study area are made up of a highly variable (laterally and vertically) sequence of sand, peat, silt and clay layers that reflect the complex history of the Holocene during which marsh-like environments, sandy dunes, and intertidal mud- and sandflats alternated.

During the Early Holocene sea level rose very fast and a large part of the Belgian continental shelf was already inundated (red line in Figure 3L3). A large coastal plain came into existence, roughly 20-30 km offshore from the present coastline. Because of the increasing wave action a large dune barrier system developed in front of the coastal plain (Figure 3L4). Behind the dune barrier, the coastal plain most likely consisted of a large (inter)tidal flat environment marked by constantly changing tidal channels, tidal flats and marshes. The landward part was most likely cut by numerous rivers that flowed towards the sea. Together with sea level rise also the groundwater level started to rise, and coastal peatland started to develop for the first time (so-called 'basal peat') (Baeteman, 2007).

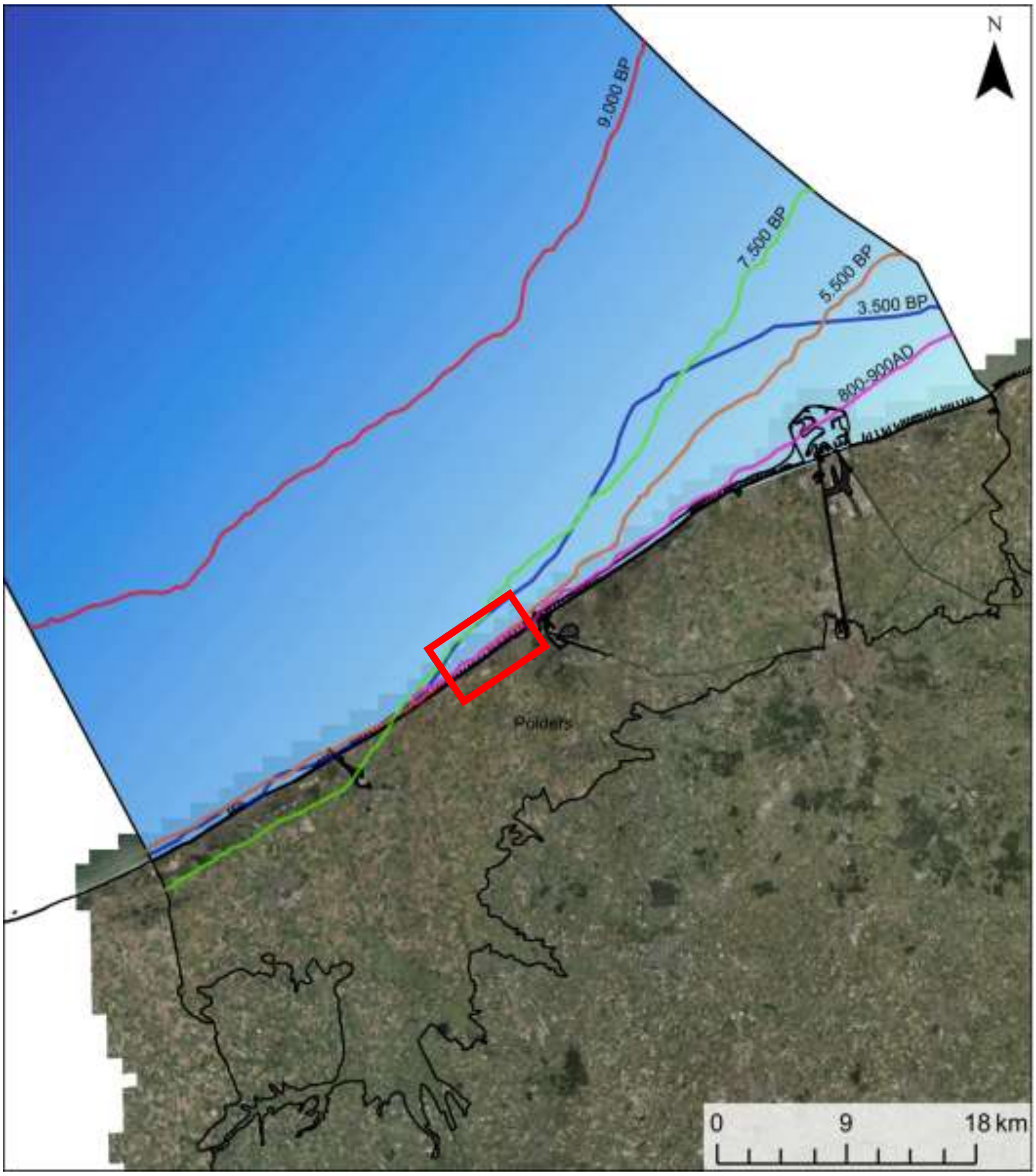

Figure 3L3: Schematic evolution of the Belgian coastline during the Holocene (De Clercq, 2013, after: Mathys, 2009). The red rectangle marks the Ostend-Raversijde site. The black line on land marks the edge of the current coastal plain.

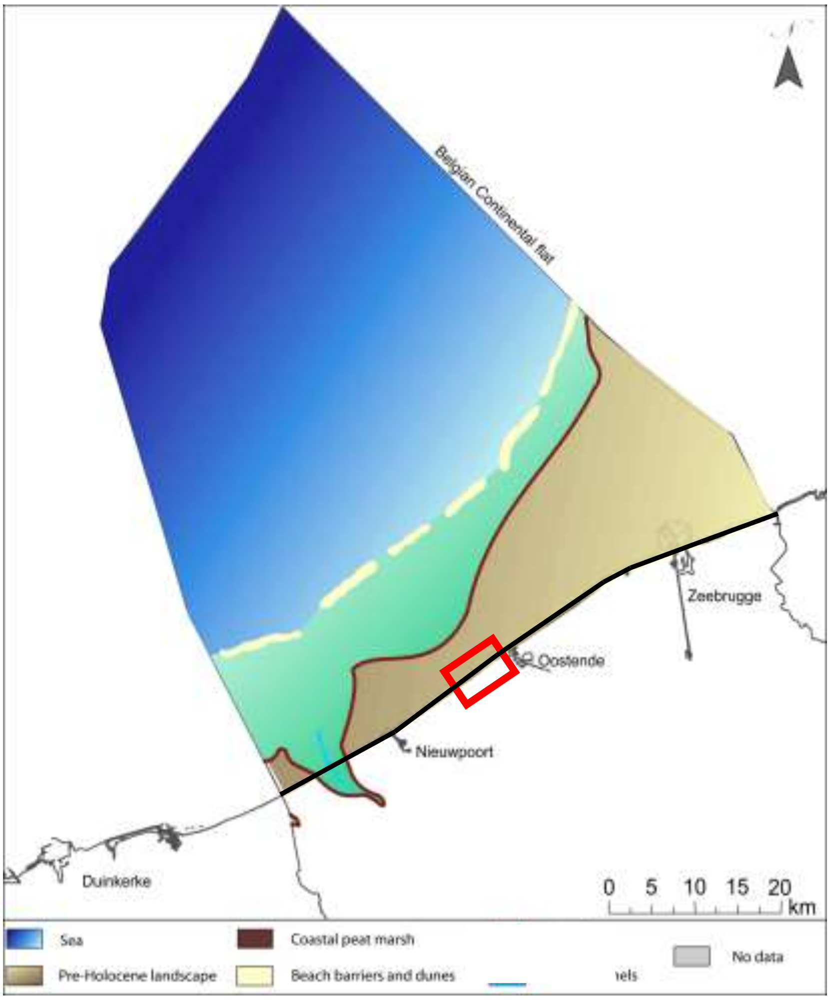

Figure 3L4: Very tentative reconstruction of the coastal plain around 9000 BP (De Clercq, 2014, http://www.sea-arch.be/nl/content/kaarten). The red rectangle marks the survey area of Ostend-Raversijde. The thick black line marks the present coastline.

Over the next 2000 years, sea level kept on rising fast and the coastline shifted further towards the land (green line in FigureL3). This caused considerable infilling of the tidal gullies with marine sand and clay. In the western part the sea intruded far inland. Around 7,000 yrs BP sea level rise started to slow down and the dune barrier system stabilized. This finally resulted in rising of the intertidal area to a level that prevented frequent flooding. For the second time, a fresh water marsh developed and peat growth was started (so-called 'surface peat') (Figure 3L5) (Baeteman, 2007; Mathys, 2009)

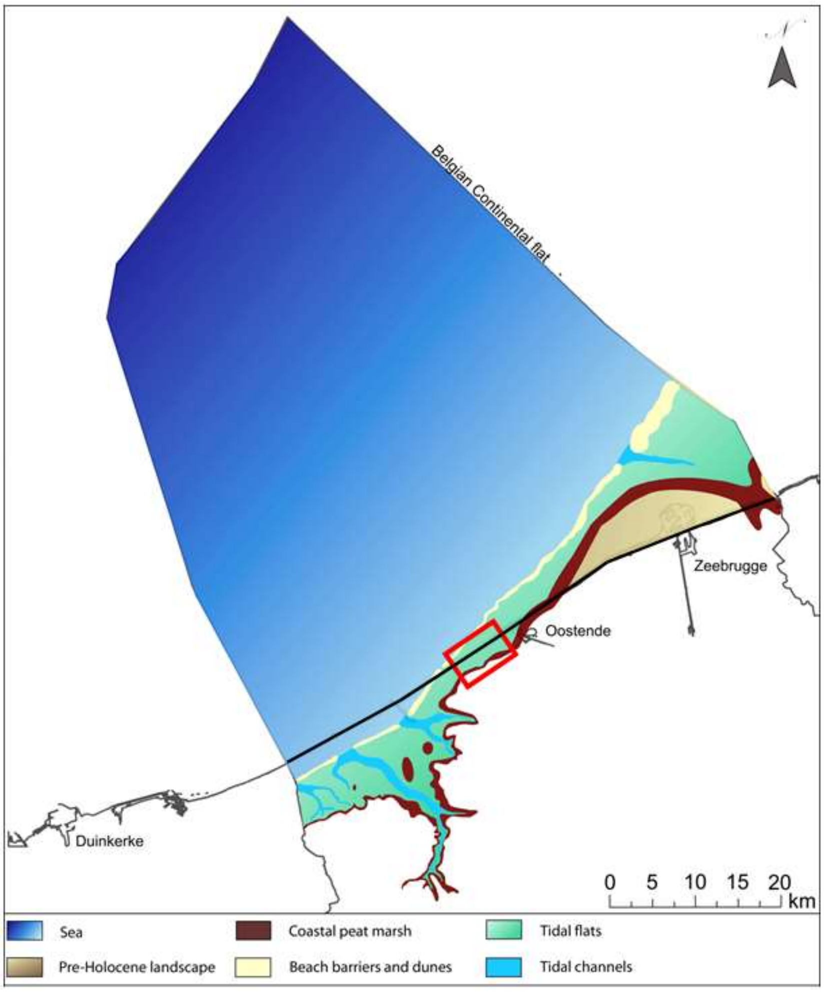

Figure 3L5: Very tentative reconstruction of the coastal plain around 7500 BP (De Clercq, 2014, http://www.sea-arch.be/nl/content/kaarten). The red rectangle marks the survey area of Ostend-Raversijde. The thick black line marks the present coastline.

Around 5500 BP sea level rise slowed down even further, causing a constant accumulation and growth of peat. An extensive coastal marsh, characterized by reed vegetation, started to cover almost the entire coastal plain (Figure 3L6). In the east the coastline shifted further inland, whereas in the west the coastline shifted slightly back (orange line in Figure 3L3).

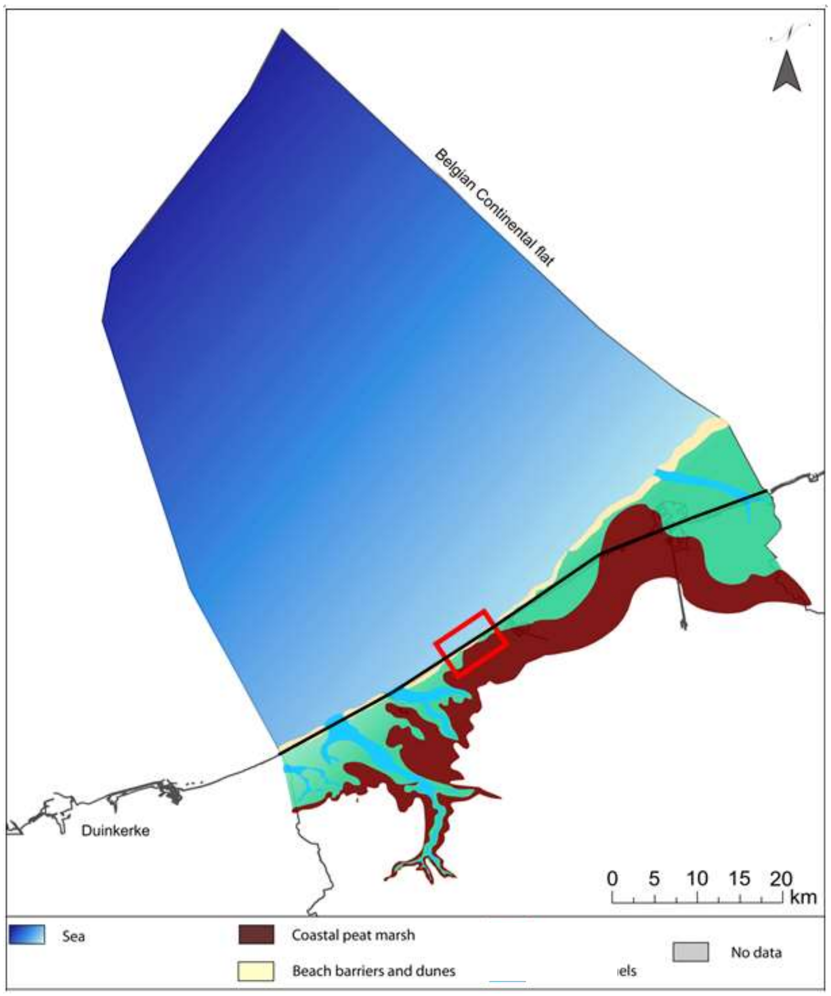

Figure 3L1: Very tentative reconstruction of the coastal plain around 5500 BP (De Clercq, 2014, http://www.sea-arch.be/nl/content/kaarten). The red rectangle marks the survey area of Ostend-Raversijde. The thick black line marks the present coastline.

Over the next 2000 years peat growth expanded over a vast area. Towards the east a wide beach barrier system developed (Figure 3L7). In the survey area, the position of the coastline does not change significantly (blue line in Figure 3L3). Around 2,500 yrs BP peat growth started to slow down. Tidal channels cutting through the marsh were now becoming eroded by enlarged precipitation run off from the *hinterland* (due to climate change and deforestation). At the fringes of the tidal channels, the peat eroded completely, causing drainage of the peat layer and subsequent lowering of the surface (ca. 1 to 1.5 meters). Due to this compaction, the fresh water marsh was converted to an intertidal area again. By 1,500 BP the peat growth comes, even in the most landward areas, to a definitive halt (Baeteman, 2007).

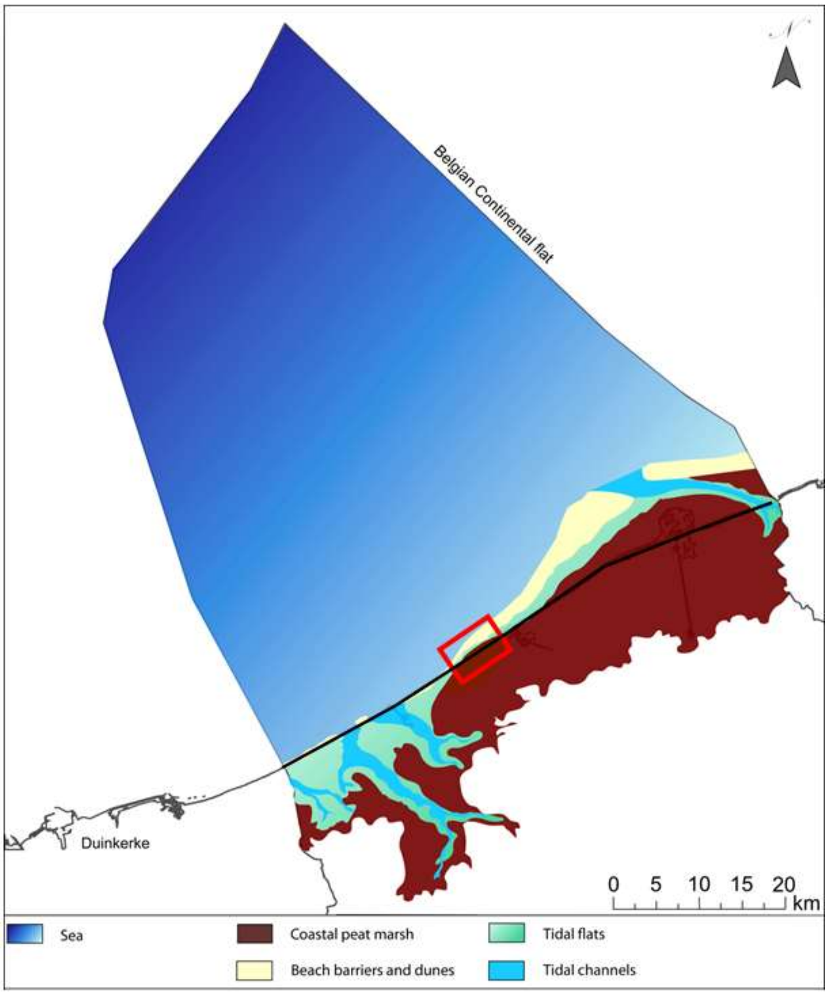

Figure 3L2: Very tentative reconstruction of the coastal plain around 3500 BP (De Clercq, 2014, http://www.sea-arch.be/nl/content/kaarten). The red rectangle marks the survey area of Ostend-Raversijde. The thick black line marks the present coastline.

During the Iron Age and Roman era the sea was located a few miles offshore from today's coastline and an area of sandy dunes formed the border between sea and land. The area behind the dunes was marsh-like and crossed by numerous creeks and tidal gullies.

From the Roman period onwards the coastal plain noticed a growing human influence. Drainage and peat extraction (see next section) further caused the surface to be lowered. After the Roman period the sea slowly progressed more inland, and a tidal flat was again installed in almost the entire coastal plain (Figure 3L8) (Baeteman, 2007). It has been suggested that this increased tidal activity was possibly the result of increasing neglect of the water management systems during the late Roman period (Ervynck et al., 1999).

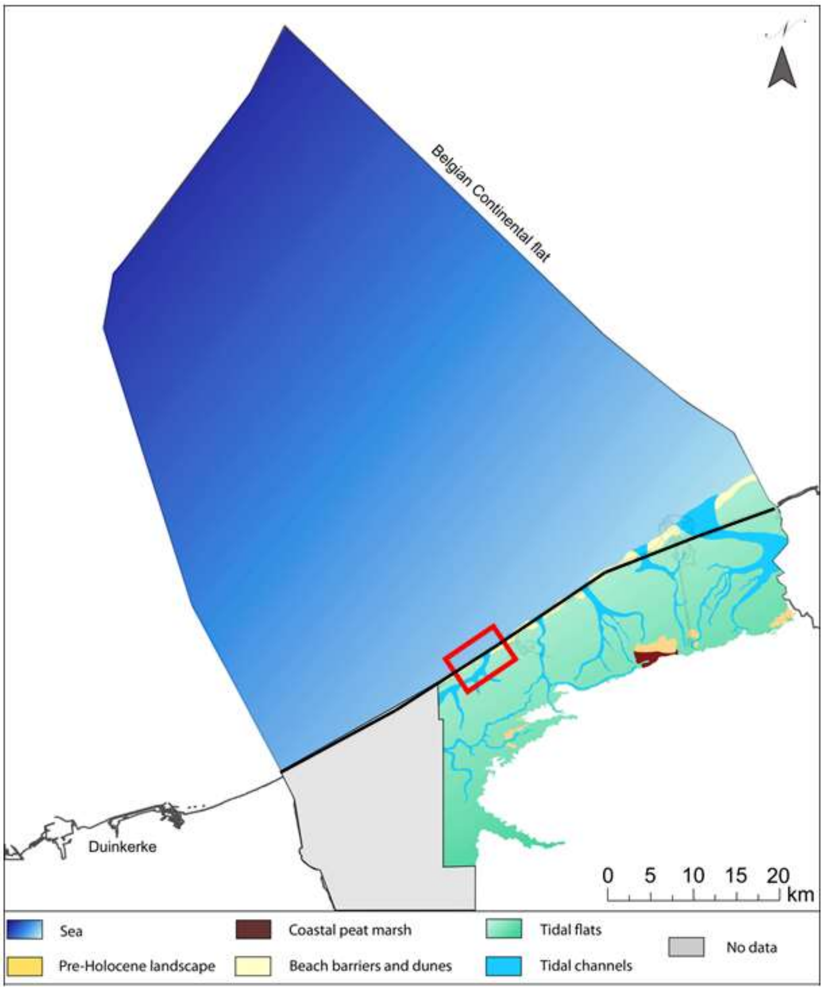

Figure 3L3: Very tentative reconstruction of the coastal plain in the Early Middle Age (De Clercq, 2014, http://www.sea-arch.be/nl/content/kaarten). The red rectangle marks the survey area of Ostend-Raversijde. The thick black line marks the present coastline.

The palaeo-geographical setting of the study area during the early Middle Ages (9th-10th century) is illustrated in Figure 3L4. The coastal plain had silted up to high-tide level, except for some tidal channels that remained open (Mathys, 2009). The village of Walraversijde, as Raversijde was called in that period, was then situated on an island/peninsula called “Testerep”. The island of Testerep stretched out from (the former settlement of) Ostend (Oostende) in the east to Westende in the west, and was entirely surrounded by channels and creeks (the medieval town of Ostend was located slightly offshore the present-day coastline). In between, a few fishing settlements were located, Walraversijde being one of them. This former settlement of Walraversijde was located roughly 1 km offshore from the present day location of the hamlet Raversijde (see also section 3L.1.2). The main tidal channel which separated *Testerep* from the mainland was called the “Testerep gully”. Walraversijde was located along a small tidal inlet called the Yde (hence the name).

Figure 3L4: Map of the medieval island "Testerep", with the most likely location of Walraversijde indicated in red. (http://www.oostende.be, 5/8/2014)

During later medieval times human interference enlarged exponentially and large parts of the coastal plain are reclaimed; people were building dikes perpendicular to the coast to protect themselves from the flooding of tidal channels. The remaining intertidal area was often silted up. In the area of Ostend-Raversijde the coastline retreated over 1 km during the storms in the 14th/15th century. By the 16th century, the old town of Oostende was almost completely drowned and the present coastline was more or less reached (Mathys, 2009).

3L.1.2 Summary of the Archaeology and History of the Study Area

Pre-Roman period

Archaeological findings on the beach of Raversijde date back from the final-Palaeolithicum (14,000-12,000 yrs BP) to the Neolithicum/Early Bronze Age (around 4000 yrs BP), and point towards prehistoric human occupation of the area. Furthermore, in the surface peat layer a wooden paddle, dating back to 5000-2800 BP was found (Demerre et al., 2013; Pieters, 1992).

Roman period

Numerous artifacts found at the Ostend-Raversijde site date back to the Roman period. Next to pottery, waste pits, and ploughing traces also traces of peat and salt exploitation were found (Demerre et al., 2013; Thoen, 1978; Pieters et al., 2010). In order to extract salt, saltpans were constructed, where the seawater flowed via trenches through a number of shallow basins. Here, the water slowly evaporated (during summer) leaving behind a thick salt layer. The final stage was to boil this down to salt blocks by heating in fires and using ''briquetage''-elements. Remnants of salt production sites were found at Wenduine and Raversijde (Thoen, 1978). It is believed that the peat was used as fuel for the salt ovens but it may also have been used as source of the salt, since this peat contained a lot of salt. With the increasing influence of the sea and the retreat of the Roman troops from the area around 300 AD the salt production was largely put to a stop.

Since 1992 detailed archaeological investigations have been carried out in the polder area behind the present dike. During these investigations the remains of a Roman dike were discovered (Figure 3L5, Pieters et al. (2013)). The dike is mainly built of stacked clay blocks, on its western side reinforced with peat blocks. The dike is oriented roughly perpendicular to the present coastline, which suggests that its purpose was most likely to embank a tidal gully that stretched further inland.

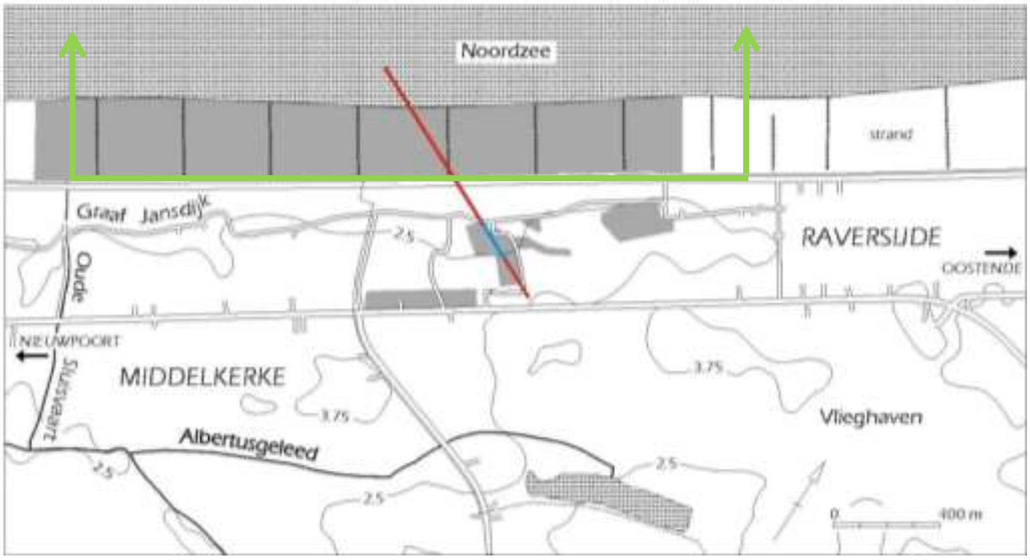

Figure 3L5: Map of present-day Raversijde. The blue line marks the remnants of the Roman dike that was excavated, the red line represents the possible continuation of the dike (Pieters et al., 2013). The (landward side of the) Ostend-Raversijde test site is indicated in green.

Middle Ages

As mentioned in section 3L.1.1, during the Middle Ages the fishing village of Walraversijde, as Raversijde was called in that period, was then situated on the island “Testerep”. The fishing village was first mentioned in 1290 (Tys and Pieters, 2009). The island of Testerep was owned by the Counts of Flanders, who rented it to the Sint-Pieters abbey of Ghent (http://www.oostende.be/blogdetail. aspx?id=1887). Around the 11th century dikes were installed along the Testerep tidal channel, in order to protect the land from flooding but which adversely also resulted in rising flood levels. As a consequence, in the late 14th and early 15th century, large parts of the island were flooded during fierce winter storms and parts of Walraversijde were destroyed. The final abandoning of the village in the 15th century was a more gradual process, also induced by war (Tys and Pieters, 2009).

The fishing village of Walraversijde was subsequently re-located behind a new dike (and from now on was called Raversijde). This so-called “Graaf Jansdijk” (see Figure 3L5) had been constructed behind the dunes, and protected the new village from floods and storms. From the original settlements of Walraversijde only a few houses and the remains of a chapel were left. The chapel finally collapsed in the middle of the 19th century (Tys and Pieters, 2009).

Traces of digging pits suggest that peat exploitation was also very common along during the Middle Ages. Except from traces of digging pits (Figure 3L6), remnants of the late Medieval fishing settlement have been discovered at Raversijde (Figure 3L7). Furthermore, in the 1950s remnants of housing (ground-plan of a late medieval house) were found on the beach (Figure 3L8).

Figure 3L6: Remnants of the trench systems and peat digging on the beach of Raversijde. (Photo E. Cools).

Figure 3L7: Aerial photo of peat excavation remnants at the beach of Raversijde (Photo E. Cools, around 1970).

Figure 3L8: Ground-plan of a late medieval house discovered on the beach of Raversijde, picture taken in 1950's (Photo E. Chocqueel).

3L.1.3 Archeological potential

Until now, only limited prehistoric (Palaeolithic) traces are found on the Belgian coast. This is mainly due to the fact that relatively few Pleistocene deposits are left (De Clercq et al., 2013). The archeological potential for the Palaeolithic is therefore rather limited. The main exceptions are the eastern coastal area close to the Dutch border, the Ostend valley and the extreme western part of the coastal area (offshore IJzer valley), where sediments pre-dating the Holocene are present.

Most of the sediments along the Belgian coast date back to the Middle and Late Holocene. Therefore discoveries of archeological artefacts (or even large-scale infrastructure) from the Mesolithic or younger are more likely. The exact location of the areas with high archaeological potential however, often remains uncertain. Peat layers can form a key role, since they offer excellent preservation qualities. In view of the recent geological history (e.g. the island Testerep) and the archaeological findings on the beach and further inland behind the dike, the Ostend-Raversijde site suggests a high archaeological potential. Furthermore the excavation of peat is a clear indication of past human activity.

3L1.4 Early Modern maps of the area – two examples

This particular case study did not aim to evaluate large series of historical maps (see case study 3M Scheldt polders), but two examples of interesting maps of the Early Modern city of Ostend and its inundated surroundings were found and ranked. The first map (Figure 3L9) was made in 1725 by land surveyor Nollet. The map shows that the entire area South of Ostend consists of tidal marshes. These came into existence due to tactical inundations during the Eighty Years' War (1568-1648). Only in 1748 first attempts to reclaim this area were made (http://www.watererfgoed.be). The topographical accuracy in the coastal area is outstanding, with detailed depictions of large and small tidal channels. It is not clear if the terrain was actually measured for making this map, and the geometrical accuracy is only mediocre, leading to a total score of 65. The inset shows a similar map, also with excellent topographical accuracy. Due to the fact no date for the map is known, chronometric accuracy is lower than for the 1725-map, leading to a total score of 60.8. For detailed information on the ranking methodology see Section 2.

Figure 3L9: Map of Ostend and surroundings (1725, Rijksarchief Brugge, Kaarten & Plans, 113, n° 8). Inset: Undated map of Ostend and inundated surroundings (Algemeen Rijksarchief, Kaarten & Plans, 8480)

3L.2 Current environmental impacts/threats and coastal management approach

The Belgian coast is one of the regions directly impacted by climate change. The sea defense is formed by only a small strip of land, which is in most areas strengthened by sea dikes and other “hard” structures, leaving only little space for natural response to for instance storms or sea level rise.

The Flemish government is aware of these threats and already in the early 1970’s breakwaters were constructed at regular intervals along the coast to protect the beach from erosion. More recently a “Masterplan for Coastal Defense” was put forward. Since 2007, investigations took place in order to define measurements which should provide safety against for instance flooding, at least until 2050. Recently an initiative for the future, called “Vlaamse Baaien” was developed by a consortium of marine industrial companies (Figure

3L10). In 2010 "Vlaamse Baaien" was included in the political agreement of the Flemish government.

Figure 3L10: Overview of the "Vlaamse Baaien" initiative, which a.o. includes the development of artificial islands in front of the Belgian coast.

The first phase of the "Vlaamse Baaien" initiative foresees in a supply of large volumes of sand on the present beaches, thus forming a more or less natural sea defense. This phase is currently under way. A second, much more contested phase of the plan, involves a.o. the heightening of sandbanks in front of the coast and the creation of small islands, with the aim to provide a more "soft" and flexible sea defense (http://www.vlaamsebaaien.com/tijdslijn). Currently a number of studies are undertaken to investigate the effect of such islands on the current pattern.

However, more knowledge on the evolution of islands and coastal barriers in the past, on how they were formed and how they disappeared (e.g. the island of Testerep) will provide a better grip on the evolution of future artificial constructions and the effects these will have on the present coastline.

The planned large-scale sand suppletion works on the beach of Ostend-Raversijde (already partially under way) are a serious hindrance for the scientific research and subsequent field studies, and will also cause further burial of the archaeological material. Furthermore, clearance of WWI munition (by deliberate explosions) on the beach of Raversijde poses another direct threat for possible buried archeological remains.

3L.3 Archaeological and Palaeoenvironmental Fieldwork

3L.3.1 Key research questions in relation to coastal change to be addressed via fieldwork

The main objective of the fieldwork at Ostend-Raversijde is to gain more insight into the recent geological evolution of the area, stretching a time period of over 5000 years, and to identify possible archaeological layers or (pre)historic artifacts buried below the current seabed/beach. This also includes former (Roman/medieval) coastal defense structures and relics of human activities related to peat extraction which took place in the area during the Medieval and Roman periods. The mapping of former tidal gullies will provide more insight in the local environmental conditions and the location of the past coastline, including the island "Testerep" whose exact location still remains uncertain.

In order to do so, several (exploratory) geophysical and geotechnical surveys were carried out in 2007, 2010 and 2012. During these campaigns a wide range of techniques was used: marine seismics, eletromagnetic measurements (EMI), hand corings and cone penetration tests (CPT). Intertidal areas offer great technological challenges due to the water depth, wave action, strong currents, salt content, and general inaccessibility of the terrain (the latter two preventing the use of radar and land seismic techniques). However at the same time the tidal effect offers a big advantage as different overlapping techniques can be applied both on land (e.g. EMI) and marine (e.g. seismics), thus covering the entire intertidal area. The latter makes this research very unique.

3L.3.2 Field data gathering methods

2007 and 2010 seismic surveys

In 2007 and 2010 two seismic surveys were carried out offshore Raversijde (Missiaen, 2008; Missiaen, 2010). The main objectives of these surveys were (1) to map the palaeogully system in more detail in the nearshore area, and (2) to map the distribution of possible man-made artefacts in the intertidal zone.

For both surveys a parametric echosounder was used. This source, which is mounted onto a pole attached to the side of the ship (Figure 3L11) emits two signals with a different frequency. The high-frequency signal (100 kHz) allows a very detailed image of the sea floor. The lower-frequency signal (between 6 and 14 kHz) penetrates deeper, resulting in an image of the underlying structure. The fast pulse rate (20-25 pulses per second) resulted in a high lateral coverage. During the measurements the echosounder was attached on a long iron pole fastened to the side of the ship. A motion sensor was used to filter out the wave movement. Positioning was done using a DGPS antenna with an accuracy of ±1 m. Different networks were recorded in the area: a large-scale network in the subtidal nearshore area (up to 1.2 km from the shore, line spacing 50 -100 m) and several small-scale networks focusing on intertidal zones in between the groynes (line spacing between 10 and 25 m) (Figure 3L12). It was hoped that the latter could provide more insight into the distribution of nearshore palaeogullies and possible remnants of ancient coastal defense structures.

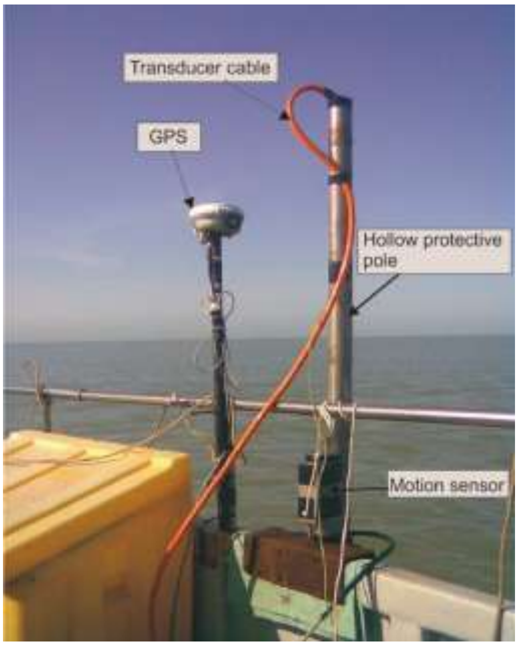

Figure 3L11: Motion sensor and GPS antenna attached to the pole holding the transducer source.

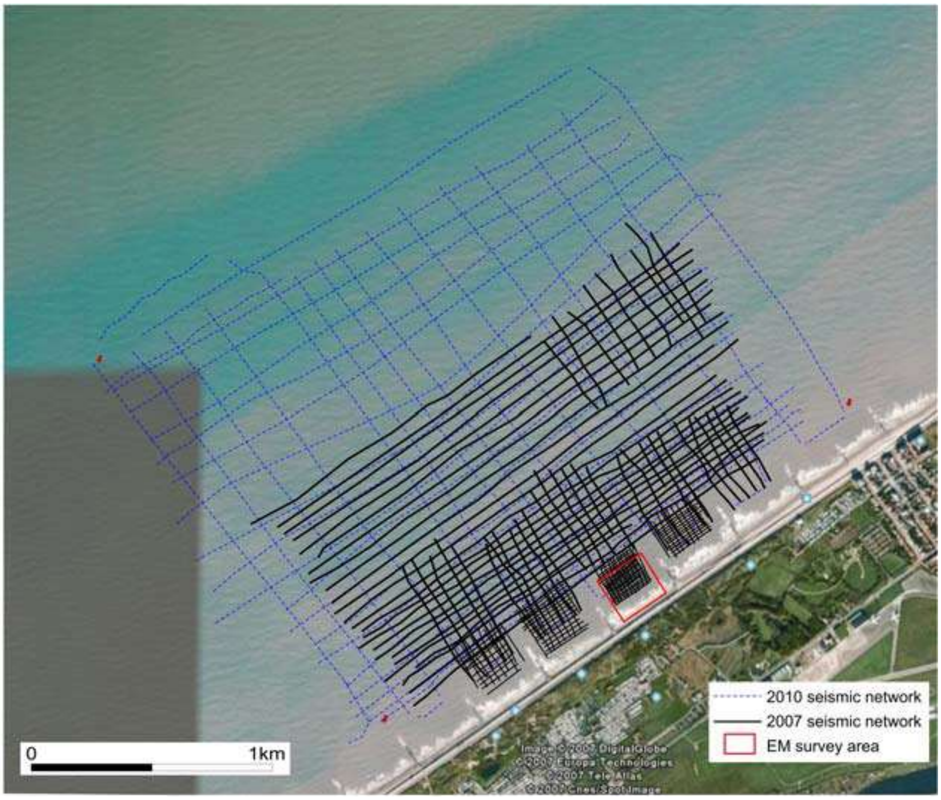

Figure 3L12: Seismic networks recorded in 2007 (blue lines) and 2010 (black lines) offshore Raversijde. The red rectangle marks the intertidal site where detailed investigations (Seismic, EMI) were carried out in 2010 and 2012.

Seismic data processing was very straightforward and included band pass filtering, stacking (where needed), smoothing and time varyable gain. Tidal correction of the seismic data was carried out using tide data obtained from a tidal gauge at Ostend and interpolated for the survey area. All seismic data were corrected to a common level. Arrival time to depth conversion was done using a sound velocity of 1550 m/s.

2010 electromagnetic (EMI) survey and shallow coring

In addition to the seismic campaigns a first series of electromagnetic induction (EMI) test measurements was carried out in 2010 by the department of Soil Management (Ghent University) at low tide on the beach (Figure 3L17). The choice for this specific area was based on photographic material (see Figure 3L7 and 3L13), suggesting the possible (buried) presence of peat exploitation remnants as well as medieval habitation. In EMI measurements an electromagnetic field is generated (induced) in the subsoil. This EM field is closely related to the conductivity of the soil. The latter will vary with the lithology: high conductivity is often related to peat deposits, and also, in a lesser extent, to (thick) clay layers. Also the presence of metal objects will increase the conductivity, making interpretation a complicated matter.

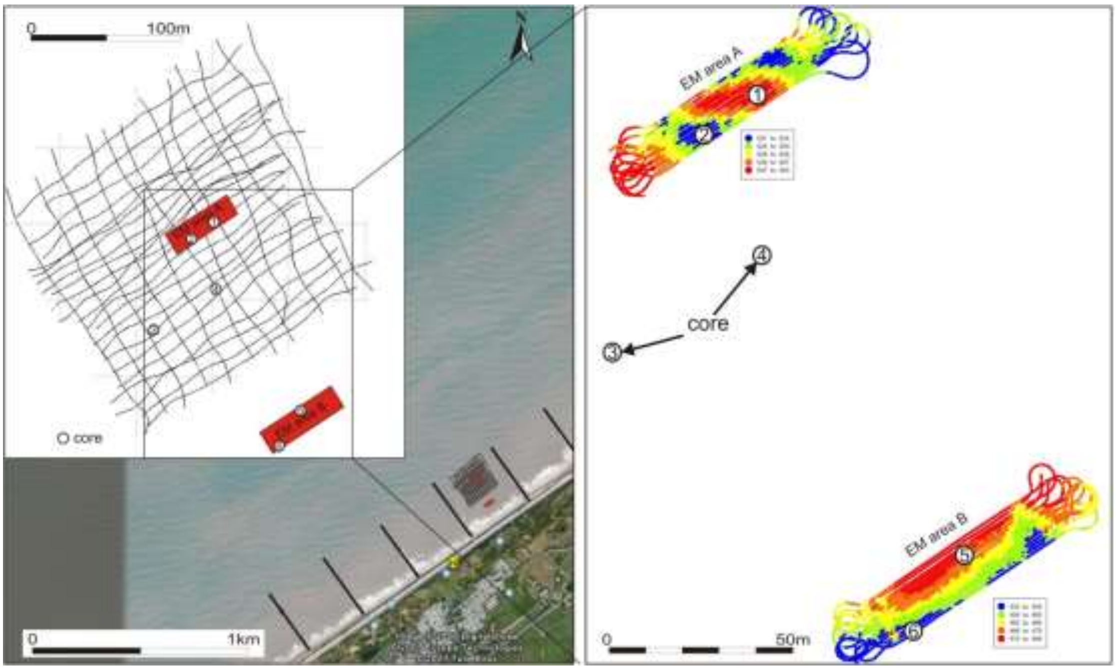

Figure 3L13: Left: Overview of the 2010 small-scale seismic network, electromagnetic (EMI) survey areas and core locations in a small intertidal area. Right: close-up of the EMI data (apparent electrical conductivity ECa, in mSm-1) (red=high conductivity, blue=low conductivity).

Additionally, in 2010 a few shallow test cores were taken on the beach to provide more ground-truth for the seismic and electromagnetic data (Figure 3L13). The cores were taken using a so-called "van der Staay suction corer", a simple hand-operated coring device especially designed for coring in water-logged sandy sediments (Verrijken and Demerre, 2010). In total 6 short cores were obtained, with depth varying between 2 and 4 m. Working with the Van der Staay core proved very difficult and time-consuming, mainly due to the large lithological variation encountered (dense peat and clay layers interfingering with loose saturated sand).

Figure 3L14: Left: Taking a Van der Staay core on the beach at Raversijde. Right: describing the core contents.

2012 seismic survey

In 2012 an additional seismic survey was done in the intertidal area where previously EMI data were gathered (for location see Figure 3L12). This time a more closely spaced network of seismic lines was collected, again using the parametric echosounder. In total 103 new profiles were recorded (Figure 3L15).

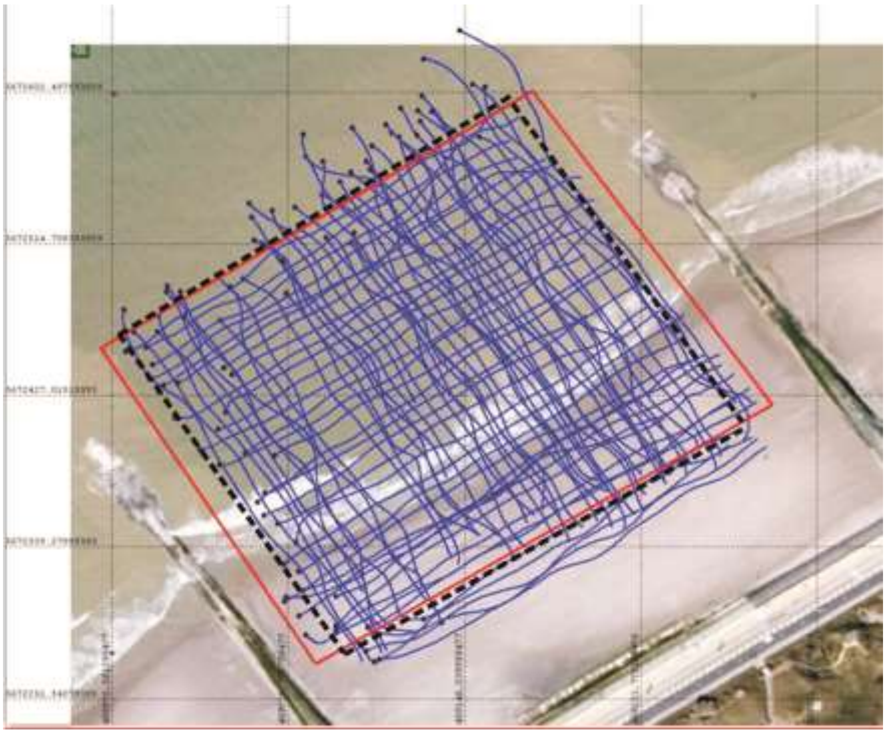

Figure 3L15: Seismic network in the intertidal area recorded in 2012 (projected against a google earth image). The red rectangle marks the area of the 2012 electromagnetic investigations. The two breakwaters can be clearly seen at the edges. For location of the network see Figure 3L12.

2012 electromagnetic (EMI) survey

In 2012 a second, larger electromagnetic (EMI) survey was carried out, again in cooperation with the department of Soil Management (Ghent University). The area covered was much larger than the previous EMI survey in 2010 (roughly 250 x 250 m), encompassing the entire intertidal area between the two breakwaters (red rectangle in Figure 3L15). The penetration depth of the electromagnetic signal into the bottom varied between 0.5 and 3m. The device that was used consisted of a Dualem-21S sensor with three different coil sizes (depth penetration of the different coils was respectively. 0.5, 1, and 3 meter). The sensor was dragged over the beach by a quad (Delefortrie et al., 2014)

2014 seismic survey

In January 2014 a last seismic survey was carried out in the area west of the previously studied area (Figure 3L16). Three different networks were recorded: one larger spaced network in the subtidal area further offshore, and three closely spaced networks in the intertidal area. Also here the parametric echosounder was used. In total 157 profiles were recorded.

Figure 3L16: Seismic networks recorded in 2014 (projected against a google earth image). The red rectangle marks the area of the 2010-2012 investigations.

2012 hand cores and cone penetration tests (CPT)

After a first attempt for shallow hand augering in July 2010 (see above), a second and third coring campaign were carried out on the beach at low tide in October-November 2012 and January 2013 (Figure 3L17). Due to the high tidal coefficient no cores were obtained from the seawardmost area. The location of the corings is given in Figure 3L18. A combination of Van der Staay and conventional augering devices were tried out this time. Again, coring was extremely tedious due to the water saturated conditions of the sand and the large (and often abrupt) variation in lithology (dense clay, loose sand, compact peat). Maximum depth reached with the hand cores was 3.5 metres (average depth 2 metres). The best technique seemed to be a combination of suction core with a pulse, used intermittingly. Still it remained extremely difficult to obtain good (and complete) core samples.

Figure 3L17: Hand augering on the beach at Raversijde.

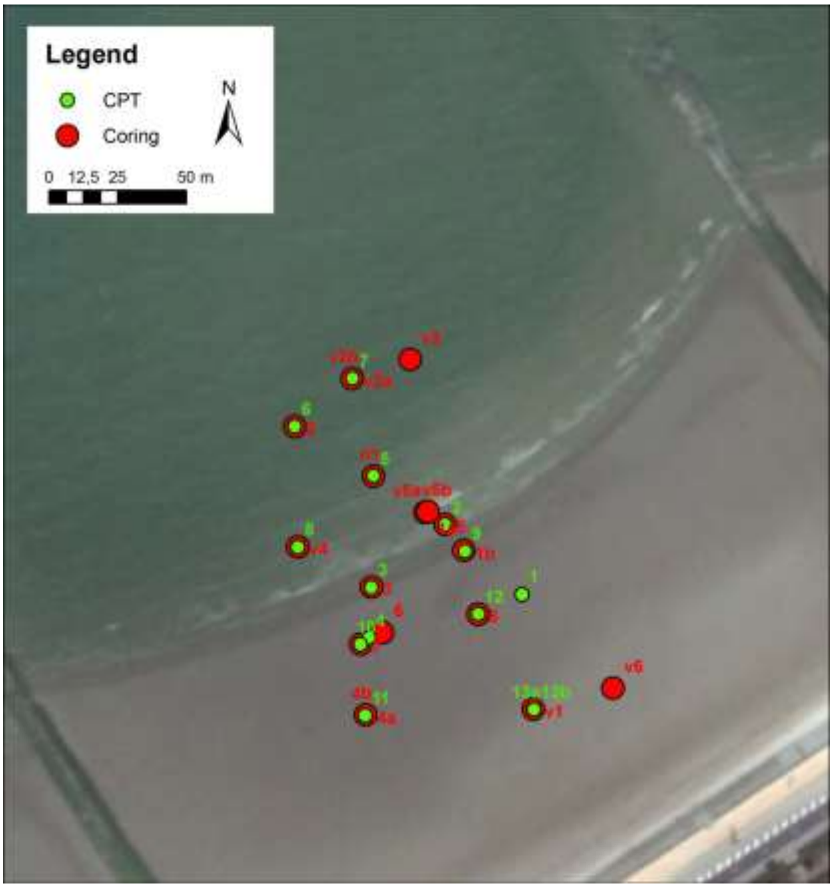

Figure 3L18: Location of the hand corings and CPTs on the beach at Raversijde.

In addition to the hand cores also 13 (electrical) cone penetration tests (CPTs, Figure 3L18) were carried out in November 2012 on the beach at low tide (Figure3L 19). Depth of the CPTs was on average 10 m. Cone Penetration Testing is a geotechnical method to sound the composition of the subsurface. The method allowed us to obtain information regarding the geology (nature and sequence of the subsurface strata) and hydrology (groundwater conditions) as well as the physical and mechanical properties of the subsurface strata (Lunne et al., 1997; Robertson and Cabal, 2012). The CPT method allows fast and continuous profiling with repeatable (and reliable) data, and is highly economical (Lunne et al., 1997).

In Cone Penetration Tests (CPT) a cone is pushed into the ground at a constant rate while continuous measurements are made of the cone resistance (i.e. resistance of the cone tip to penetration) and the sleeve friction (i.e. resistance of the sleeve). The ratio of sleeve friction divided by cone resistance, called the friction ratio, is used to classify the soil.

Figure3L 19: Cone penetration testing on the beach at Raversijde.

3L.4 Field data analysis and discussion

3L.4.1 Sea floor topography

Based on the seismic data recorded in 2010 and 2012 a map was made of the seafloor topography in the survey area (Figure 3L20). The map clearly shows that the sea floor sloping towards the shore is marked by a step-like form, creating a distinct terrace. This can also clearly be observed on the NS-oriented profiles shown in Figure 3L21.

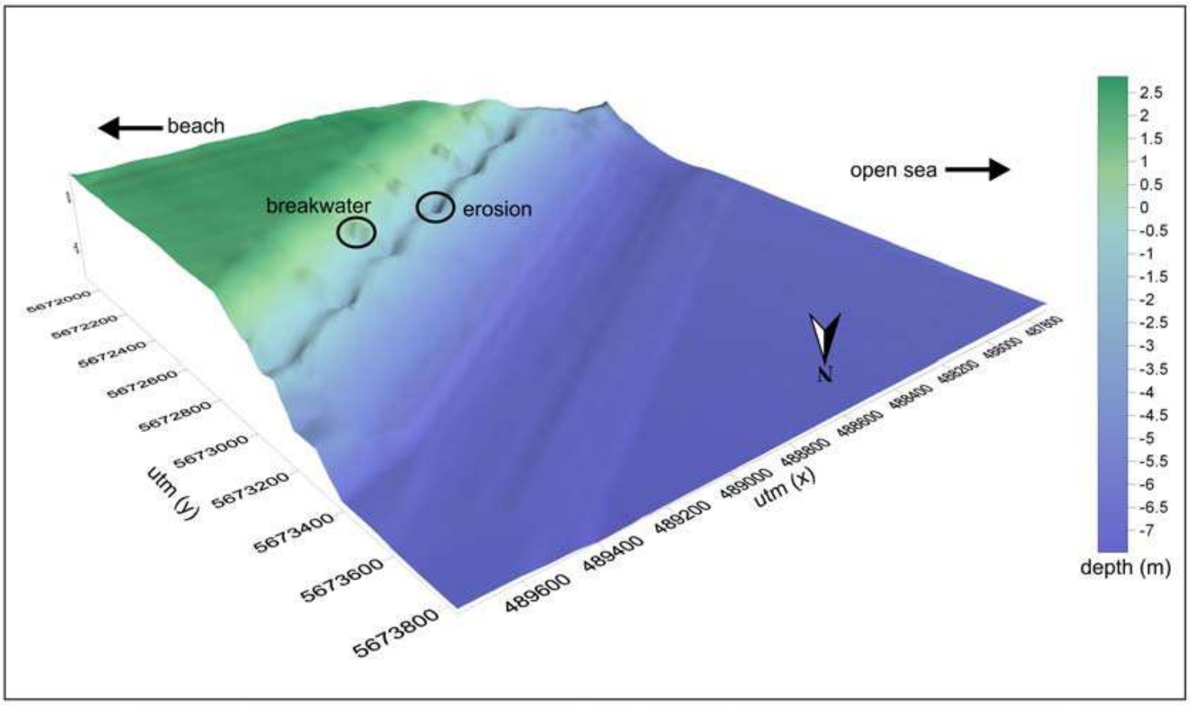

Figure 3L20: Seafloor topography map of the survey area based on the high-frequency (100 kHz) seismic data. The breakwater constructions and associated erosion areas are clearly observed.

On the whole the seafloor surface is very smooth. Only on a few locations some small irregularities were observed on the seafloor, as shown in Figure 3L21. The seafloor irregularities are all located in the nearshore area. At first sight they do not seem to be directly associated with buried structures or channel infill structures. However in some cases there seems to be a link with outcropping layers (e.g. Figure 3L21 - top) which suggests a natural origin. However the marked location of the seafloor irregularities -in a narrow band parallel to the coast- suggests that they may well be related in some way to remnants of an old dike or coastal defense structures.

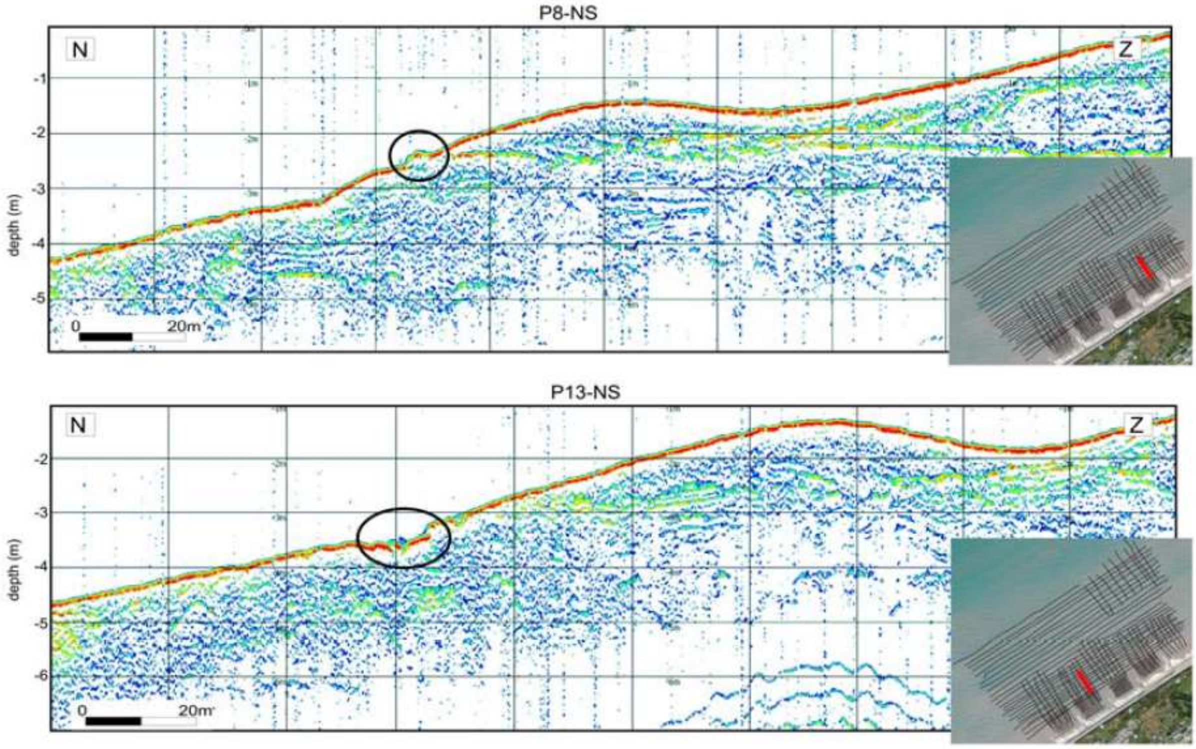

Figure 3L21: Seismic profiles offshore Raversijde showing small irregularities in the sea floor. The location of the profile is marked in the inset on the right (red line). Depth in meter below MLWL (Mean Low Water Level).

The regularly spaced breakwaters also stand out clearly on the topography map (Figure 3L20), as well as the erosion pits seaward of the breakwater constructions. The latter are most likely a result of scouring around the obstructions. Figure 3L22 shows two seismic profiles parallel to the coast that cross two of the groyne constructions and the associated erosion areas. The erosion areas are marked by a shallow infilling structure (dotted lines).

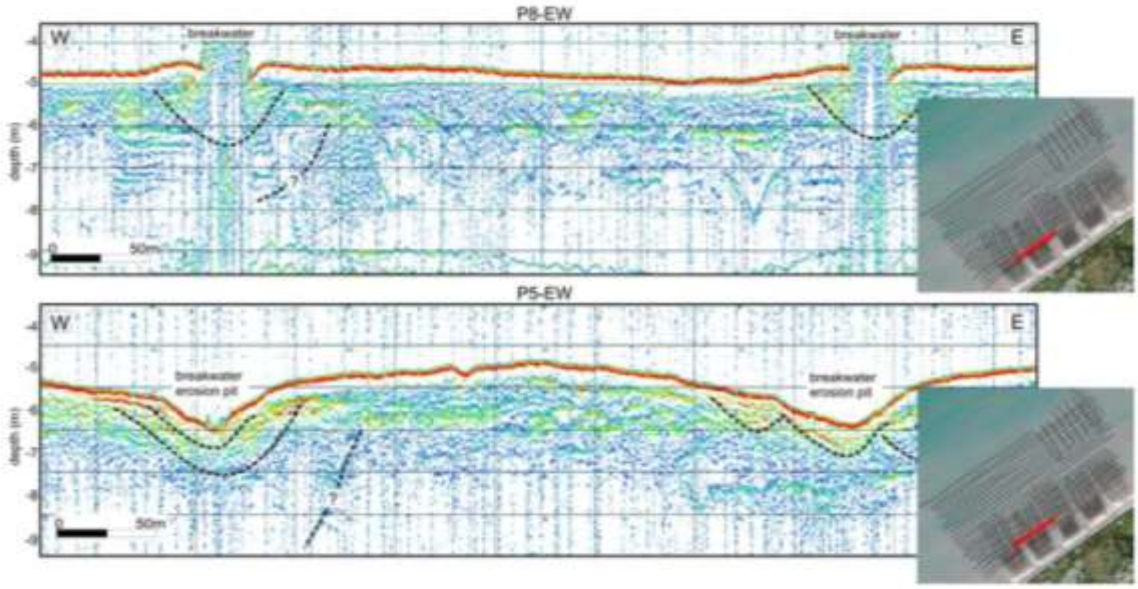

Figure 3L22: Seismic profiles offshore Raversijde showing two breakwater constructions and associated erosion areas. The location of the profile is marked in the inset on the right (red line). Depth in meter below MLWL.

3L.4.2 Large-scale palaeogully system

The seismic data obtained in 2007 allowed us to identify the remnants of a number of buried tidal palaeochannels. However, due to the high spatial variability of the shallow sediments and the relatively large profile spacing it was not possible to accurately map the channel pattern. The latter was only possible after the 2010 survey. The results show that the channel system is in fact much more complex than previously presumed. Figure 3L31 shows a new (tentative) interpretation map of the palaeogully system in the nearshore area. However even with a much closer line spacing in 2010 it was still not always possible to precisely track the channel pattern.

The seismic images are furthermore often hampered by the presence of shallow gas, which limits the penetration depth. Especially in those areas it was difficult to map the channels. Nevertheless a general pattern can be observed of more or less parallel (or sub-parallel) palaeochannels that are oriented roughly perpendicular to the coast. The latest data from 2014 further confirm this channel pattern (Claerhout, 2014).

In addition to this large-scale channel pattern, traces of a recent tidal channel were observed running roughly parallel to the shoreline (Figure 3L23). The same feature was also observed more towards the west, on the 2014 data. At first it was thought that this could indicate an old coastal defense feature. But a closer look at the data revealed that we are most likely dealing here with a palaeochannel that marks the northern (seaward) edge of the island Testerep (see Figure 3L4) (Claerhout, 2014). Indeed it is known that islands are often marked by strong tidal currents that 'encircle' the island (Pingree and Maddock, 1979).

Figure 3L23: Interpretation map showing the palaeogully system observed offshore Raversijde. The yellow line marks the recent palaeogully parallel to the shore. The red circles mark small seafloor irregularities.

Figure 3L24 shows an example of a seismic profile marked by buried palaeogullies (the location of each profile is indicated on the bottom right, depth is indicated in meters below mean lowest low water at springtide MLLWS). The gullies sometimes show a chaotic crisscross pattern, and younger gullies overlying older gullies at different angles. In most cases the channel fill is marked by a clear lateral stacking structure. In some cases a more chaotic infilling was observed which may be due to a local increase in shallow gas or to minor collapse events. A clear distinction between the steep erosional side (=outer bend) and more gradual sloping side (=inner bend) of the channel was often not possible.

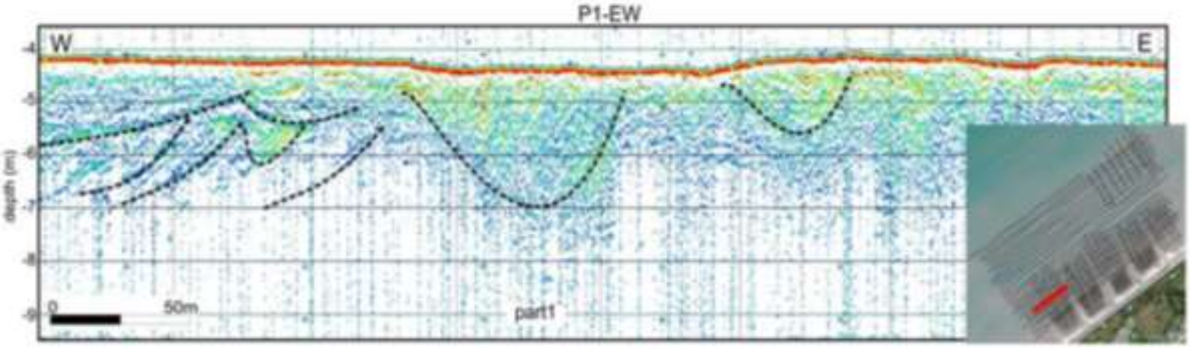

Figure 3L24: Seismic profile parallel to the shore showing various palaeogully systems (dotted lines). The location of the profiles is marked in the inset on the right (red line). Depth in meter below MLWL.

On the latest seismic data from 2014 a particularly large and wide palaeochannel was observed running roughly perpendicular to the shoreline (Figure 3L30). The location of the channel suggests a possible relation to the Yde gully running close to the village of Walraversijde on the island of Testerep (see above and Figure 3L8).

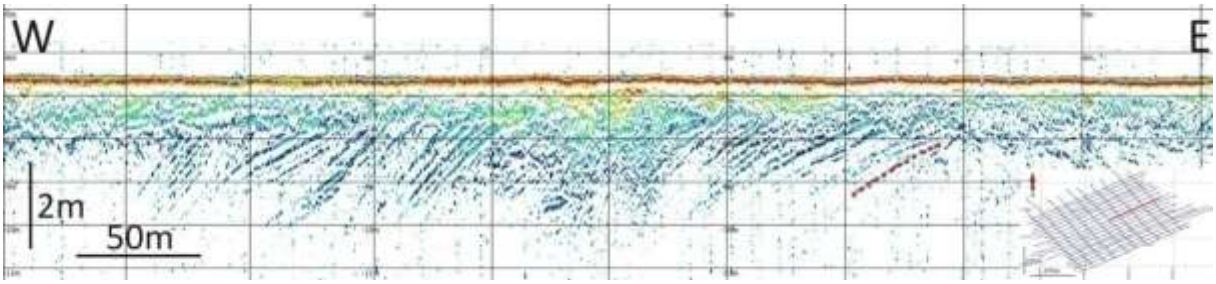

Figure 3L25: Seismic profile parallel to the shore showing a large and wide palaeochannel system, possibly related to the Yde gully. The location of the profile is marked in the inset on the right (red line).

3L.4.3 Small-scale palaeogully systems in intertidal areas

In general, the seafloor in the intertidal areas is very smooth, with a gradual shallowing towards the coast from roughly +2.5 m to – 1.5 m (all depths relative to MLWL). Interpretation of the seismic data nearest to the shore is often hindered by the shallow echo which obscures the underlying structure. Locally the presence of shallow gas limits the seismic penetration making a correct interpretation very difficult.

In general the observed palaeochannel pattern in the intertidal zones is very chaotic, with both shallow and deeper gullies often crisscrossing (Figure 3L26) The channels do not always stand out very clear and their infill structure is often rather chaotic, which suggests that some of these presumed channels could also be related to shallow gas. The areas nearest to the shore are rather marked by gullies running perpendicular to the shore, whereas the zones further offshore show a channel pattern running more parallel to the shore. On many of the seismic profiles also an undulating reflector pattern can be observed. In the extreme nearshore part often an irregular, shallow reflector is observed which is locally interrupted and which could be human-induced (peat extraction, settlement remnants?).

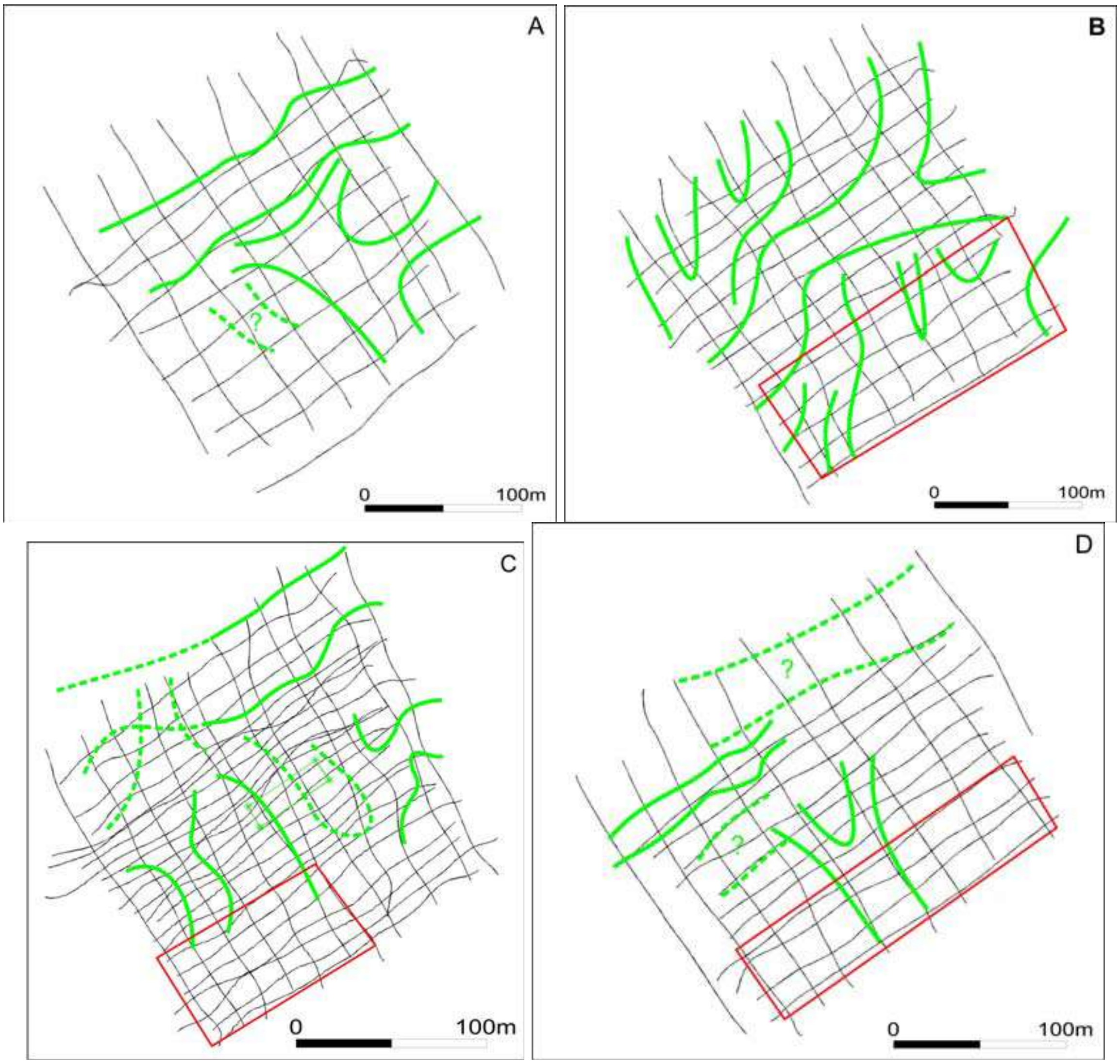

Figure 3L26: Tentative interpretation map of the palaeogully system (thick green lines) in different intertidal areas. The red area indicates the presence of a shallow interrupted reflector which is possibly related to human intervention.

3L.4.4 2010 electromagnetic (EMI) data and shallow cores

The first EMI measurements in 2010 only yielded two small data areas, one close to the dike and one further offshore (see Figure 3L13). Only the latter showed an overlap with the seismic data. Four of these cores overlap with the seismic network, of which also two overlap with the offshore EMI data.

Figure 3L27 shows an example of a seismic profile crossing the offshore EMI area. Areas of high conductivity seem to correspond with a relatively strong shallow reflector, whereas low conductivity seems more associated with a chaotic seismic image. This suggests that the shallow reflector could be related to a peat-rich layer – indeed peat will enhance the electrical conductivity. However, we should keep in mind that this interpretation is still very tentative due to the limited areal extent of the EMI data in 2010.

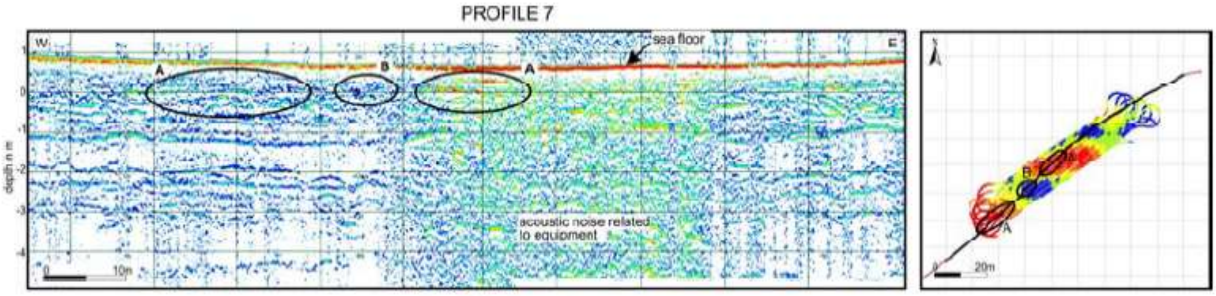

Figure 3L27: Seismic profile crossing the offshore EMI area. Depth in m below MLWL. The location of the profile is shown on the right (black line), plotted against a background map showing the electrical conductivity. A and B refer to the zones corresponding with respectively high (red) or low (blue) conductivity zones.

Comparison with shallow core data shows that in general there seems to be a fairly good correlation between seismic and core data (due to gas disturbance, however, the lower part of core 1 cannot be correlated precisely with the seismic data). Shell-rich layers mostly stand out as marked reflectors on the seismic data, and also the transition from clay to sand and vice-versa often yields a distinctive reflector. As expected the dense clay layers stand out clearly on the seismic data, regardless of the adjacent sediment.

3L.4.5 2012 seismic data and EMI results

Seismic data

Five strong sub-bottom reflectors were identified on the 2012 data in the intertidal area (see Figure 3L28). The reflectors are parallel or sub-parallel, sometimes wavy. The two shallowest reflectors appear only in the nearshore part.

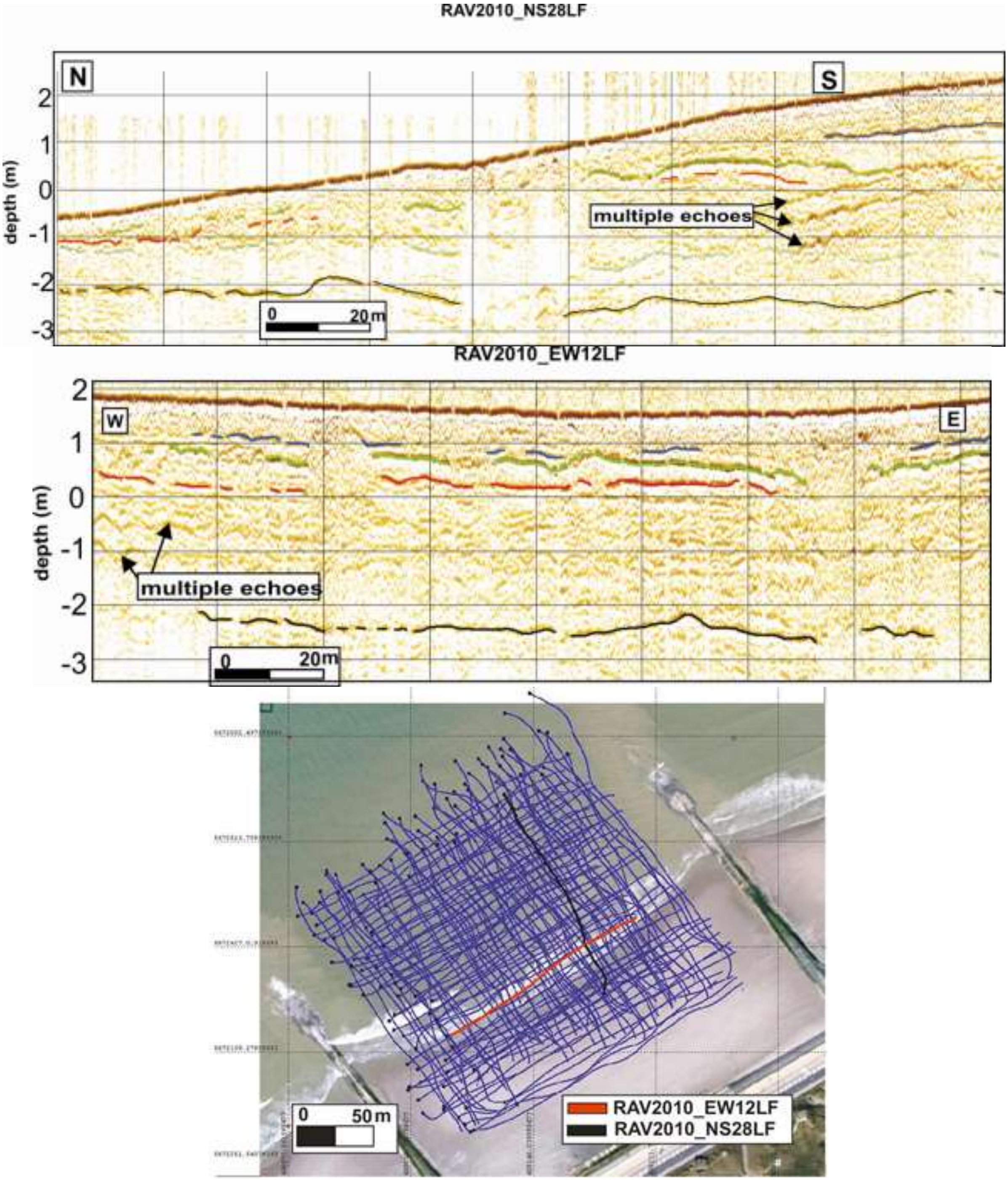

Figure 3L28: Seismic profiles showing the different strong reflectors observed in the intertidal area in 2012 (top: NS profile, bottom: EW profile). The light blue reflector was not well visible on the EW profiles. The location of the profiles is shown at the bottom.

Apart from the 5 main reflectors, the densely spaced seismic data of 2012 demonstrate a wide variety of phenomena in the area. The first feature is related to the presence of shallow gas. This was observed in the whole study area. Near the shore, the gas starts roughly at 1m and reaches down to 3.5 m below the sea floor. In the offshore part the gas appears between 1m to 2m below the sea bed. A number of features were related to palaeochannels. In the offshore part, both a deep palaeochannel and shallower complex palaeochannel were observed. In the central part of the study area, an additional complex shallow channel system was observed oriented roughly parallel to the shore.

The most important feature was related to strong shallow reflectors that are often interrupted (Figure 3L29). These reflectors are observed in the entire network, but they are most marked towards the shore. The nearshore area is marked by the presence of two parallel to subparallel strong shallow reflectors. Towards to the north both of the shallow reflectors are discontinuous and show abrupt gaps. The gaps in continuousness of the reflectors are possibly related to human interventions, e.g. peat excavation. Figure 3L29 shows the location of the strong shallow reflectors in the area.

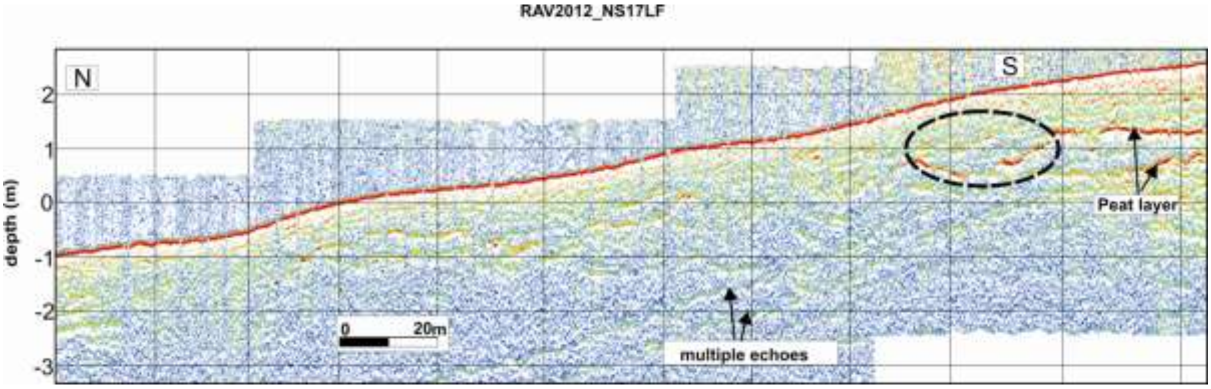

Figure 3L29: Seismic profile showing a strong shallow reflector on the right marked by irregular gaps (black dotted circle).

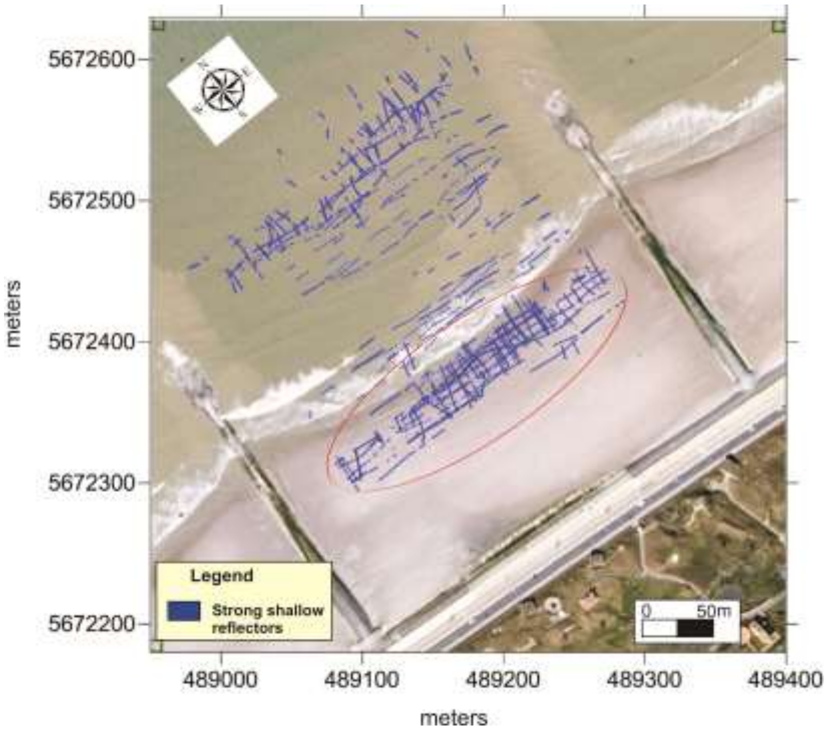

Figure 3L30: Spatial distribution of strong shallow reflectors in the intertidal area. The red ellipse is the area where two (sub-)parallel reflectors have been observed. Outside of this area the shallow reflectors are less strong and less continuous.

Electromagnetic data and correlation with seismic data

The conductivity data resulting from the EMI measurements in 2012 were corrected for the influence of the salty sea water (the sand being much dryer (and therefore less salty) closer to the dike). After this trend removal, and notwithstanding the overall very high conductivity values, still a characteristic pattern could be observed on the data. The results of the electromagnetic data are shown in Figure 3L31. A distinct area with low conductivity (in black) was observed towards the dike in the south, and an area with high conductivity (in white) was observed further offshore. Although the resolution of the data decreases for deeper penetrations, the pattern remained clearly visible on all data for the different coil configurations.

Pronounced high conductivity on the data may be caused by different things, for instance the presence of metal objects, or shallow peat layers. However, also thick shallow clay layers are known to produce an increase in conductivity.

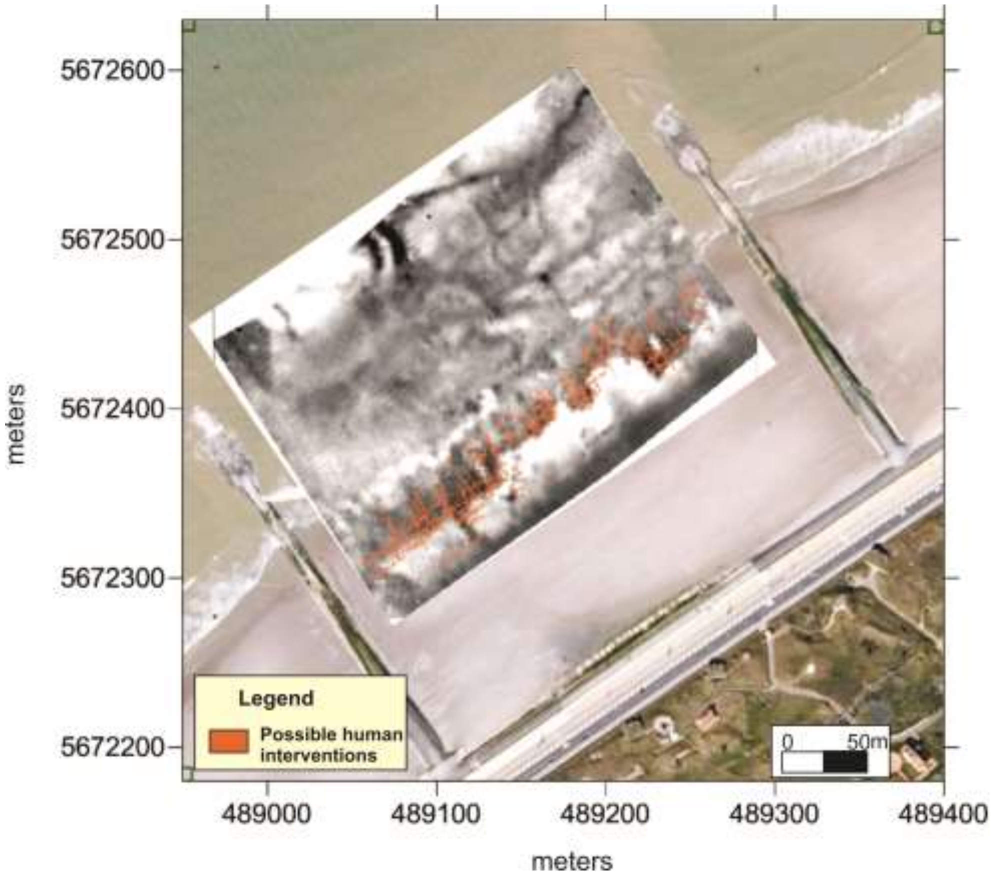

Figure 3L31: Results of the 2012 electromagnetic measurements in the intertidal area (after Delefortrie et al. (2014)).White areas indicate high conductivity, black areas indicate low conductivity. The orange lines mark the gaps in the strong shallow reflectors on the seismic data, supposedly related to human interventions. The correlation between the seismic and EMI data is obvious.

Combining the seismic data with the EMI data showed a good correlation between the two (Figure 3L36). The high conductivity on the electromagnetic data (white zones on the map) are likely caused by shallow peat layers (since peat increases the conductivity). It is clear that there is a strong correlation between the interrupted high-amplitude shallow reflectors observed on the seismic data and the area of high conductivity. The two fit almost perfectly. This seems to confirm that the gaps in the shallow seismic reflectors are most likely related to peat extraction patterns.

The correlation between the other features (palaeochannels etc.) observed on the seismic data and the electromagnetic data was not always very clear. That is likely due to the depths of the channels which are locally deeper than the penetration depth of the electromagnetic signal. In the offshore part of the EMI data a circular area with extremely low conductivity (black color) was observed. Its location and distribution seems to suggest a possible link with shallow palaeochannels.

3L.4.6 Comparison of hand corings and CPT´s

A comparison between the results of the CPTs and the hand corings was made, especially with relation to the presence of peat layers. The results were reasonably good. As an illustration two CPT-logs are shown in Figure 3L32 . The CPT-log on the left in Figure 3L32 clearly shows the presence of peat (blue peak in the friction ratio, marked by an arrow) at 2 - 2.5 m depth. Coring 4b, at the same location, confirms this peat layer. The CPT-log on the right in Figure 3L32 shows no clear peaks in the friction ratio, which is confirmed by corings v2a and v2b at the same location.

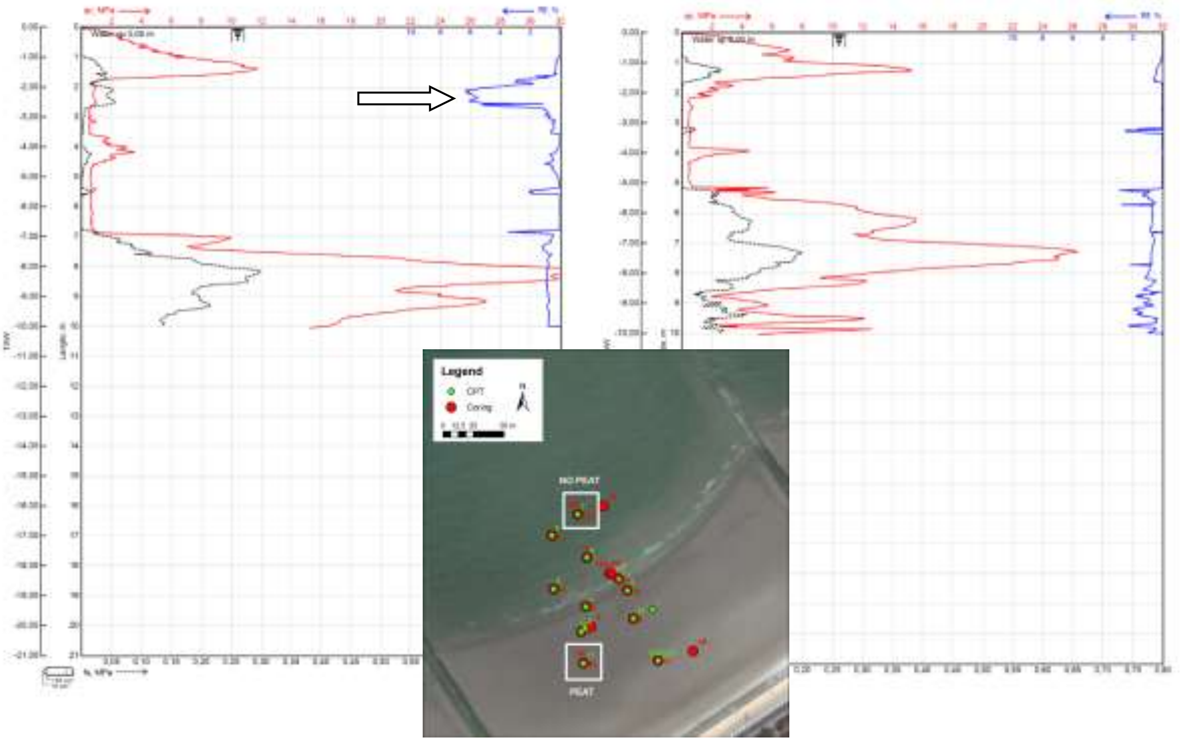

Figure 3L32: CPT-log 11, clearly showing a peat layer (marked by the arrow) at 2 - 2.5 m depth. Right: CPT-log 7, showing no peat layers in the upper few meters. The location of the CPTs and cores is shown at the bottom.

The results were not always straightforward however. In a few cases peat was detected in the CPT but not in the nearby core (or the other way around). This is possibly due to the large lateral heterogeneity in the subsurface sediments, and also to the fact that many cores did not reach deep enough. Also the fact that hand coring was extremely difficult in the intertidal area (taking up to 1-2 hours for a core of 3 meter) and core depths may often be erroneous due to compaction of peat in the core.

3L.5 Conclusions and recommendations

3L.5.1 Conclusions of the field work

The results of the different field surveys at Ostend-Raversijde so far confirm that we are dealing with a very complex area which is marked by a high level of heterogeneity and lateral variability in the shallow subsurface structure, typical of high-energetic (inter)tidal areas. A complex pattern of often criss-crossing (both shallow and deeper) palaeogullies was mapped. Some of these palaochannels seem to be related to the (vanished) medieval island of Testerep and the Yde gully that gave its name to the village of Walraversijde. It is the very first time that proof for the existence of this island has been given.

Also in the intertidal zones in between the breakwaters a chaotic palaeochannel pattern was observed, with both shallow and deeper gullies. Due to the presence of shallow gas the channel pattern is not always easily followed.

The seafloor is generally very smooth and slopes towards the shore in a step-like form, creating a distinct terrace. It is not clear yet whether this 'terrace' can be linked to the former island of Testerep (some sort of relic?). A number of small seafloor irregularities were observed close to the shore. Although there may be a link with locally outcropping layers, their location (in a zone roughly parallel to the shore) suggests a possible relation to coastal defense structures.

In the intertidal areas patterns of irregular, interrupted shallow reflectors were observed on most seismic data. This reflector pattern seems to be related to human interference. This is confirmed by electromagnetic measurements carried out at low tide in one of the intertidal zones. The results indicate that the interrupted reflector pattern is most likely due to the extraction of peat. The latter is also confirmed by old aerial photographs of the area showing chaotic patterns of outcropping peat. In the presence of (larger) palaeochannels the peat seems to be eroded.

Shallow hand cores and CPTs obtained in the intertidal area further confirm the link with buried peat sediments. One of the cores located near to the dike showed a thin layer of ash which could be related to remnants from human settlements. However, so far no further (geophysical) proof of these house remnants was found.

3L.5.2 Recommendations

The current research is one of the first studies that has been carried out in the intertidal and subtidal area integrating overlapping marine and terrestrial data (geophysical, geological and geotechnical). This was mainly possible due to the high tidal variations that allow us to obtain marine data very close to the shore and land data relatively far offshore on the beach.

The marine seismic data gives a clear image of the geological layers and features below the sea floor. However, shallow gas often disturbs the seismic image, especially in the presence of peat layers (due to the organic material). Over the years, however, new acquisition methods such as the parametric echosounder have been developed which allow us to obtain high-quality seismic data in increasingly shallow water (less than 1 meter water depth) and even in the presence of shallow peat layers.

Electromagnetic data so far has only been used on land, and in salt-free conditions. The good results of this study are very promising for future work of this technique in intertidal environments marked by a high (and variable) salt content. In this case study for the first time marine seismic data and terrestrial electromagnetic data were combined from the same area. The results were impressive and show that there is good correlation between these very different and complementary data. Both techniques are very efficient, able to provide high-quality data in a fast way (a couple of hours for areas of roughly 300 x 300 m). This is crucial in view of the short measurement periods due to the tide. However, additional ground-truth data such as shallow cores and CPTs are always needed for a final confirmation. Obtaining high-quality shallow cores on the intertidal beach remains very problematic, and it seems that electrical CPT's may be a good alternative here.

The results of the fieldwork presented here open important new perspectives for detailed research of intertidal areas with regard to archaeological and palaeolandscape studies.

As a concrete example of the applicability of above mentioned techniques, Ostend might prove to be an interesting case. Ostend was, just as Raversijde, formerly located on the

Testerep island. At the end of the 14th century, storm floods forced the inhabitants to leave. A new city was erected southeast of the tidal channel that divided Testerep from the mainland. In the following centuries both the old and the new city remained intact. The division was by then formed by the harbor (Figure 3L33).

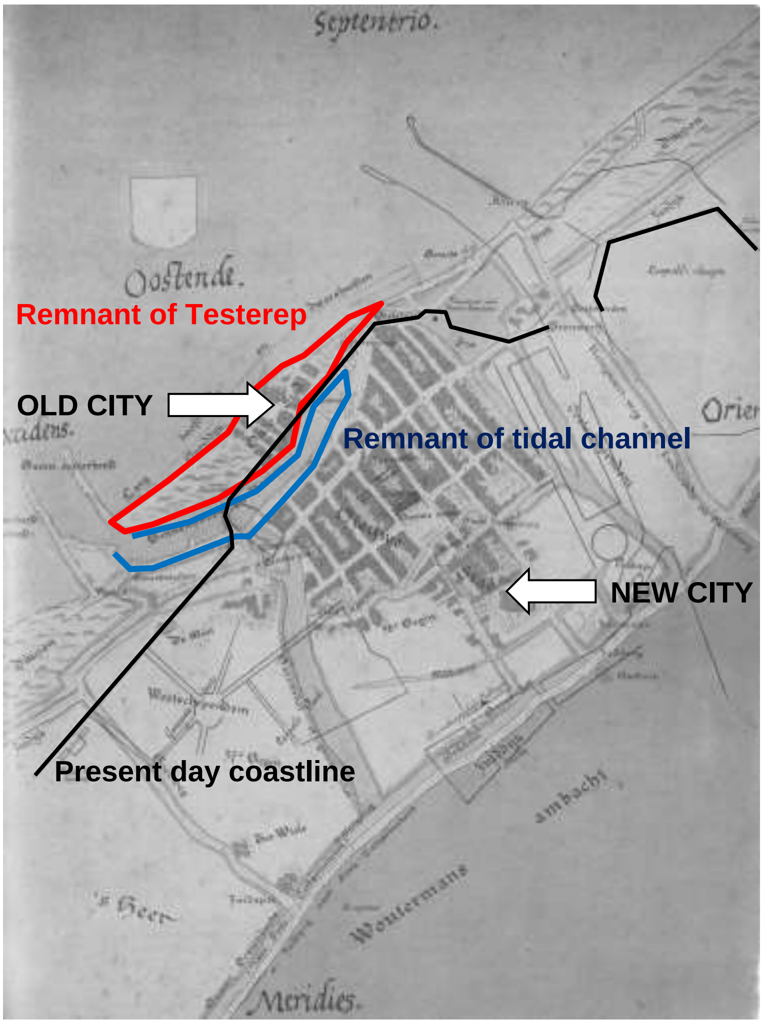

Figure 3L33: Map of Ostend around 1560 (copy of the original map of J. Van Deventer), with indication of important elements.

During the Eighty Years war (1568-1648), the verges of the city were converted to fortifications. Due to this modifications and the fighting in and around the city, the old town was largely destroyed (http://www.watererfgoed.be). Today, parts of the old city are under water and remain unknown, and also the exact location of Ostend on *Testerep* is still unknown. Integrated use of the new techniques discussed in the previous chapters could provide valuable new insights here.

In this matter also the very recent (May 2014) acquisition of a vibrocorer by the Flemish Marine Institute (VLIZ) may play an important role in the future. The cores that can thus be obtained may provide the necessary offshore groundtruth that is currently still lacking, including absolute dating of the sediments. This will allow more detailed information on the landscape evolution of this highly complex area.

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For further information on the project and to access the full Technical Report please go to www.archmanche.hwtma.org.uk/downloads

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