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Kustgenese-2 'diepe vooroever'

A description of the multibeam surveys 2017 & 2018

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A description of the multibeam surveys 2017 & 2018

Albert Oost
Veronique Marges
Tommer Vermaas
Thaiënne van Dijk
Marios Karaoulis

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Client	Project	Attribute	Pages
Rijkswaterstaat Water, Verkeer en Leefomgeving, UTRECHT	1220339-004	1220339-004-ZKS-0062	52

Keywords
Kustgenese-2, lower shoreface, diepe vooroever, sedimentology, geology

Summary
This report is part of the Kustgenese-2 programme “Diepere Vooroever”, which focuses on understanding the morphodynamics and sedimentology of the Dutch lower shoreface in order to sustainably manage the Dutch coastal system and keeping the coast safe. The goal of this research is to gain insight into the sedimentary built-up of the coast and which processes determine the exchange of sediment over the lower shoreface.

To this end two multibeam surveys have been carried out in 2017 and 2018 at the study sites: Noordwijk, Terschelling and Ameland. By analysing the morphological features of the seabed, it is possible to understand the dominant marine processes during deposition and reworking of the sediment. Furthermore, the backscatter data were tested to their applicability for the lower shoreface.

From the observations it becomes clear that sediment is transported on all water depths (up to -22m). Changes over the period 2017-2018 were especially large at Noordwijk and (partially) Terschelling, where observations were done in 2017 during a stormy period and in 2018 after a long quiet period. Changes in the Ameland area were also present (2017 and 2018 observations both after a long quiet period).

At several locations the older sedimentary units present just below or at the surface influence present-day development of the lower shoreface, as is shown by examples at Terschelling and Noordwijk. Several structures encountered in front of Terschelling were not well understood and might be related to gas or water expulsion from the sediment.

From comparing the 2017 and 2018 observations and the differences between Ameland (two quiet periods) and Terschelling & Noordwijk (one stormy and one quiet period), it shows that the influences of storms reach all the way to the deepest parts of the observation areas (-22m). Many of the features observed after storms are indicative of erosional events. In deeper water this is partly due to currents (deep scoured troughs at the Terschelling site in 2017; flattened bedforms at the sand waves at Noordwijk in 2017) and partly due to waves and currents (hummocks at the Terschelling site in 2017). In shallower parts of the deeper shoreface waves seem to play a more important role (erosional features at Noordwijk in 2017).

Under quiet conditions coast parallel tidal currents are dominating the sediment transport on the deeper part of the shoreface. In general, it is observed that bedforms brought about by coast-parallel tidal currents dominate in deeper water: for Ameland and Noordwijk below -14/-15m and for Terschelling below -18m during fair weather wave conditions. The slow infill of shallow fishing traces at Noordwijk suggests that during fair weather conditions sediment transports in the zone between -15 and -18m are small. Observations and interpretations as described here will be incorporated in a “Technical Advice” of the Diepe Vooroever study.

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Samenvatting
Dit rapport maakt deel uit van het Kustgenese-2 programma "diepere Vooroever", dat zich richt op het begrijpen van de morfodynamiek en de sedimentologie van de Nederlandse diepere vooroever ten behoeve van duurzaam beheer en veiligheid van het Nederlandse kust systeem. Het doel van dit onderzoeksproject is het verkrijgen van inzicht in de sedimentaire opbouw en dynamiek van de kust en welke processen de uitwisseling van sediment bepalen over de diepe vooroever.

Hiertoe zijn twee multibeam opnames uitgevoerd in 2017 en 2018 in de studie terreinen: Noordwijk, Terschelling en Ameland. Door de morfologische kenmerken van de zeebodem te analyseren, is het mogelijk om de dominante mariene processen te begrijpen tijdens de depositie en de omwerking van het sediment. Daarnaast werden de backscatter-gegevens getest op hun toepasbaarheid voor de lagere vooroever.

Uit de waarnemingen wordt duidelijk dat op alle waterdiepten (tot -22m) sedimentverplaatsing optreedt. De veranderingen in de periode 2017-2018 waren groot bij Noordwijk en (deels) Terschelling, waar in 2017 waarnemingen werden gedaan na een stormachtige periode en in 2018 na een lange stille periode. Ook in het Ameland gebied was sprake van veranderingen (2017 en 2018 observaties beide gedaan na een lange rustige periode).

Op een aantal plaatsen zijn de oudere sedimentaire eenheden net onder, of aan, het oppervlak van invloed op de huidige ontwikkeling van de diepere vooroever, zoals blijkt uit voorbeelden op Terschelling en Noordwijk. Van verschillende structuren die op de vooroever van Terschelling werden aangetroffen, is de genese niet duidelijk. Ze zouden kunnen worden gerelateerd aan het uittreden van ondiep gas of water uit het sediment.

Uit de vergelijking van de 2017 en 2018 observaties en de verschillen tussen Ameland (twee rustige periodes) en Terschelling en Noordwijk (een stormachtige en een rustige periode), blijkt dat de invloed van stormen tot de diepste delen van de beschouwde gebieden reikt (-22m). De meeste sedimentaire structuren die worden waargenomen na stormen zijn indicatief voor erosie. In dieper water is dit deels te wijten aan stromingen (diep uitgeschuurde troggen op dieper water in de Terschelling-site in 2017; afgevlakte bodemvormen op de zandgolven bij Noordwijk in 2017) en deels door golven en stromingen (hummocks op de Terschelling-site in 2017). In de ondiepe delen van de diepere vooroever blijken golven een belangrijker rol te spelen (erosie-sporen Noordwijk in 2017).

Onder rustige omstandigheden domineren kust-parallelle getijdestromingen het sediment transport op het diepere deel van de vooroever. Bodemvormen teweeggebracht door kust-parallelle getijde-stromingen domineren in dieper water: voor Ameland en Noordwijk beneden-14/-15m en voor Terschelling onder-18m. De trage opvulling van ondiepe visserijsporen bij Noordwijk suggereert dat bij rustige weersomstandigheden sedimenttransporten in de zone tussen -15 en -18m klein zijn. De hier beschreven waarnemingen en interpretaties zullen worden opgenomen in een "technisch advies" van de Diepe Vooroever-studie.

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Version	Date	Author	Initials	Review	Initials	Approval	Initials
0.1	may 2019	Albert Oost Veronique Marges Tommer Vermaas Thaienne van Dijk Marios Karaoulis		Ad van der Spek Mirjam Snellen (Delft University of Technology)		Frank Hoozemans	
1.0	august 2019	Albert Oost Veronique Marges Tommer Vermaas Thaienne van Dijk Marios Karaoulis		Ad van der Spek Mirjam Snellen (Delft University of Technology)		Frank Hoozemans	
1.1	december 2019	Albert Oost Veronique Marges Tommer Vermaas Thaienne van Dijk Marios Karaoulis		Ad van der Spek		Toon Segeren	

Status
final

Contents

1 Introduction

1.1 Kustgenese-2

The Dutch coastal policy aims for a safe, economically strong and attractive coast. In order to achieve this, the coast and the shoreface are maintained with sand nourishments. The nourished maintenance zone is called ‘coastal foundation’. The offshore boundary of the coastal foundation is set at the NAP -20m depth contour, while the onshore limit is formed by the landward boundary of the ripple area on land and by the shortest line through the tidal inlets (open coast).

In 2020 the Dutch Ministry of Infrastructure and Water Management will decide on the future annual nourishment volume, for the next decade. The Kustgenese-2 (KG2) programme is aimed to generate knowledge to support this decision process. The subproject “Diepere Vooroever” (DV, i.e., lower shoreface) of the KG2 programme, commissioned by Rijkswaterstaat to Deltares, focuses on a main question (Offerteaanvraag Kustgenese):

BV001: What are possibilities for an alternative offshore boundary of the coastal foundation?

The question has been translated into several more detailed, research questions. The present report studies the morphology of the Dutch lower shoreface and as such contributes to the following research questions underlying main question 1:

ZB110: What is the sedimentary built-up of the coast, in terms of bedforms, sedimentary structures, bottom profiles and grain size distributions?
ZB120: Which processes determine the exchange of sediment between the shoreface and the deeper shoreface (North Sea bed) and what is their frequency of occurrence and their contribution?
ZB140: In which subareas (or zones) can the coastal profile be subdivided, which are similar in (stability) of the profile, sedimentary built up and dynamics?

The report will contribute to answer these research questions posed in the Technical report “Diepe Vooroever”. More background information and a detailed description of definitions can be found in the literature study report of the “Diepe Vooroever” subproject (Van der Werf et al. 2017). All depths are given with reference to NAP (Dutch Ordinance Level), which is approximately mean sea level.

1.2 The Dutch lower shoreface

The shoreface is the area seawards of the low water line that is affected by waves and tidal currents. Along the Dutch coast the lower shoreface is defined as the zone between approx. the -8m and -20m depth contours, with typical bed slopes between 1:100 and 1:1000 (Figure 1.1; Van der Werf et al., 2017; van Alphen & Damoiseaux, 1986). However, it should be noted that the above-mentioned bed slopes cannot be observed readily outside the Holland area. The lower shoreface is the zone below the fair-weather wave base, where tidal currents and storm waves dominate.

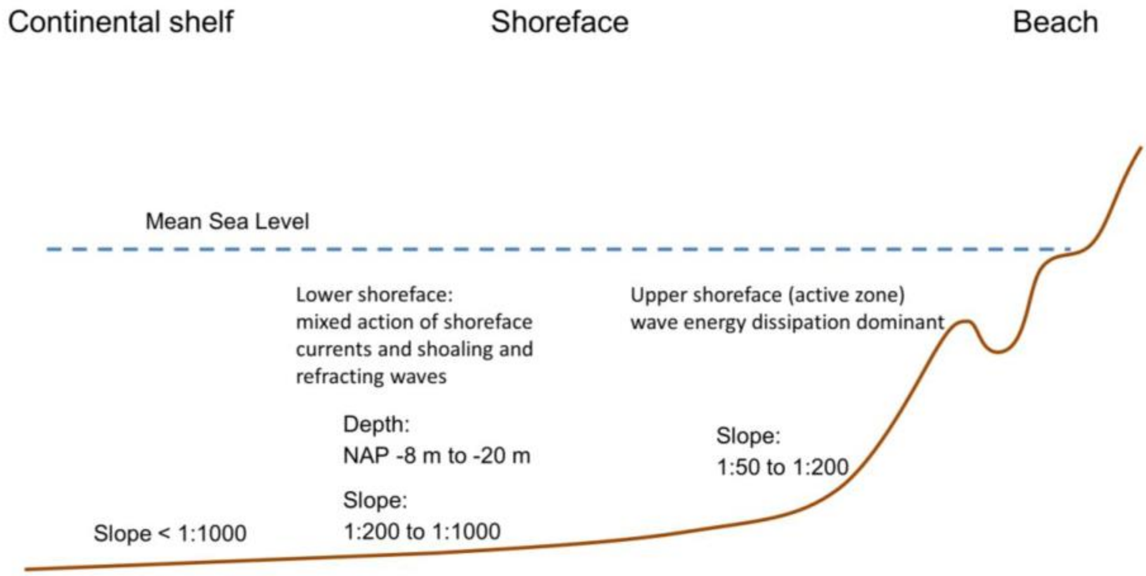


Figure 1.1 Typical Dutch cross-shore coastal profile (not to vertical scale).

The following hydrodynamic influences are to be expected which may influence the morphological development of the area:

- Waves which stir the seabed. During fair weather, waves reach down to about -5m (fair weather wave base). Storm waves can reach much deeper and exert their influence on depths of -13m or more (Cleveringa, 2000). It is to be noted that storms occur more often during the winter than during the summer half year, which may lead to a marked seasonality of the morphological features;
- The tidal wave which travels along the coast generates a tidal current rose which is strongly ellipsoid, with strong almost coast parallel ebb and flood currents and velocities near the seabed are around 0.5 m/s. The variation in tide-driven flow at the lower shoreface is shown by the M2 component, which can be derived by harmonic analysis on depth averaged (ADCP) velocity data (Figure 1.2); Schrijvershof et al., 2019).

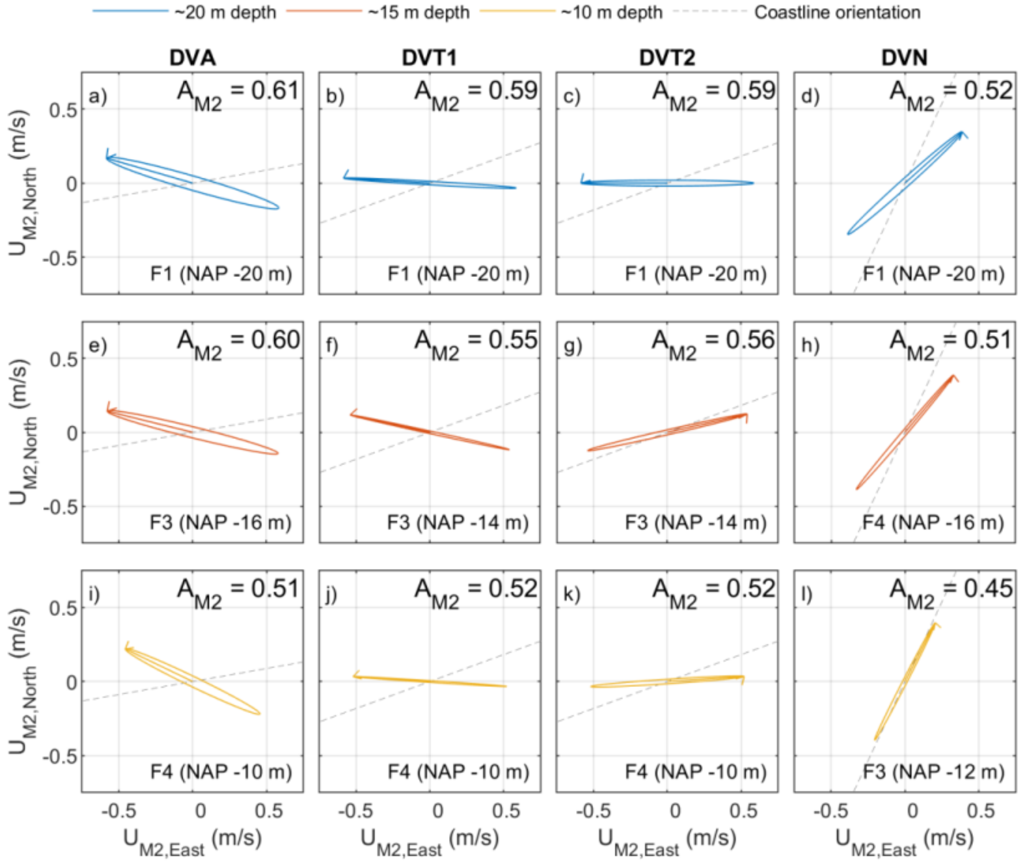


Figure 1.2 Ellipses of the M2 tidal component derived by tidal analysis on the observed depth averaged currents. The figure shows a NE-SW oriented ellipse at Noordwijk (DVN) and an E-W oriented ellipse at the Wadden coast (DVA, DVT1, DVT2) (Schrijvershof et al., 2019).

- The near-bed wave orbital velocity scales linearly with the significant wave height, which increases with shallower depths. Characteristics orbital velocities on the Dutch lower shoreface are in the order of a few dm/s but can reach up to 1 m/s when the relative wave height (Hs/h) attains a value of ~0.3. The maximum observed orbital velocity is ~0.8 m/s at the lower part (-20m water depth) and >1 m/s at the shallower part (15m water depth; Schrijvershof et al., 2019).
- Characteristic residual depth averaged velocities on the lower shoreface are in the order of a few dm/s in longshore direction and a few cm/s in cross-shore direction. During energetic wind or wave conditions the residual current can exceed 0.5 m/s in longshore direction and up to ~0.4 m/s in cross-shore direction (Schrijvershof et al., 2019).
- Residual velocities on the lower shoreface are significantly altered from the tide-driven flow during energetic wind and (non-breaking) wave conditions. During these conditions the strength of the residual current increases with decreasing depth and increases with the intensity of the wind and wave conditions. This can be described well by a linear relation of the depth-averaged residual current strength with wave energy. These relations are, however, not valid for less energetic conditions. The residual current velocity profile during observed energetic conditions is completely landward directed over the complete water column, which is a significant change from the mild conditions where the profile varies from landwards at the surface to seawards lower in the water column (in accordance to a Stokes drift driven profile; Schrijvershof et al., 2019).

- Under influence of a retour current which is laden with sediments, it would in theory be possible that density driven bottom currents move over the seabed down slope. In the German Bight such recent deposits have been recognized (Aigner, 1985).
- At Ameland Inlet, tidal currents flow more or less perpendicular to the coast, especially during ebb-tide. Especially at the downdrift side, the interaction between these currents and the coast parallel tidal currents may lead to a more circular tidal current rose, as shown by Sha (1990). Furthermore, for the Ameland site storm surges can increase the tidal volumes in the backbarrier area, resulting in strong outflow through the inlet and over the ebb-tidal delta after waning of the storm.
- For the Noordwijk site a slow spiralling estuarine circulation current brought about by the density differences of riverine fresh water and sea water and the net northward flow direction is present (Grasmeijer et al., 2019).

The knowledge about the Dutch lower shoreface is limited. It remains unclear what the relative importance is of the different marine processes such as tides and waves. This knowledge gap is mainly caused by lack of observations. It is important to understand the hydro-morphodynamics between -8 and -20 m. A detailed picture of the bed morphology is a first. One way to study the impact of marine processes on the seabed is by means of multibeam surveys.

1.3 Objectives

Better understanding the role of different (hydrodynamic) processes on the lower shoreface is one of the main objectives for the subproject ‘Diepe Vooroever’. This knowledge will provide insight in the morphodynamics of the lower shore face which will help to make clear the role in the coastal system which provides a basis for a more accurate choice of the lower boundary of the coastal system.

The goal of this report is to gain insight into the physical processes that occur on the lower shoreface, such as tides, the relative importance of (storm) wave action for sediment transport in the lower shoreface etc. By analysing the morphological features of the seabed, it is possible to understand the dominant marine processes during deposition and reworking of the sediment. The analysis of the backscatter data is performed to test the application of this data and method on the area of the lower shoreface.

1.4 Research areas

This report presents the data and description of multibeam surveys from the three research areas along the Dutch coast (Figure 1.3), their analysis and interpretation. Below a short description is given of each area.

1.4.1 Ameland Inlet research area

The Ameland inlet has been present since at least the early middle ages, but probably since Roman times or earlier onwards. Since the 19th century it has shifted over more than 1 km to the east. By and large, it may be stated that the ebb-tidal delta lobe is a rather constant feature on the larger scale. However, at any given location erosion and sedimentation alternate through time due to the shifting of channels and bars in the ebb-tidal delta and shifts of the delta lobe. The ebb-tidal delta lobe forms a relatively steep slope locally going down some 8m over some 800 m. The ebb-tidal delta lobe and the inlet are active morphological features of which the formative processes determine to a large extent the morphological development of that part of the area. Only for deeper water (-18 to -20m) these influences are less marked and coast-parallel tidal currents become more important.

1.4.2 Terschelling research area

The island of Terschelling is part of the barrier island chain of the Wadden Sea. There are many indications from geological observations (e.g. Sha, 1990) that during the Holocene the barrier chain has retreated in a coastward direction. At the specific location of the Terschelling research area, nautical maps and historic information indicate that at least since 800 AD the area was part of the shoreface of Terschelling (Oost, 1995). A large washover system may have been present in medieval times (unpubl. results Oost), but will probably not have influenced the area significantly. Since at least 1900 the coastal position has been rather stable. The slope of the Terschelling shoreface is gradual; going down only some 7m over 5 km.

1.4.3 Noordwijk research area

The Noordwijk area is part of the closed barrier coast of Holland and differs as such from the two Wadden Sea sites. The sediments present stem to a large extent from older fluvial deposits of the river Rhine and tidal channel deposits. The coast at Noordwijk has probably been eroding since Medieval times and retreating over 200-1000m since 1600 AD (Van der Spek et al., 1999) and is as such an erosive feature. The lower shoreface morphology is dominated by shoreface-connected ridges and sand waves. The shoreface-connected ridges might also, to some extent, be erosional features (van Heteren & van der Spek, 2008).

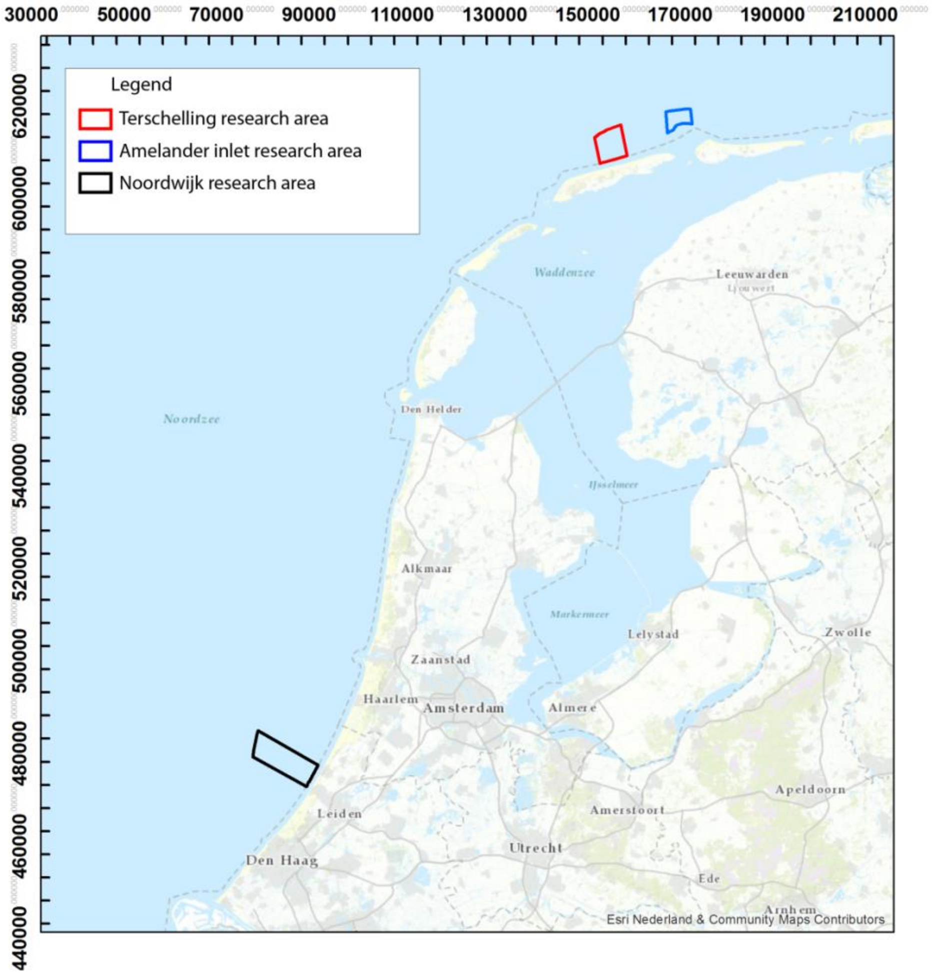


Figure 1.3 Overview map with the three research areas

1.5 Approach

1.5.1 General

To study the development of the seabed two series of observations were done using multibeam and multibeam backscatter analyses.

1.5.2 Multibeam observation

In a multibeam echo sounder (MBES) the sound wave is emitted in a fan shape beneath a ship's hull. MBES uses beamforming to extract directional information from the returning soundwaves, producing a swath of depth readings from a single ping, therefore covering a much larger area than when using single-beam echo sounding (SBES), resulting in a much larger data density than with single beam echo sounding. Such surveys show seabed morphology and erosional structures in detail and thus may give clues to what role tides, other currents and storm waves may play in the development of the lower shoreface. During the surveys the MBES system also recorded the backscatter data, which gives information on the intensity of the scattered (not reflected) sound signal.

1.5.3 Analyses

The multibeam observations were visually analyzed to discern areas of special interest. Such areas were studied in more detail. The analyses from the subsequent observations were intercompared to notice differences and similarities. Where needed further computer enhancements were made.

In paragraph 2.3 we describe the applied methods for multibeam backscatter, and in paragraph 3.4 the preliminary results (initial acoustic classification map). Since a full analysis was beyond the aim of this project, this initial map still needs improvements in the tuning of the acoustical settings for optimal, results. Also, the acoustic classes remain to be coupled to sediment characteristics from box core samples properly. In a separate section, we compare the results of the MBES-backscatter acoustic classification to the classical method of seabed sediment mapping.

2 Method

2.1 Multibeam surveys

Multibeam surveys were carried out in three areas of the Dutch lower shoreface: Noordwijk, Terschelling and Amelander Inlet (Figure 1.3), each area was measured twice: in 2017 and 2018 (see also next paragraph). The three research areas were chosen in locations where tidal processes were assumed not to be dominant and where data from other measurement campaigns are already available (see Van der Werf et al. 2017 for details on the areas).

For each survey raw data was processed by RWS-CIV and delivered to Deltares as xyz data. The data were interpolated using inverse distance weighting (IDW) method to a 50 cm resolution grid. From the resulting maps various areas were chosen to illustrate the most prominent features in the area. More information on the data can be found in Van der Werf et al. (2019).

2.2 Time of collection

Rijkswaterstaat conducted dual-head multibeam surveys with their ship Arca in 2017 and 2018 (Table 2.1):

Multibeam surveys 2017:

- Seaward of the ebb-tidal delta of Ameland Inlet: early September 2017.
- Offshore Terschelling: November and December 2017
- Offshore Noordwijk: September, October and November 2017.

From the wave data it becomes clear that the surveys at Ameland (red vertical lines in Figure 2.1) were conducted at the end of a relatively quiet period which started mid-January, but rougher conditions than in 2018. The survey at Noordwijk (green lines) was conducted during a relatively turbulent period. The Terschelling survey was conducted towards the end of 2017 and observations were thus after a relatively turbulent period and interrupted by a storm.

Table 2.1 : Overview of the multibeam surveys of the three study areas.

From (yyyy-mm-dd)	**Until**
Ameland	
2017-09-05	2017-09-07
2018-08-07	2018-08-08
Terschelling	
2017-11-28	2017-11-30
2017-12-12	2017-12-12
2018-10-09	2018-10-12
Noordwijk	
2017-09-21	2017-09-21
2017-09-25	2017-09-26
2017-10-19	2017-10-20
2017-10-23	2017-10-24
2017-11-13	2017-11-16
2017-11-20	2017-11-23
2018-09-13	2018-09-28

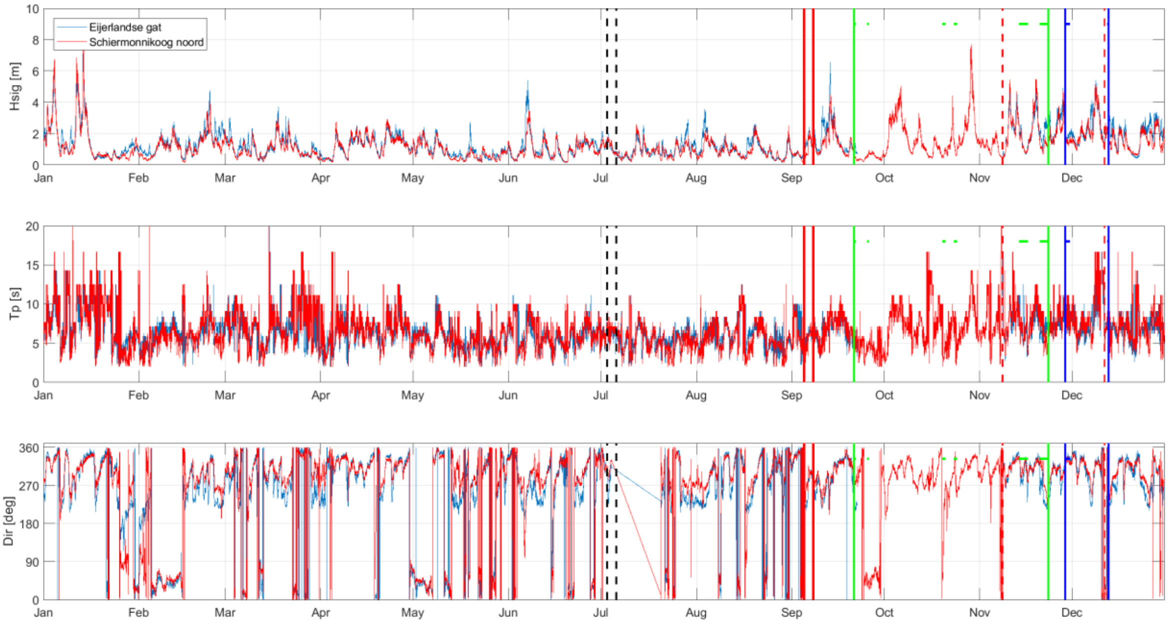


Figure 2.1 Overview of the wave conditions in 2017 for the stations near Ameland and Schiermonnikoog. The top panel shows registered significant wave heights, the middle panel the related wave periods and the lower panel wave directions. The various periods during which multibeam surveys were conducted are marked with two vertical lines: Red = Ameland, dashed: measurement frames operational; Green = Noordwijk; Blue = Terschelling; Black dashed: vibrocore and boxcore sampling period (for description cores see Oost et al., 2019).

Multibeam surveys 2018:

- Seaward of the ebb-tidal delta of Ameland Inlet: August 2018
- Offshore Terschelling: October 2018
- Offshore Noordwijk: September 2018.

From the wave data of stations near Ameland and Terschelling the weather conditions preceding the survey can be determined (Table 2.1; Figure 2.2). From this it becomes clear that all the surveys of 2018 were conducted at the end of a relatively quiet period, which started mid-January.

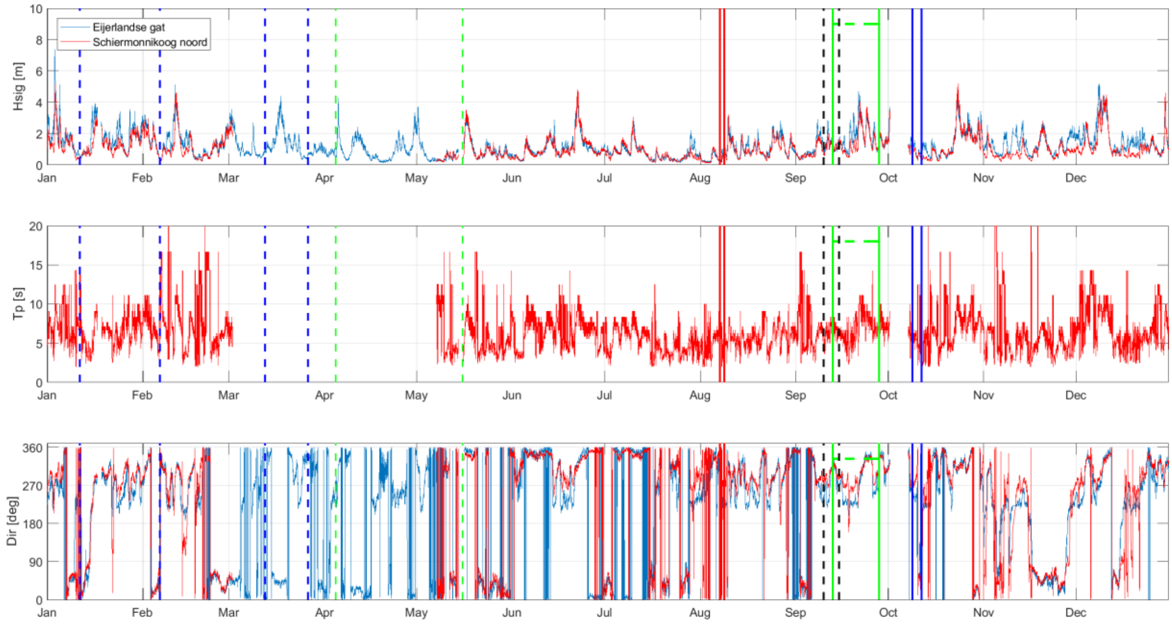


Figure 2.2 Overview of the wave conditions in 2018 for the stations near Texel (Eierlandse Gat) and Schiermonnikoog. The top panel shows registered significant wave heights, the middle panel the related wave periods and the lower panel wave directions. The various periods during which multibeam surveys were conducted are marked with two vertical lines: Red = Ameland; Green = Noordwijk, dashed: measurement frames operational; Blue = Terschelling, dashed: measurement frames operational (two periods); Black dashed: rectangular boxcore sampling period (see Oost et al., 2019).

2.3 Backscatter processing

Multibeam backscatter

The established (classical) method for seabed sediment mapping is based on sediment type or median grain size as determined from bed samples or cores, with sub-bottom seismic data - if available - for a better handle on extent, which are then interpolated in the areas where data are absent in order to create a map. However, the information from samples or cores is point data, often with low data densities, i.e. with large distances between the cores, leaving the exact distributions largely unknown. With recording the backscatter intensity from multibeam echo soundings, the sediment characteristics at the bed are revealed at high resolution (e.g. Ivakin and Sessarego, 2007; Lurton and Lamarche, 2015), which means that mapping can be done from observed distributions of measured backscatter intensities rather than “blind” interpolation.

The idea of acoustic bed classification from backscatter data is that the backscatter strength varies over the swath and that the shape of this angular response is representative for certain bed characteristics, e.g. seabed morphology, roughness, sediment type. When the measured backscatter data are corrected for these factors, such as morphology, the shape of the angular response is believed to represent a certain sediment type (Lurton and Lamarche, 2015, and references therein), so that sediments of different grain size distributions can be discriminated.

To date, in the Netherlands, multibeam echo sounding is merely used for bathymetric purposes and the backscatter data remained largely unused (except for scientific research and a few initial tests). Delft University of Technology (e.g. Simons and Snellen, 2009; Snellen et al., 2018; Gaida et al., 2018a) developed a method for the acoustic classification of bed sediments, using multibeam backscatter data, which in a knowledge exchange with Deltares is here applied on the Ameland 2018 data within the Kustgenese 2 project as a pilot.

Bed classification method

Delft University of Technology developed a bed classification method based on the Bayes technique. The Bayesian method accounts for the intrinsic variability of the backscatter strength by assuming that the measured backscatter per beam, corresponds to a sum of Gaussian distributions, where each Gaussian distribution corresponds to a distinct seabed sediment type (Simons & Snellen, 2009; Snellen et al., 2018). By applying the Bayesian decision rule, an optimal number of acoustic classes is calculated, and the classes are obtained from the individual Gaussian distributions. The acoustic classes can be coupled to sediment type from grain-size distributions from bed samples (ground truthing). Although some ambiguity is still the case, for example, the angular response of gravel may be similar to that of finer sediment types, this method is successful for seabed sediment mapping at high-resolution (Gaida et al., 2018a).

Data processing workflow

For this pilot the data collected at the Ameland site in 2017 was used. We received data in Kongsberg file format, with extension '.all'. Data from each survey line is saved under a different filename. In total, we received 68 data files for the corresponding survey lines. We noticed that the GPS positions that were saved in the '.all' files had an incorrect offset in the Northing (y direction) of 13.1 m. Thus, we corrected each survey line to remove the 13.1m offset. The processing flowchart is based on the TU Delft workflow.

Pre-Processing

1 We imported the '.all' file in python using the python package (https://github.com/pktrigg)
2 We corrected for the GPS offset, by calculating the trajectory of the sail line and removed the offset.
3 We applied a filter to remove data points at which GPS information was not stored.
4 We applied a noise filter on the data, to remove false pings (especially due to water bubbles). This is a moving window filter, that scans 10 consecutive pings, calculates the average backscatter value and removes data that differ more than 1.8 dB.
5 We removed pings with bad backscatter values. The threshold is set to 100 dB.
6 We removed pings that have beam angles greater than 75 degrees, as that angle greater than 75 degrees cannot be used for classification (see references).
7 We removed pings with false bathymetry values.
8 We applied a 1-D smooth filter on the bathymetry, and we removed pings that differ more than 1.483 times the average depth in that ping (Z-score filter).
9 On the filtered bathymetry data, we calculated the slope (for the correction of slope in the backscatter measurements). The slope correction is based on the slope angle, pixel size, acoustic frequency and footprint, the true incident angle, the grazing angle, and the beam widening across track and along track. This process is described in TU Delft code. New backscatter values are stored in the data.
10 We calculated the backscatter strength (in dB per m^2) per angle of incidence. We calculate this separately per side for each of the of the sonar heads. Averaging over a couple of pings and beams is applied to account for the footprint (ensonified area), depending on the beam angle and water depth. The first soundings are selected by original beam angle and pings. Afterwards, the selected soundings are sorted considering modified incident angle (considering slope) to account for location and new incident angle. Data are stored for the next step of acoustic bed classification.

Acoustic Bed Classification

The acoustic bed classification is based on the Bayesian method by Snellen et al. (2018), Gaida et al. (2018a, 2018b) and Simons and Snellen (2009).

The steps in the method can be summarized as follows:

- to collect a sufficient number of measurements, that allows for the calculation of a Gaussian distribution, representing the substrates present in the area.
- To estimate the optimal number of classes that each represent a sediment type, by fitting several Gaussian distributions to approximate the overall measured distribution and applying a Chi-square test.
- To determine the intersection points of the overlapping Gaussian distributions in order to define the acoustic classes.

Using dual-head, dual-frequency multibeam echo sounding (4 frequencies), the data processing considered the effect on the backscatter strength of the frequencies (as described in Gaida et al., 2018b).

3 Observations

3.1 Ameland Inlet

3.1.1 Area description

The study area is situated directly seaward of the main ebb channel of the ebb-tidal delta of Ameland Inlet. The multibeam survey of 2017 shows the bedforms between -8.0 and -21.1m water depth and has been carried out after a prolonged period of relatively calm weather conditions (Figure 3.1). Hence, the morphology is expected to reflect the fair-weather conditions. This also holds for 2018, where the water depth varied between -9.0 and -20.8m (Figure 3.2).

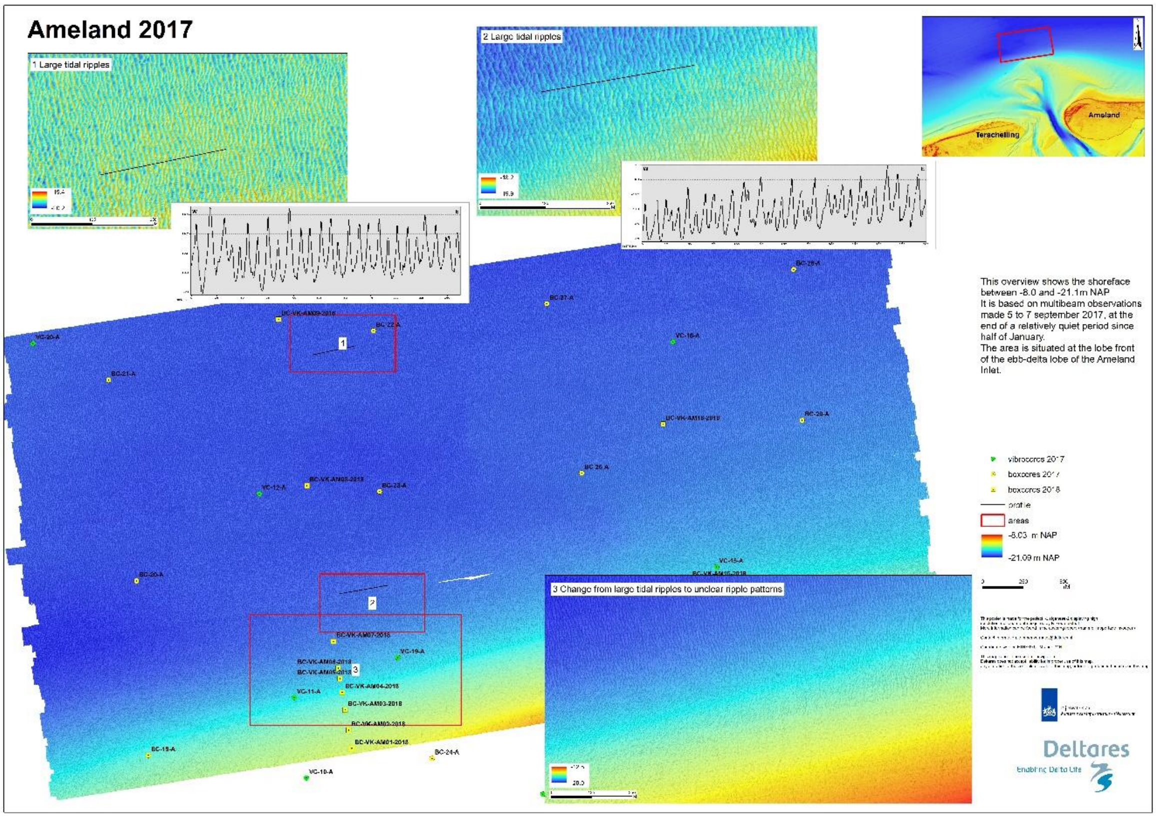


Figure 3.1 Overview multibeam observations 2017 seaward of the ebb-tidal delta of Ameland Inlet with details given in insets.

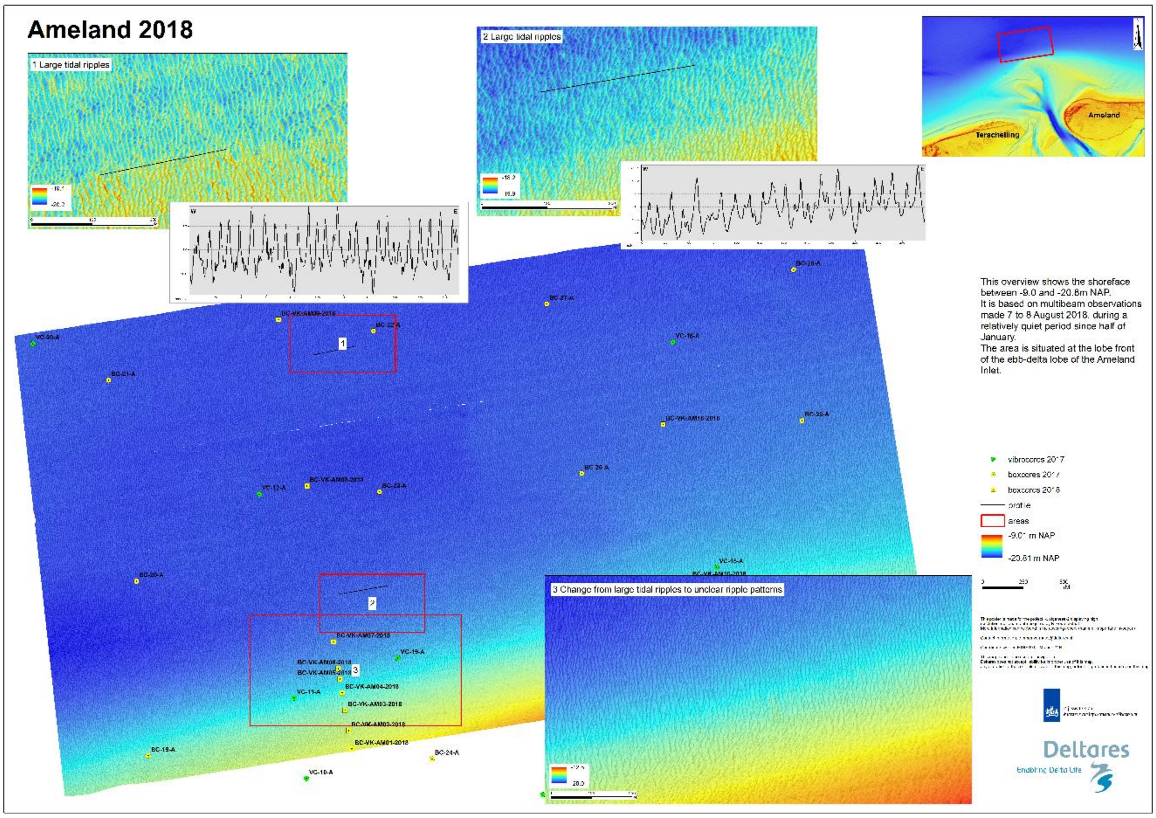
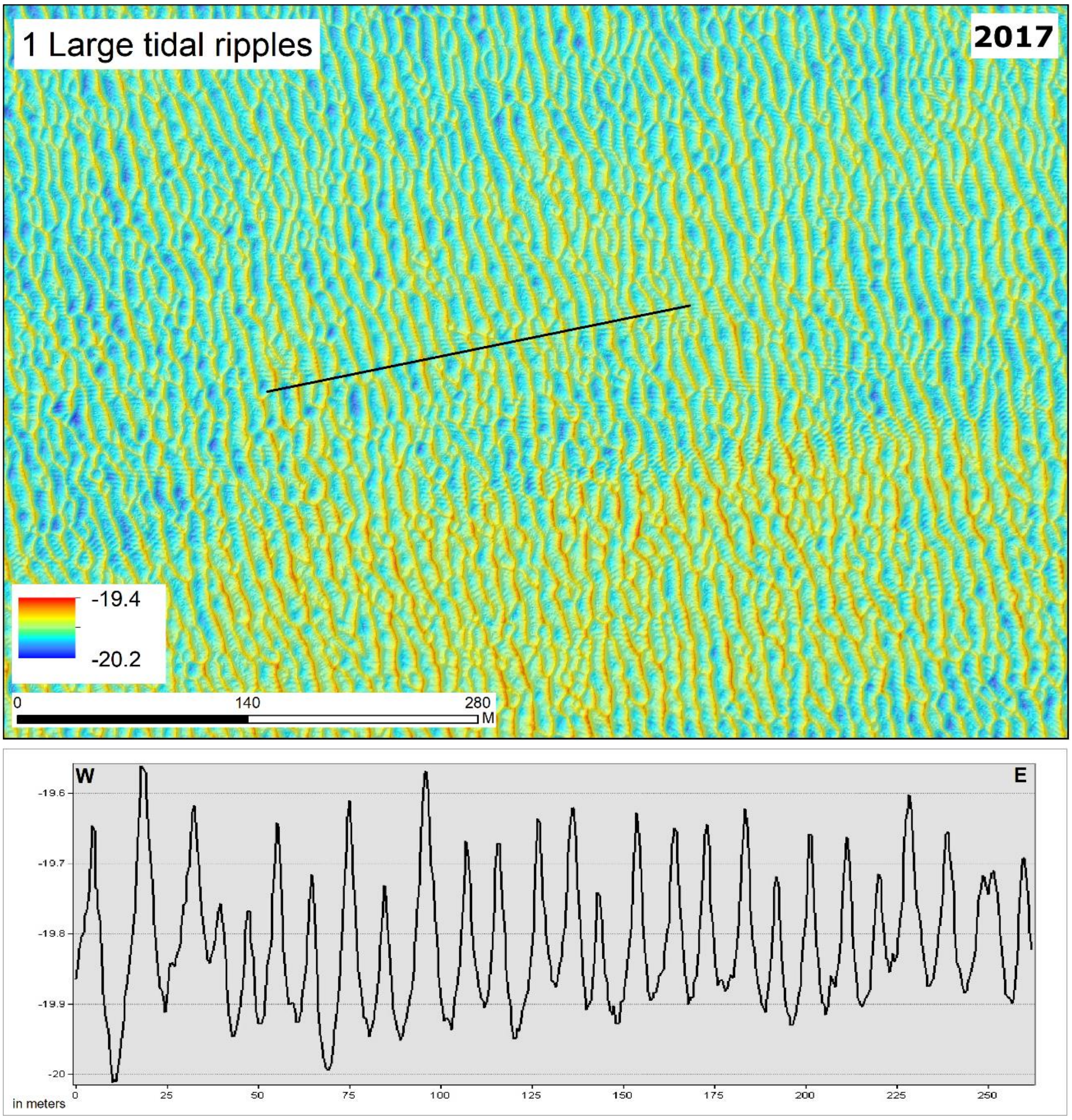


Figure 3.2 Overview multibeam observations 2018 seaward of the ebb-tidal delta of Ameland Inlet with details given in insets.

3.1.2 Tidal large ripples (area I) -19.4m to -20.2m

In 2017 this area (Figure 3.3) is characterized by what are, by definition, large ripples with a wave length of about 10m and a height of 0.2 to 0.5m, which by and large stand perpendicular to the coast. The large ripples are almost symmetrical with a slightly steeper flank to the east which is in good accordance with the dominant (flood) tidal current direction. The tops of the large ripples interconnect and form a chain-like pattern.

In 2018 the southern part of the area is much shallower than in 2017. The area is characterized by large ripples with a wavelength of about 11m and a height of 0.2 to 0.3m. The large ripples are almost symmetrical with a slightly steeper flank to the west.


1 Large tidal ripples
2017
-19.4
-20.2
0
140
280
M
W
E
-19.6
-19.7
-19.8
-19.9
-20
in meters
0
25
50
75
100
125
150
175
200
225
250

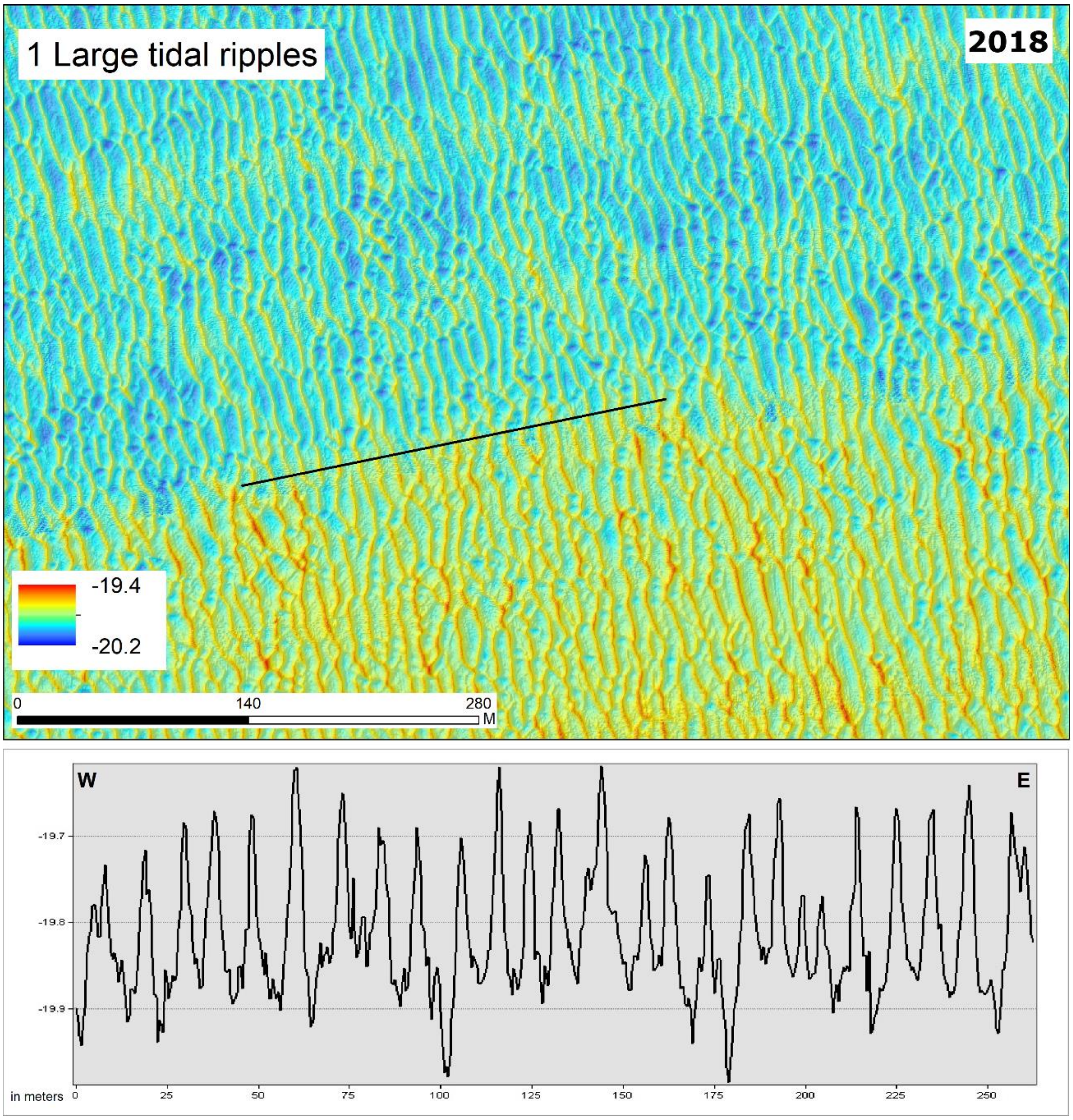
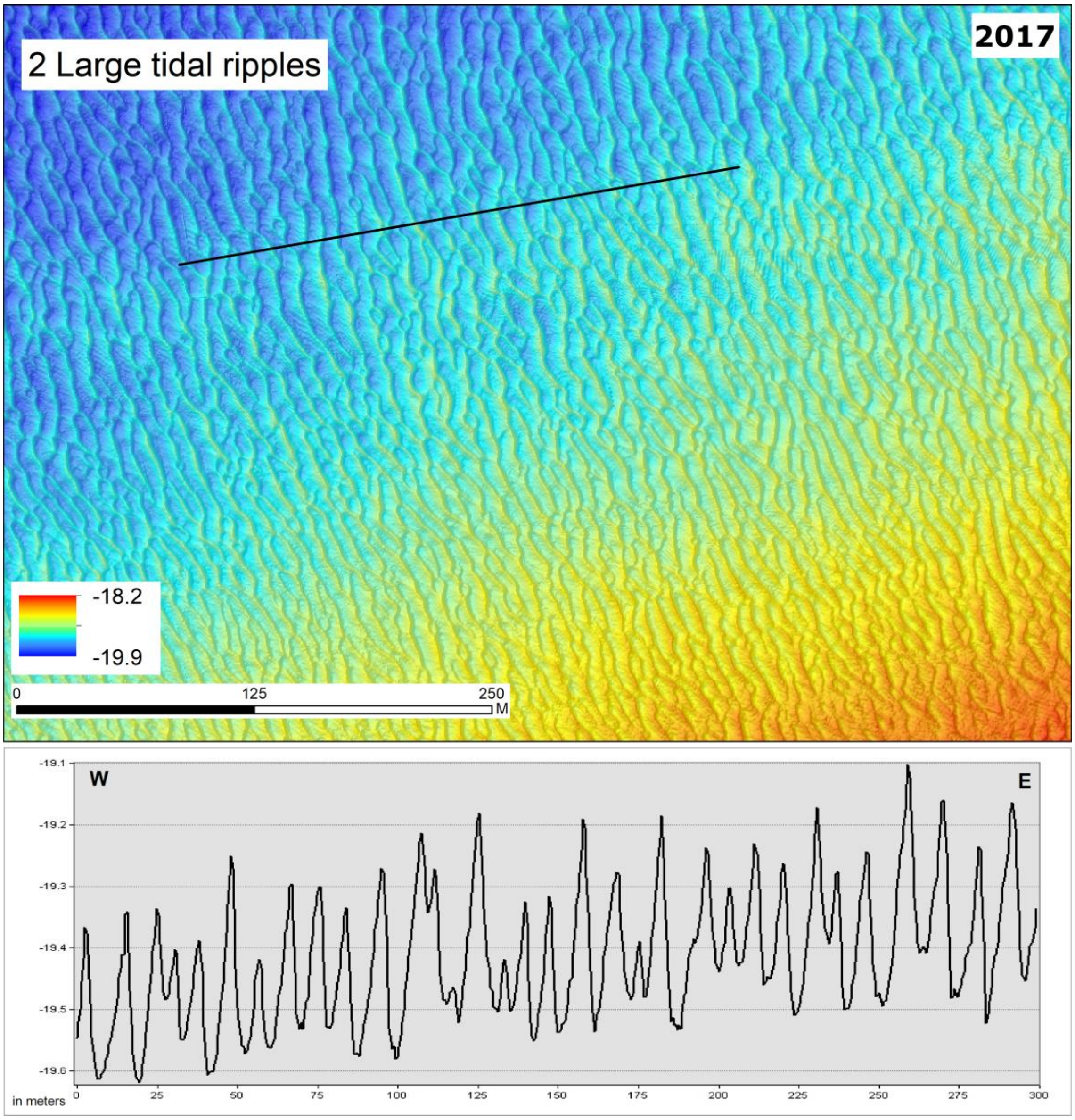


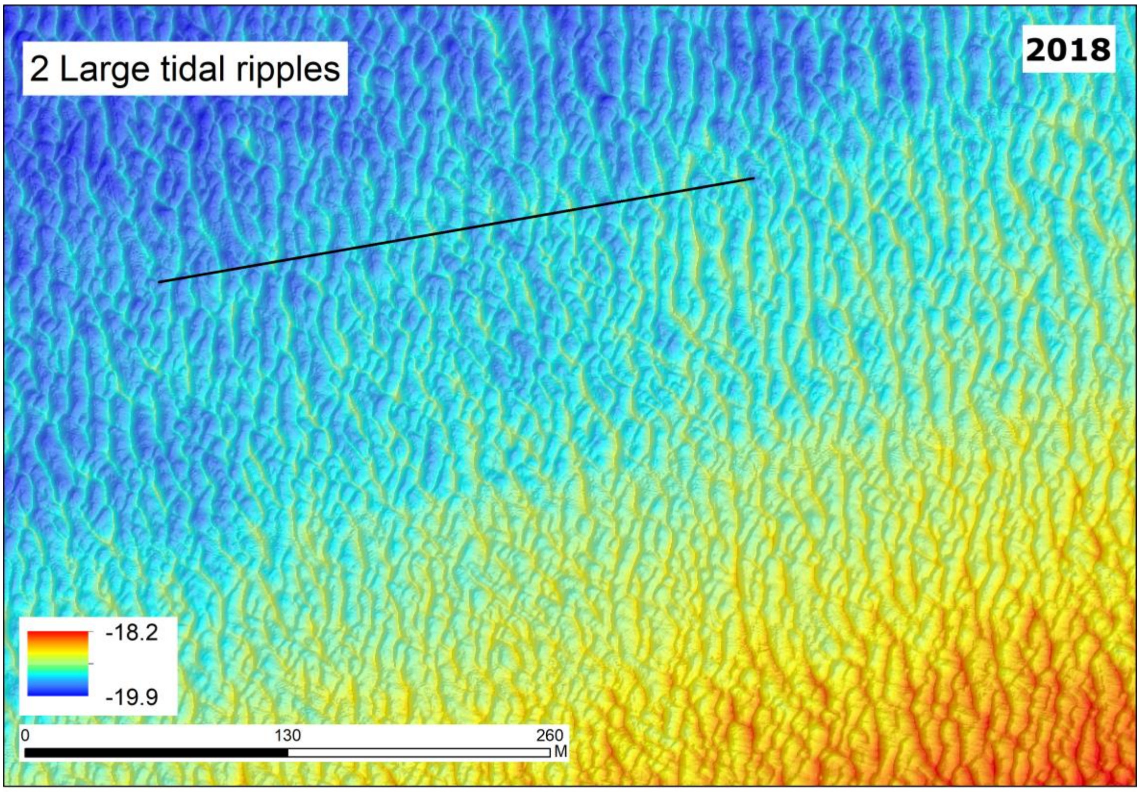
Figure 3.3 Large ripples on the lower shoreface of the ebb-tidal delta of Ameland Inlet, top view and cross section of the same area in 2017: upper panel and 2018: lower panel. See Fig. 3.1 and 3.2 for location.

3.1.3 Tidal large ripples (area II) -18.2m to -19.9m

In 2017 large ripples were present in this area of which the crests stand perpendicular to the coast (Figure 3.4; 9m wavelength and a height of 0.15-0.5m). The bedforms seem to be built up of several large ripples on top of each other and are largely symmetrical. These large ripples are also formed by coast-parallel tidal currents. In shallower reaches the ripple pattern becomes somewhat obscured (SE corner).

In 2018 this area is comparable to the situation of 2017, although the general impression is more chaotic. The whole area is now covered with large composed large ripples with a slightly larger wavelength and comparable wave height with respect to 2017 (12.5m wave length and a height of 0.2-0.4m). Also, the orientation has changed somewhat to a more north-south direction. The large ripples also show a more chainlike character.


2 Large tidal ripples
2017
-18.2
-19.9
0
125
250
M
W
E
-19.1
-19.2
-19.3
-19.4
-19.5
-19.6
in meters
0 25 50 75 100 125 150 175 200 225 250 275 300



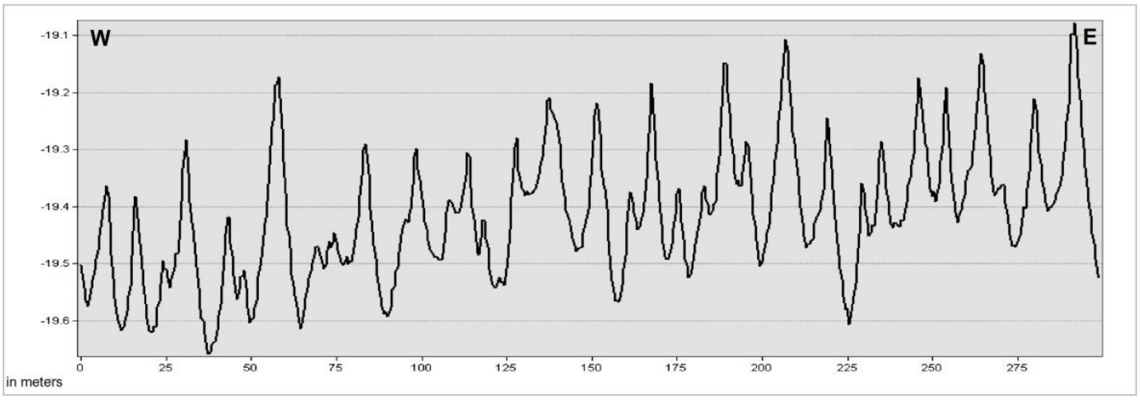
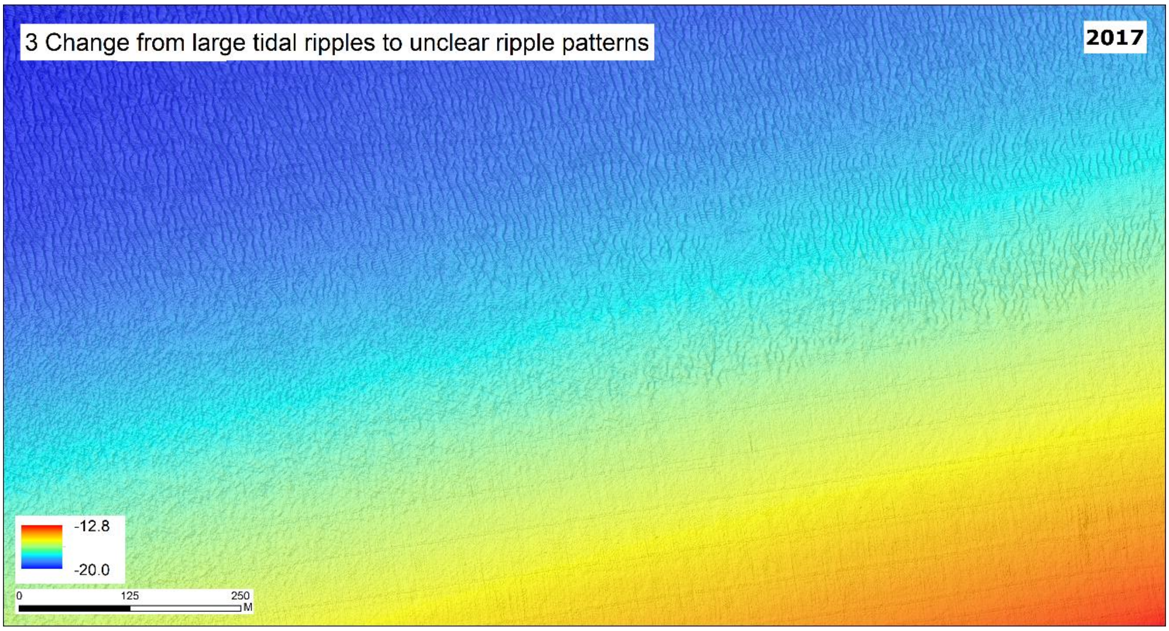


Figure 3.4 Tidal large ripples on the inshore part of the lower shoreface of the ebb-tidal delta of Ameland Inlet, top view and cross section for the same area in 2017: upper panel and 2018: lower panel. See Fig. 3.1 and 3.2 for location.

3.1.4 Tidal large ripples to irregular ripples -12.8m to -20m

In 2017 large ripples oriented perpendicular to the coast and with a steeper flank to the east change halfway this area (around --18m, at the edge of the dark- and light blue zones; Figure 3.5) into an irregular, three-dimensional pattern and, more to the southsoutheast, above ca. --16m (yellow zone in Figure 3.5), into an area with a relatively featureless bed.

In 2018 a larger part of the same area is covered with large ripples which are bigger than in 2017 and a steeper flank to the east. The orientation is slightly more N-S. The transition from more or less regular large ripples to a more or less flatbed occurs at -15m in 2018.



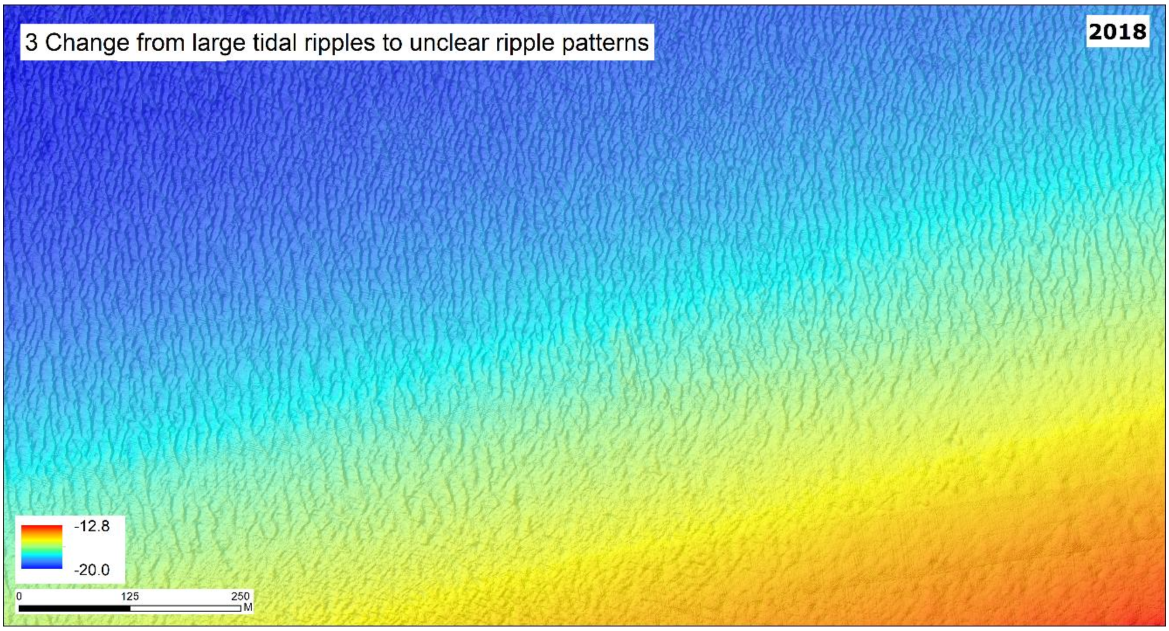


Figure 3.5 Tidal large ripples changing into irregular three-dimensional bedforms on the lower to middle shoreface of the ebb-tidal delta of Ameland Inlet of the same area in 2017: upper panel and 2018: lower panel. See Figures 3.1 and 3.2 for locations.

3.2 Terschelling

3.2.1 Area description

The area is situated on the lower shoreface of the central part of the barrier island Terschelling. In 2017 the area was surveyed after a prolonged period of relatively stormy weather conditions. Hence, the morphology is expected to show an impression of the storm conditions. In 2017 the depth of the survey area was between -14.3 and -21.0m (Figure 3.6). Note that the most northern part of the 2017 survey shows a remarkable difference in seabed appearance when compared the part south of it (see Figure 3.6 and Figure 3.8, top panel). The 2017 Terschelling survey was interrupted by a storm (see 2.2) and the northern part is likely to have been surveyed after the storm (based on the corresponding measurement time to surface area with deviating ‘smooth’ morphology). Its ‘smooth’ appearance is possibly caused by the storm waves that will have removed the small-scale bedforms.

In 2018 the area was surveyed after a prolonged period of calm weather and might thus show a different morphology because of this. In 2018, the area was larger than in 2017 and the depth in the survey area was between -9.4 and -21.0m. Ripple fields, such as visible in the Ameland surveys, are, except for larger water depths, largely missing in both the 2017 and 2018 observations.

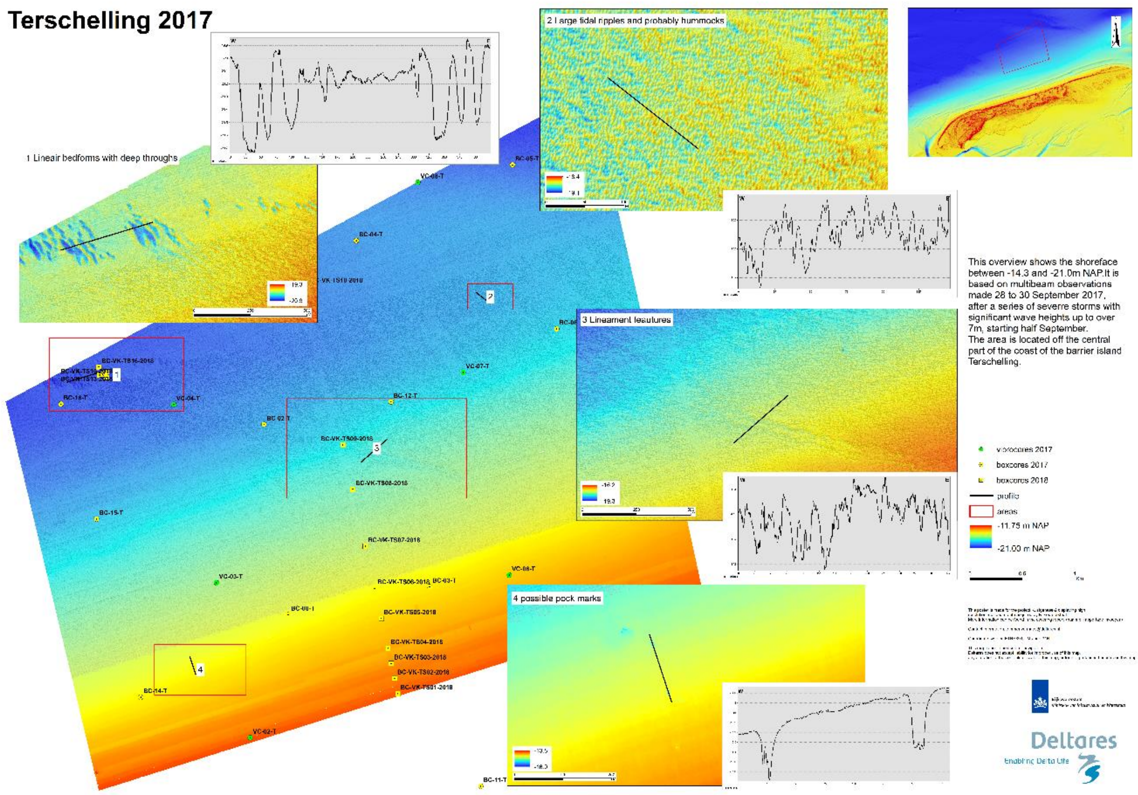


Figure 3.6 Overview multibeam observations 2017 seaward of Terschelling with details given in insets.

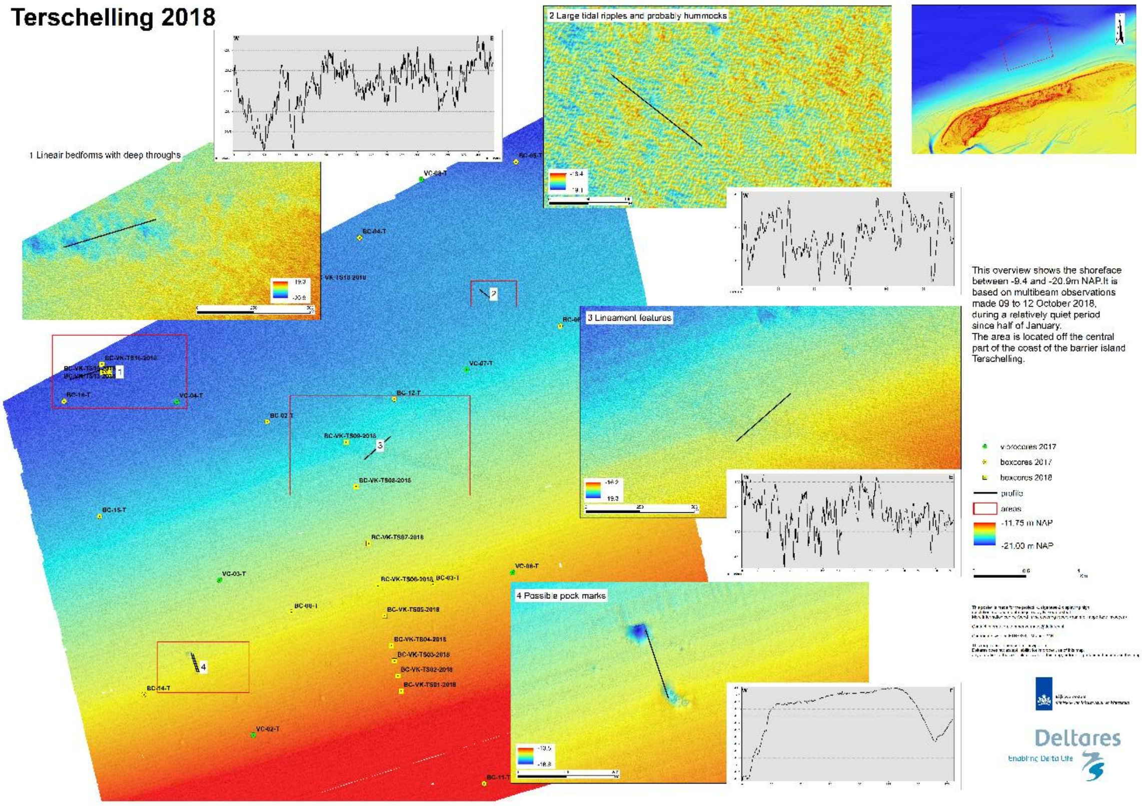


Figure 3.7 Overview multibeam observations 2018 seaward of Terschelling with details given in insets.

3.2.2 Linear bedforms with deep troughs -19.3 to -20.9m:

In 2017 this area is characterized by linear bedforms which are oriented perpendicular to the coast, indicating that the bedforms are probably generated or reworked by tidal currents (Figure 3.8 & Figure 3.9). Indeed, from dedicated box cores taken in 2018, it became clear that the bedforms do show internal bidirectional, large-scale angular bedding, indicative of current-driven transport in several directions. With a wavelength of 30 to 35m and a height of 0.5m these are at the maximum dimensions for bedforms which are, by definition, termed: “large ripples”. The bedforms are almost symmetrical with a slightly steeper flank to the west. However, on a closer look, the bedforms turn out to be more complicated. On several places the large ripples are higher and steeper and have wide, steep-sided troughs.

More to the south, the ripple structures do not show large troughs but are covered with “small bulges” with a diameter of some 2-3m and with an elevation of ca 0.1m. Given the dimensions these features are most likely hummocks. The difference with the rest is probably caused by the interruption of the survey by a storm.

In 2018, after a prolonged and (relatively to 2017) quiet period all the structures seem to have largely vanished; only locally some remnants can still be observed. Large ripples are locally still visible in the 2018 profile but are covered with smaller ripples (Figure 3.9, lower panel). The bedforms have given way to a somewhat irregular surface. It consists of small northnorthwest-southsouthwest oriented large ripples considerably smaller than those observed in 2017, which occasionally form larger compound large ripples. To the south, bedforms are more or less oriented east-west and have a steeper flank to the south.

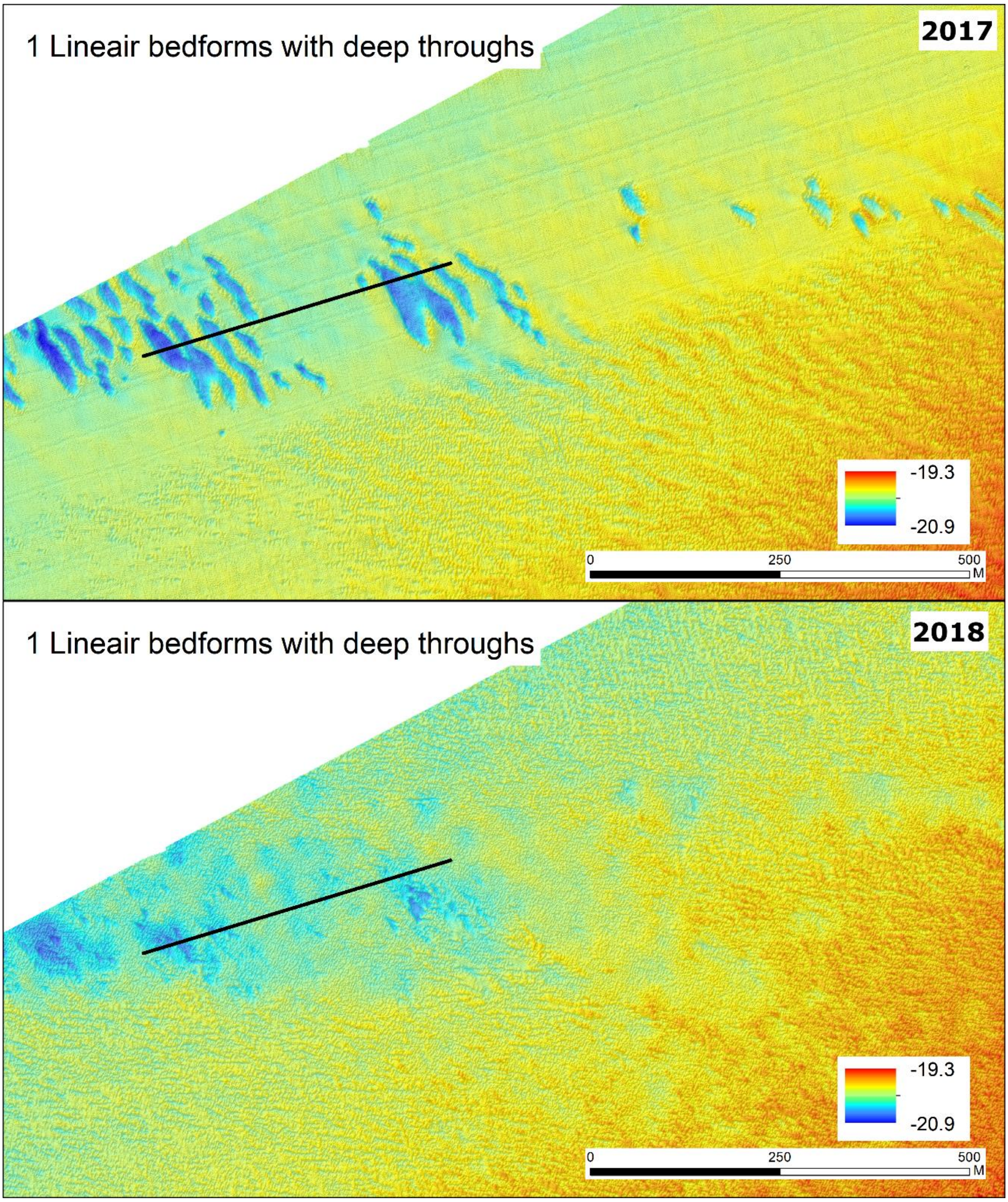


Figure 3.8 linear bedforms with deep troughs north of Terschelling of the same area in 2017: upper panel and 2018: lower panel. See Figures 3.6 and 3.7 for location.

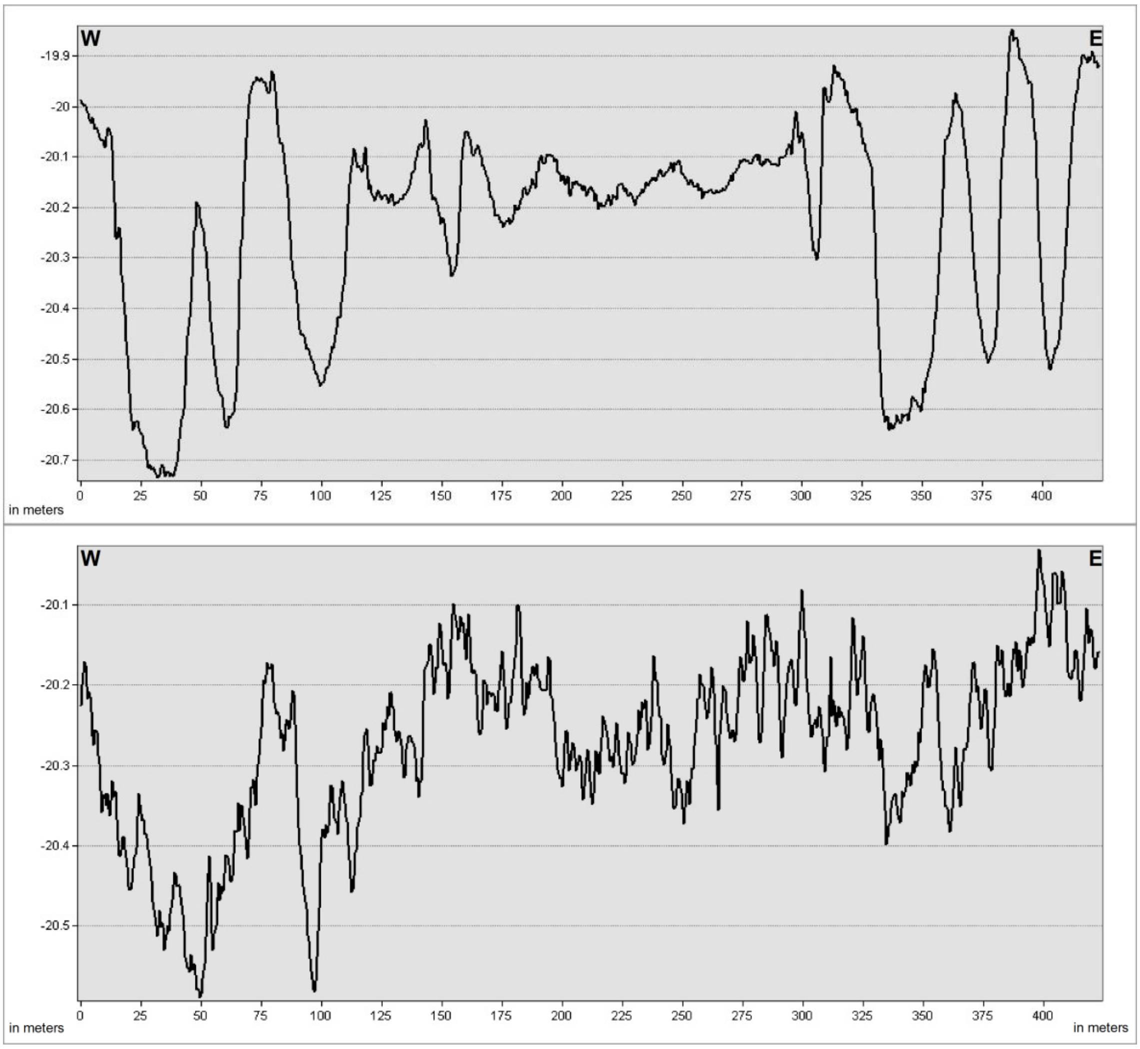


Figure 3.9 Cross-sections through linear bedforms with deep troughs: for the same profile line in 2017 upper figure and 2018: lower figure. See Figure 3.8 for location.

3.2.3 Tidal large ripples and probably hummocks -18.4m to -19.1m

In 2017 this area (Figure 3.11) is dominated by a kind of “small bulges”. The diameter is approximately 3.3m and they are roughly 0.1m high and are most likely hummocks. Such structures are formed by the combination of an oscillating motion, which is caused by large storm waves and unidirectional flow. The big waves erode the seabed in an irregular fashion without a clear orientation and suspend the bed material. The surface is subsequently covered with sand from suspension after waning of the storm. Next to that bedforms with orientations northwest-southeast form an unclear pattern.

In 2018 the area the morphology of the area is quite comparable to that of 2017. The “small bulges” are present. Furthermore, bedforms which cross each other and have orientations westnorthwest-eastsoutheast and northnortheast-southsouthwest are present. It leads to a very unclear pattern. It seems that the originally present hummock-forms were reworked.

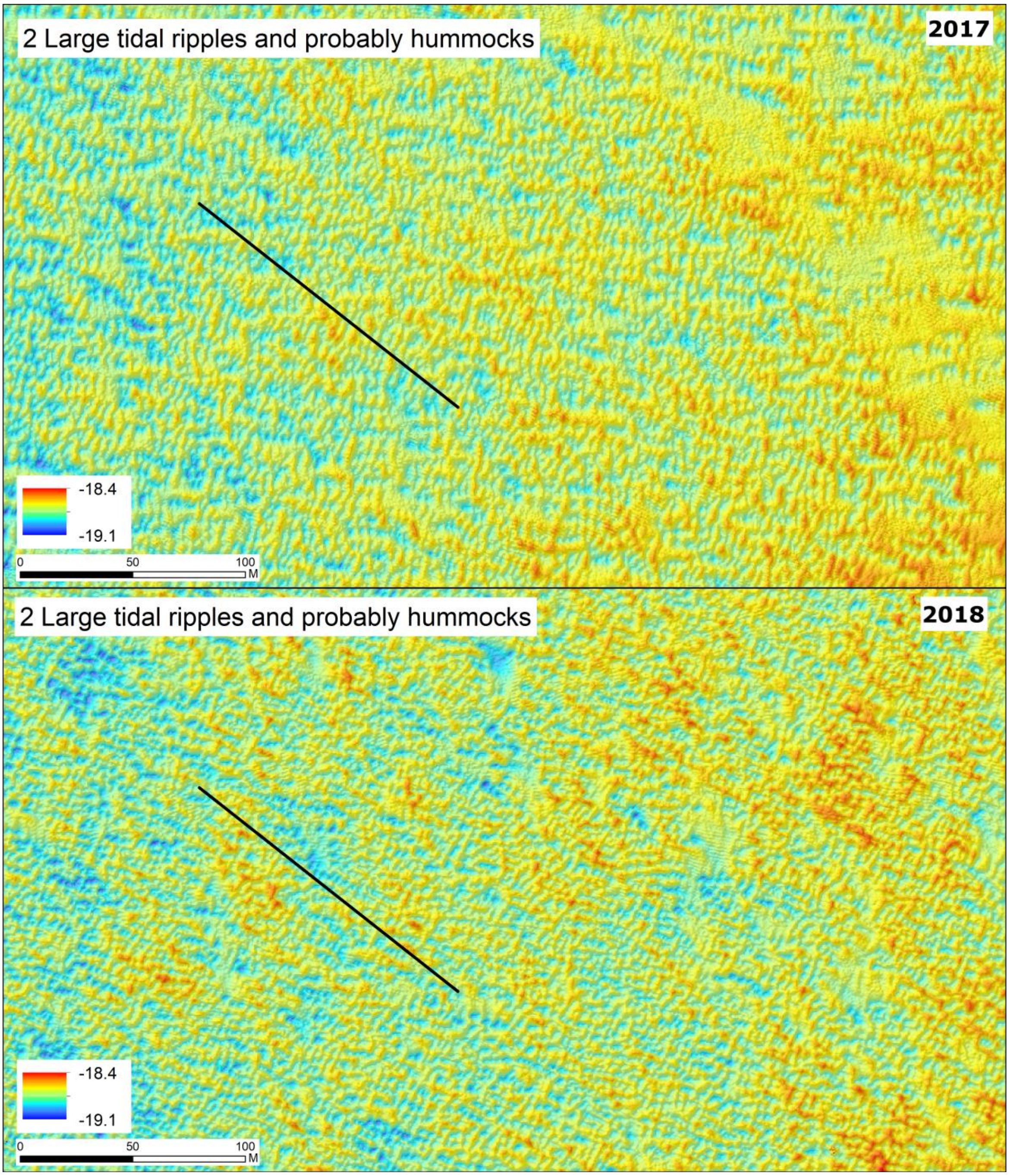


Figure 3.10 : Tidal large ripples and probably hummocks on the lower shoreface of Terschelling of the same area in 2017: upper panel and 2018: lower panel.

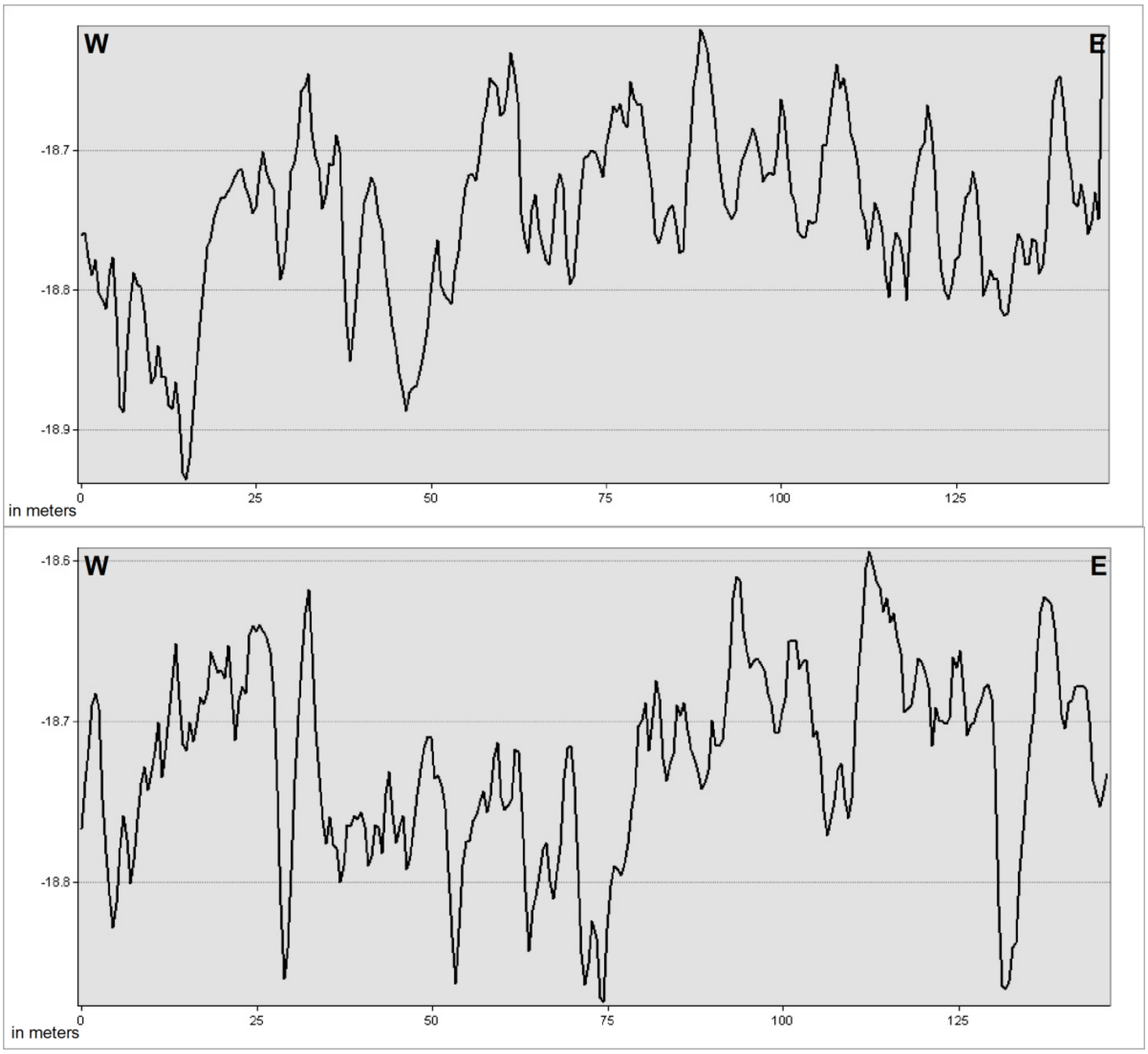


Figure 3.11 Cross-sections of tidal large ripples and probably hummocks on the lower shoreface of Terschelling along the same profile line: upper panel: 2017; lower panel 2018. For locations see Figure 3.10.

3.2.4 Lineament feature -16.2m to -19.3m

In 2017 this is the zone (Figure 3.12) where a shallow (0.3m deep and up to c. 100m wide) westnorthwest-eastsoutheast oriented lineament feature is present (of which several can be observed in the Ameland-Terschelling area), which can be followed to deeper water over a distance of 4 km to end in the linear-bed-forms-with-deep-troughs area. The feature fans out towards deeper water. On either side of the feature a higher area is present which might be a natural levee.

In 2018, the feature visible in 2017, had largely vanished and vague ripples oriented westnorhtwest-eastsoutheast with a steeper flank to the south fill the floor of the feature. Interestingly, the pit that is visible in the 2017 survey at c. 400m northeast of the cross-section in Figure 3.12 is still visible in the 2018 survey.

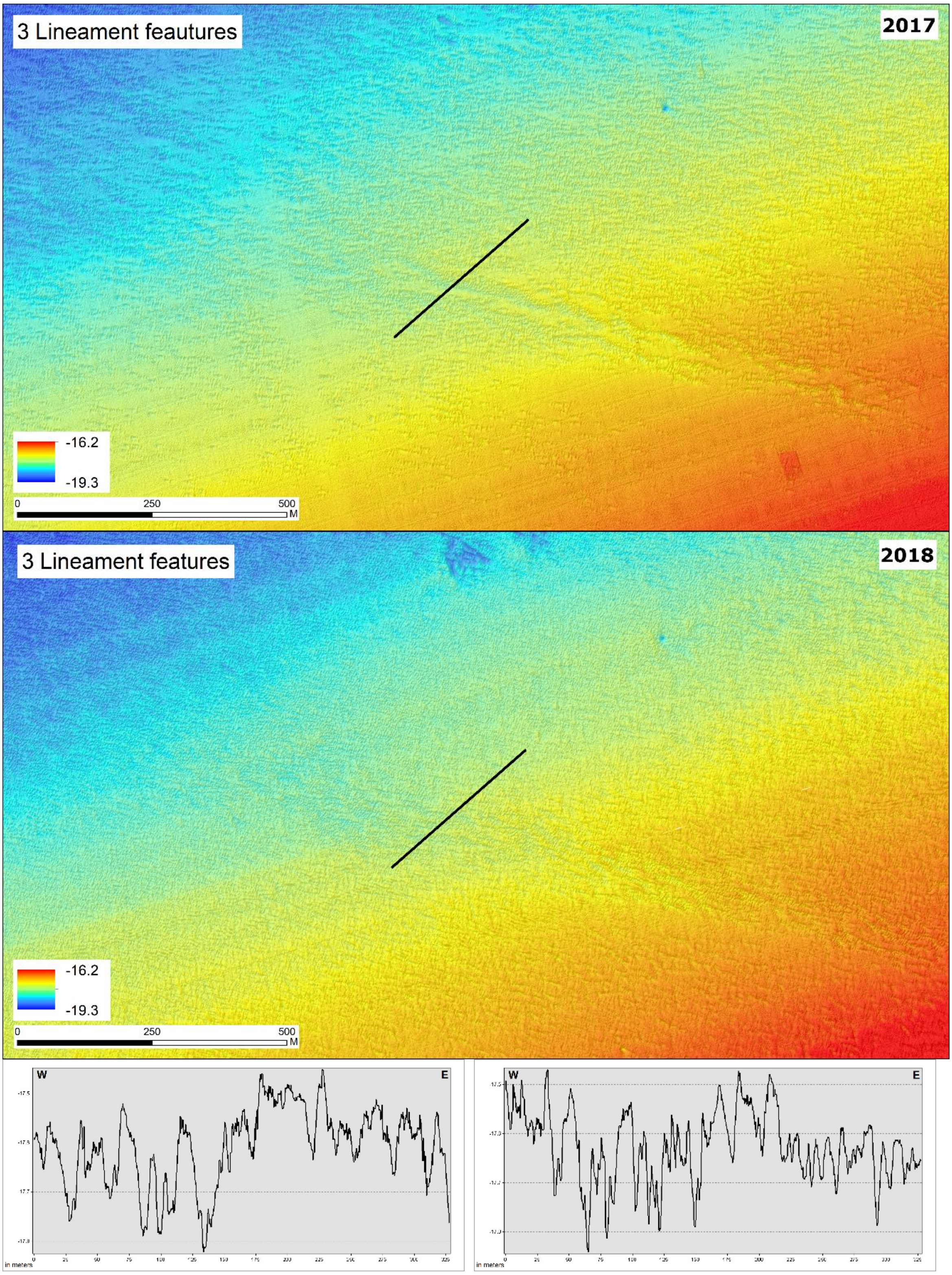


Figure 3.12 Shore-normal lineament features on the lower shoreface of the same area in 2017: upper panel and 2018: middle panel, cross-sections in lower panel (left 2017, right 2018).

3.2.5 Possible pockmarks -15 to -16m

Many of the sedimentary features encountered in the 2017 survey were less clearly or not visible on the survey results of 2018, which suggests that these most likely are related to storm conditions of 2017 and reworked during the quiet weather period of 2018. Here we have features which are clearly developing from 2017 to 2018 (Figure 3.13). They consist of small, mostly circular holes of 2-40m in cross-section and with depths up to 6 dm. In some cases, the larger ones are clearly consisting of several smaller ones. The position of the two larger holes clearly differs between 2017 and 2018. Some of the holes are characterized by a small outer rim surrounding them.

Both features indicate that it is likely that either a fluid (fresh ground water?) or gas is escaping from the subsurface, leading to small-scale blow-out features. These holes are called 'pockmarks'.

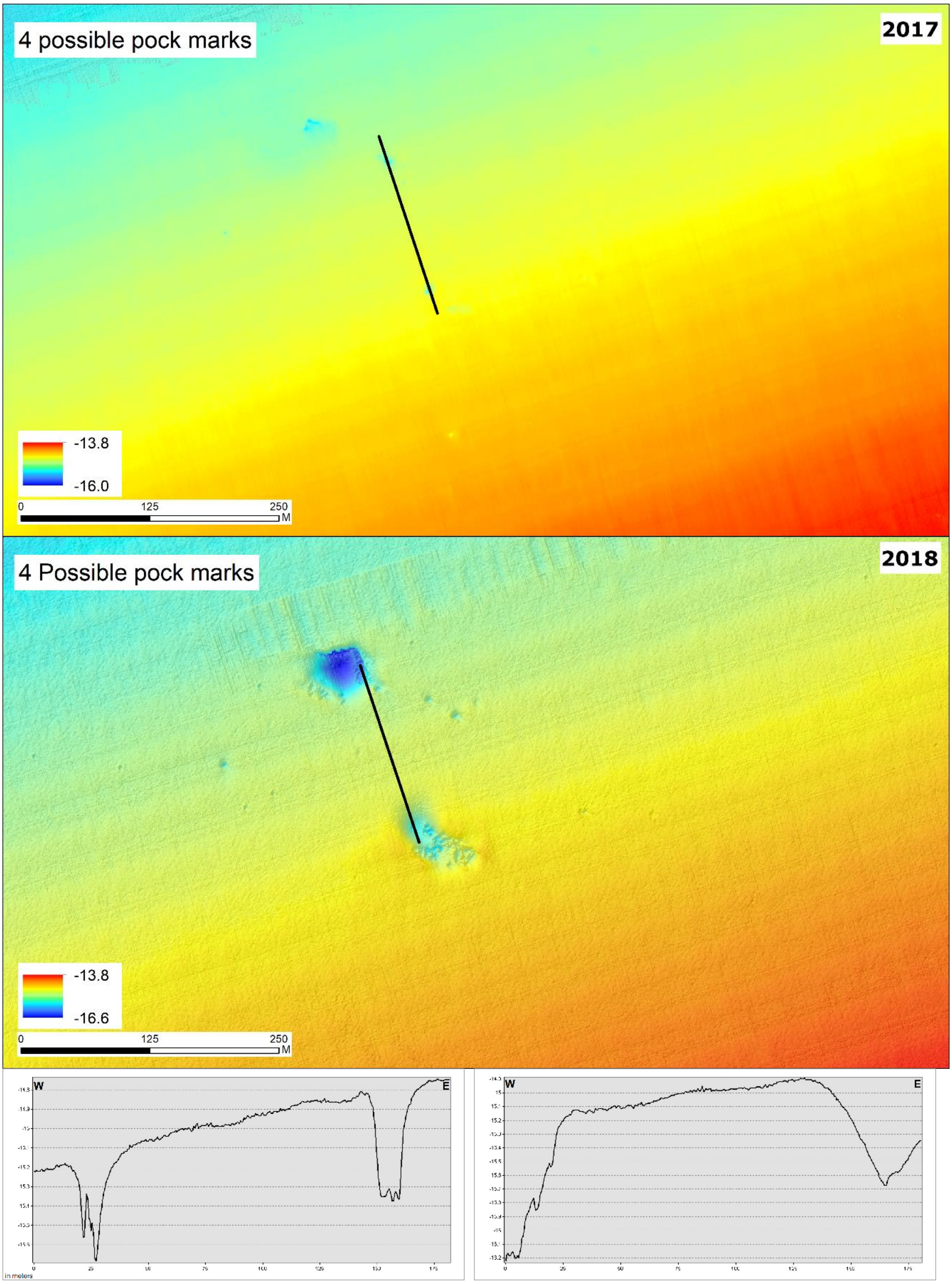


Figure 3.13 Possible pockmarks, top view and cross-section, on the shoreface of Terschelling of the same area in 2017: upper panel and 2018: middle panel, cross-sections in lower panel (left 2017, right 2018).

3.3 Noordwijk

3.3.1 Area description

The Noordwijk closed barrier coast significantly differs from the open barrier coast due to its orientation, the presence of large sand waves in deeper water and, at ca. -17m water depth (4-5 km off the shore) of shoreface-connected ridges as can be observed on the overview pictures. In 2017, the area was surveyed after a prolonged period of relatively stormy weather conditions. Hence, the morphology is expected to reflect the storm conditions. In 2017, depths in the research area ranged between -10.1 and -21.8m (Figure 3.14). The multibeam survey of 2018 was preceded by a prolonged period of calm weather and is thus expected to reflect this in the morphology. In 2018, depths ranged between-11.15 and -24.6m (Figure 3.15). In general, tidal large ripples as observed at the Terschelling and Ameland Inlet sites are not present at this location.

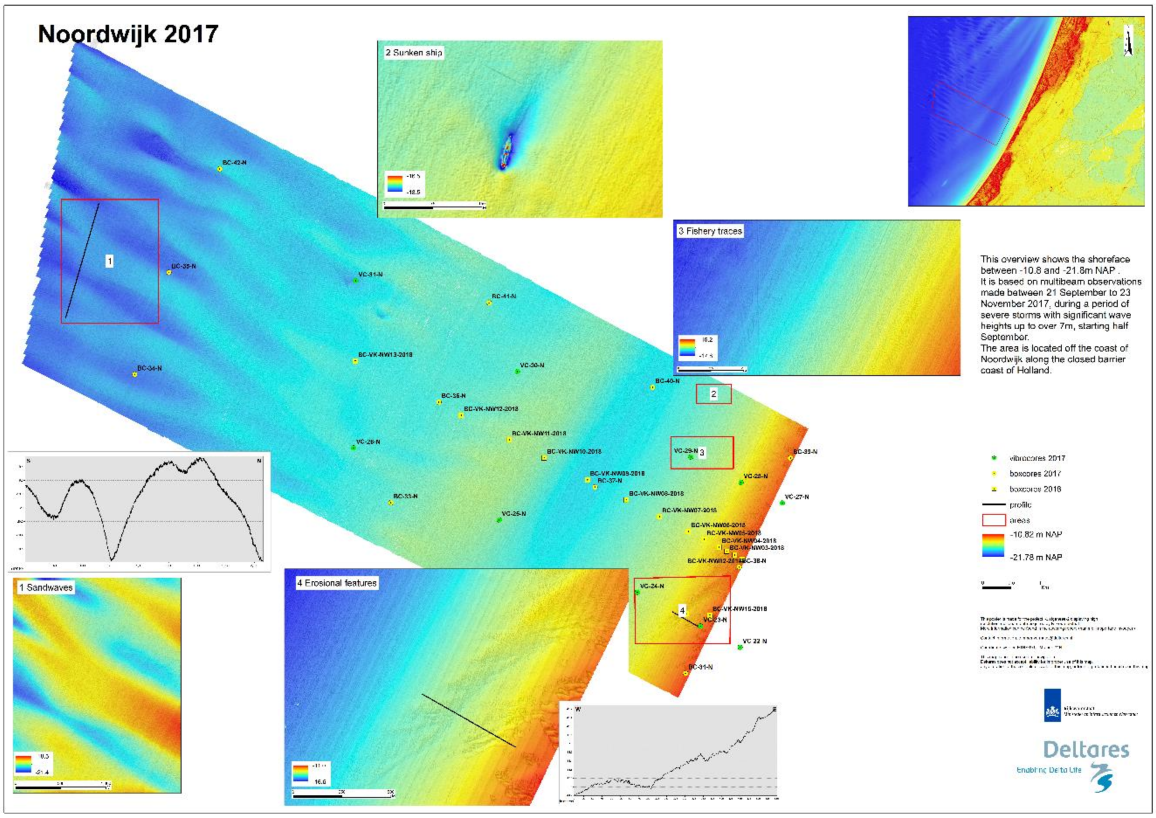


Figure 3.14 Overview multibeam observations 2017 off the Noordwijk coast with insets of details.

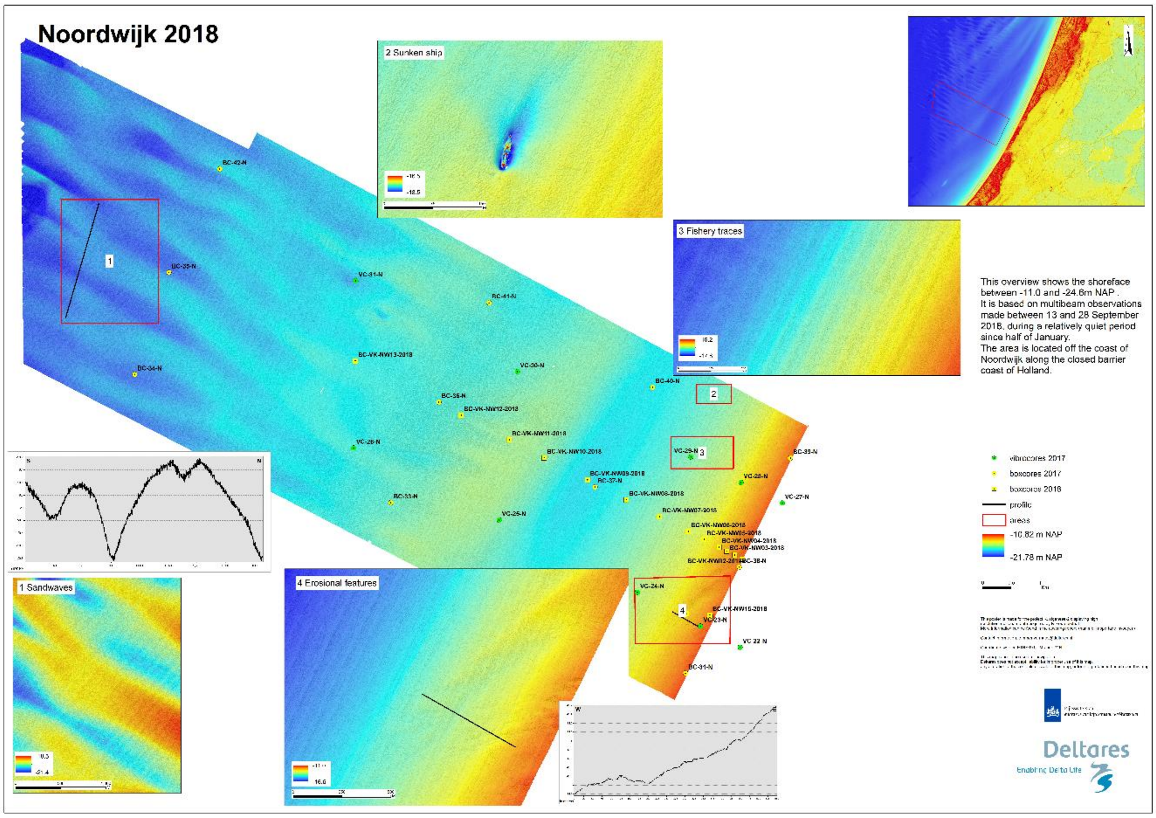


Figure 3.15 Overview multibeam observations 2018 off the Noordwijk coast with insets of details.

3.3.2 Sand waves -18.5 to -21.4m

In 2017 this is an area characterised by large bedforms perpendicular to the coast (Figure 3.16 and Figure 3.17). With a wavelength of c. 800-1000m and a height of 1.5-1.7m these are identified as sand waves[1]. They have a slightly steeper flank to the north. On top of the sand waves smaller ripples are present in 2017 and somewhat larger ripples in 2018. The sand waves migrate with some m/yr. Comparison between 2017 and 2018 learns that the direction of travel differs from place to place: partially to the north, partially to the south (Figure 3.17). This is in close agreement with available literature. Comparing the overview pictures shows that in 2018 the sand waves are more pronounced and extend further to the shoreface-connected ridge than 2017.

[1] *Sand waves are typically 30–500m in length and the height is 3–15m, in the North Sea they do not migrate significantly; large scale ripples (also called megaripples) have typical lengths in the order of meters and heights in the order of decimeters (Williams et al., 2005).*

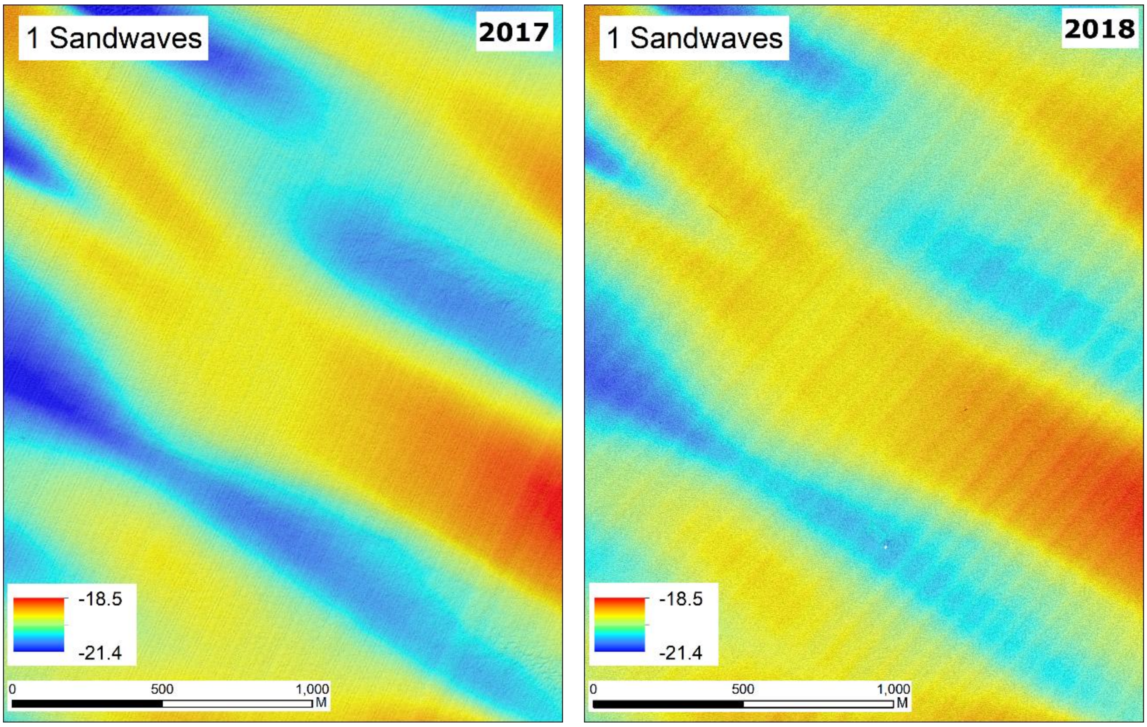


Figure 3.16 Sand waves off Noordwijk, top view of the same area in 2017: left panel and 2018: right panel.

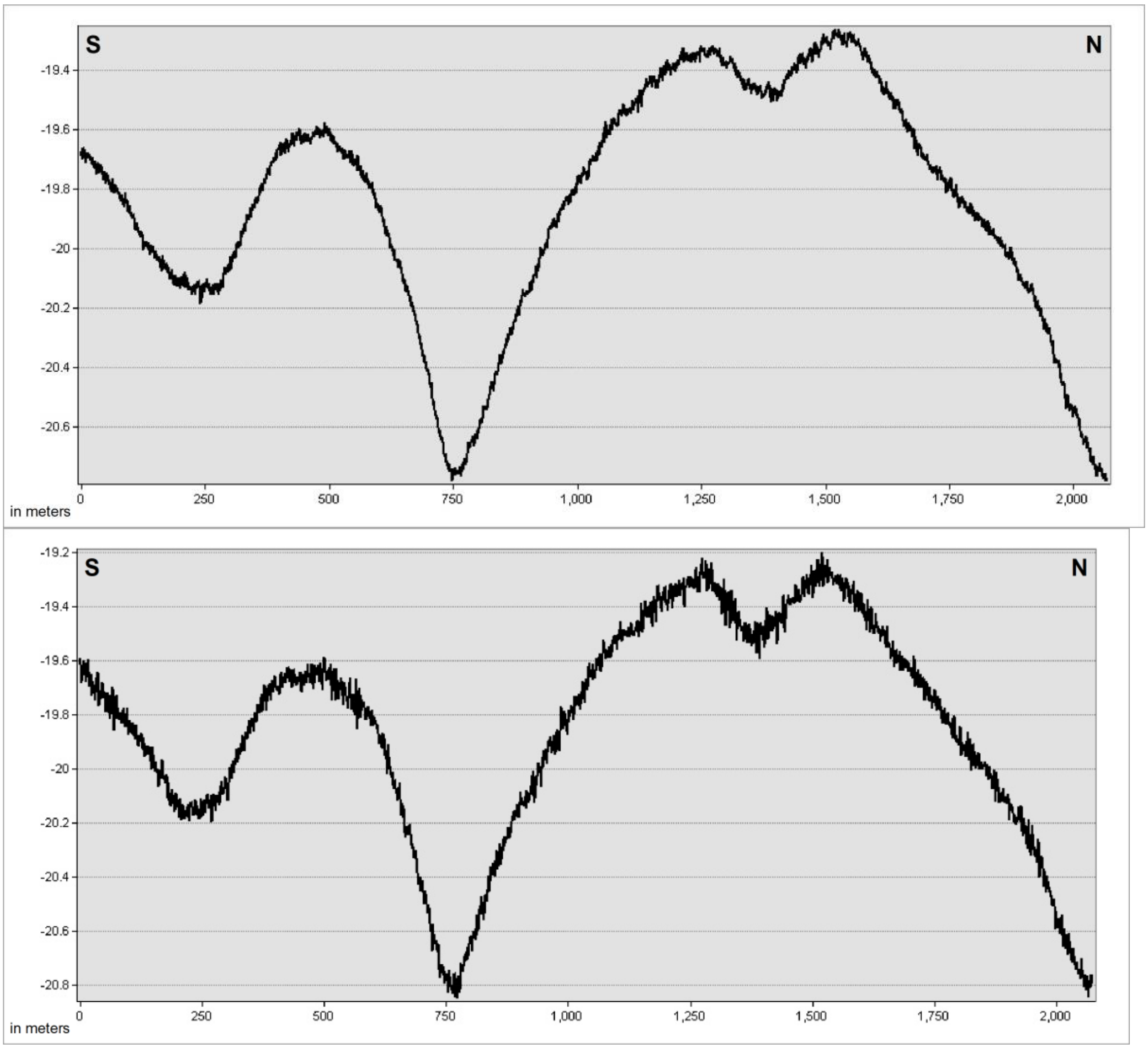


Figure 3.17 Sand waves off Noordwijk, cross-section along the same profile line for 2017: top panel and 2018: lower panel. For locations see Figure 3.17.

3.3.3 Shipwreck at ca. -17m

In 2017 and 2018 scour holes eroded around hard objects can be observed, for example the ca. 40m long shipwreck in the depth zone around -17m (Figure 3.18). Over the period between the observations of 2017 and 2018 erosion was calculated to be 3.9m (mainly at starboard) and sedimentation 1.9m (starboard, bow and stern of the ship), indicating strong sediment transports.

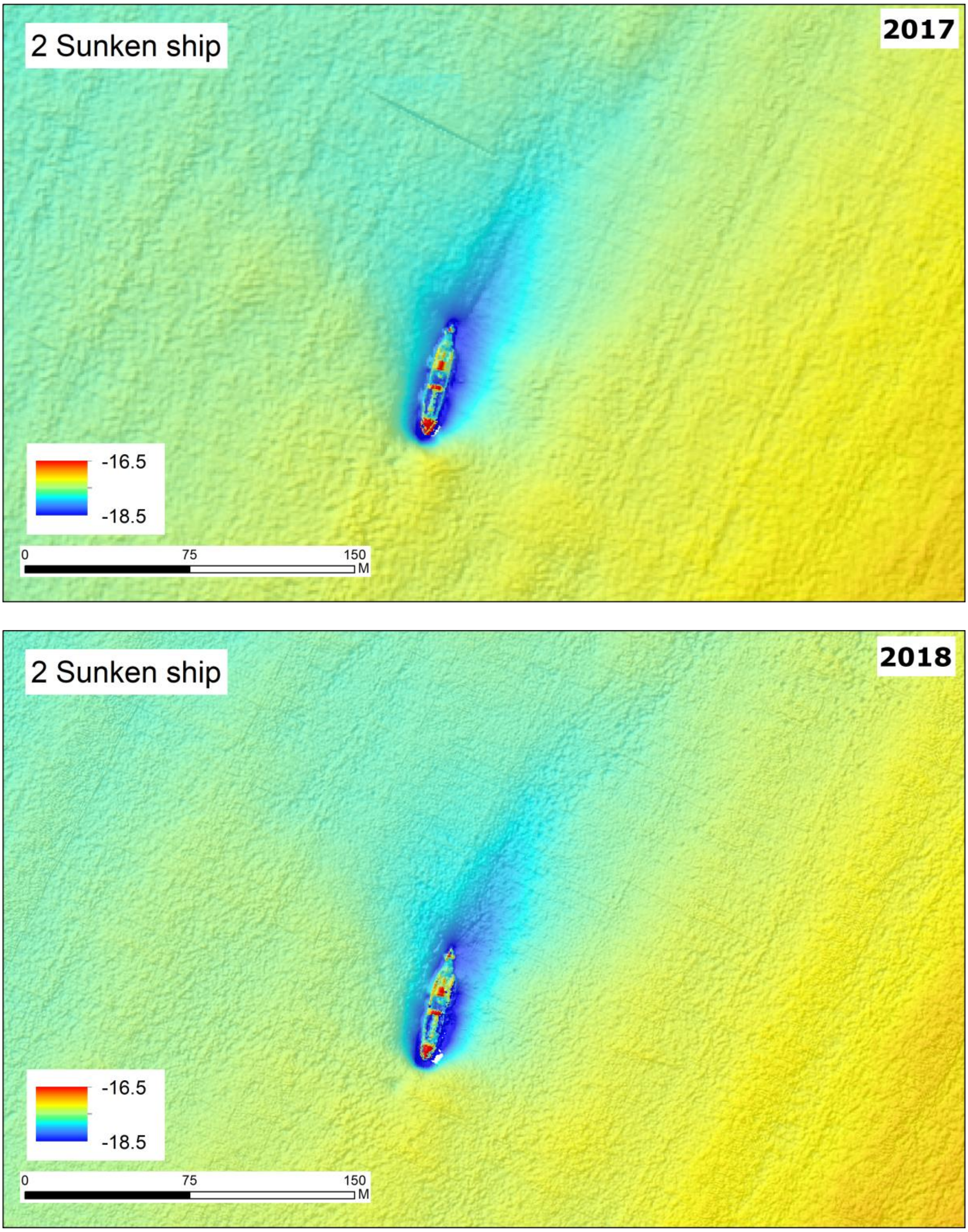


Figure 3.18 Shipwreck offshore Noordwijk: of the same area in 2017: upper panel and 2018: lower panel.

3.3.4 Fishery traces -15.2 to -17.8m

In this inset, traces of trawling nets are visible (Figure 3.19), which have ploughed the seabed. Note that the fresh traces of 2017 can still be observed vaguely on the plate of 2018. Also, new traces have been generated.

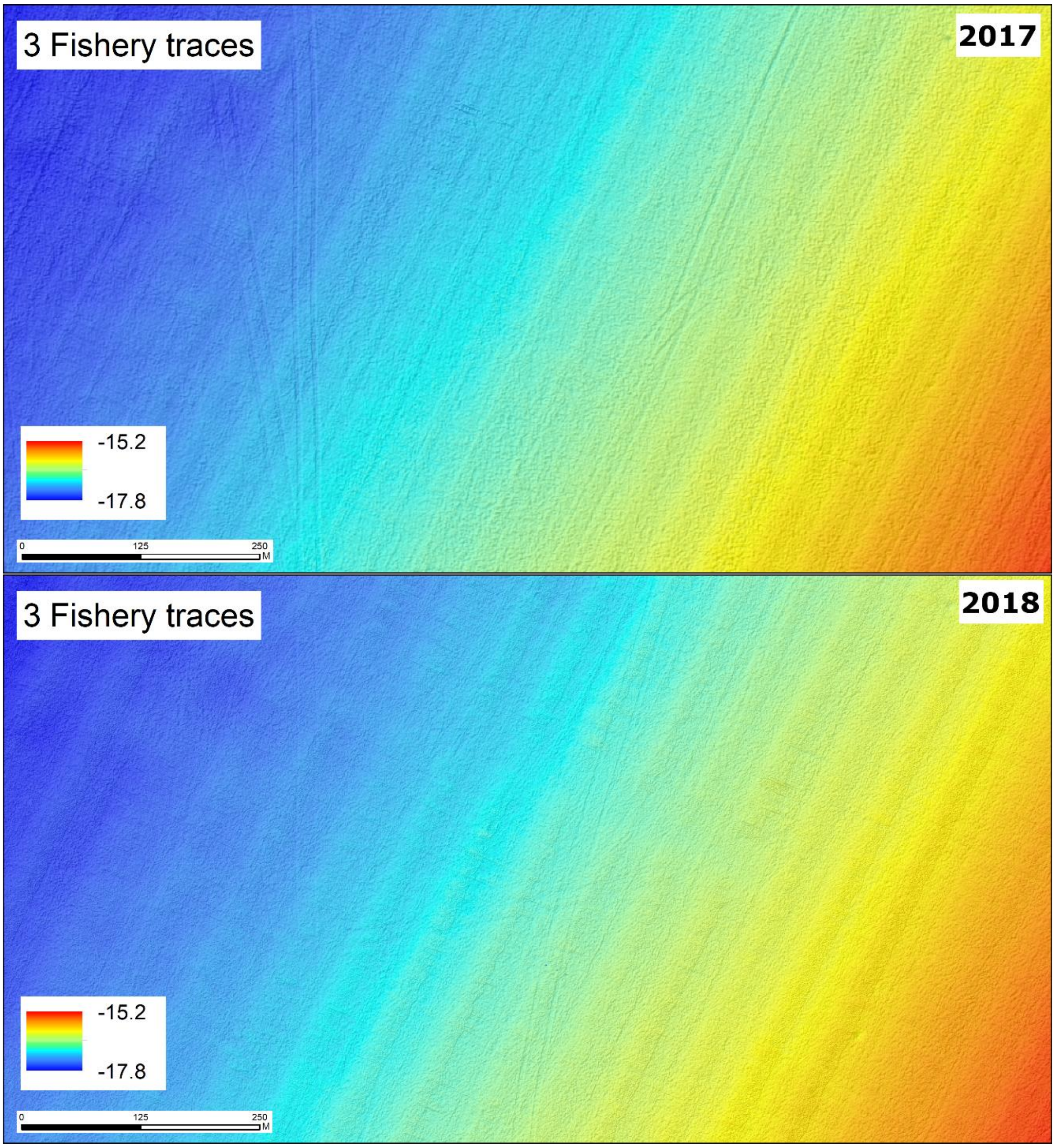


Figure 3.19 Fishery traces off Noordwijk of the same area in 2017: upper panel and 2018: lower panel.

3.3.5 Erosional features on the slope -11 to -14m

In 2017 this is the zone (Figure 3.20) where 0.2-0.7m deepened structures and, at their SSW side, sediment accumulations, are present in the shallower part of the shoreface (around -11m) and on the slope to deeper water. A rough surface structure can be observed on a part of the 2017 observation. The deepened structures merge partly into elongated shallow “gullies” which go downslope under an angle to the coast (southsouthwest orientation). One of these gullies continues to depths of -14m. More to the south the trenches end up halfway on the slope. All structures visible in 2017 have largely been obliterated and smoothened out in 2018.

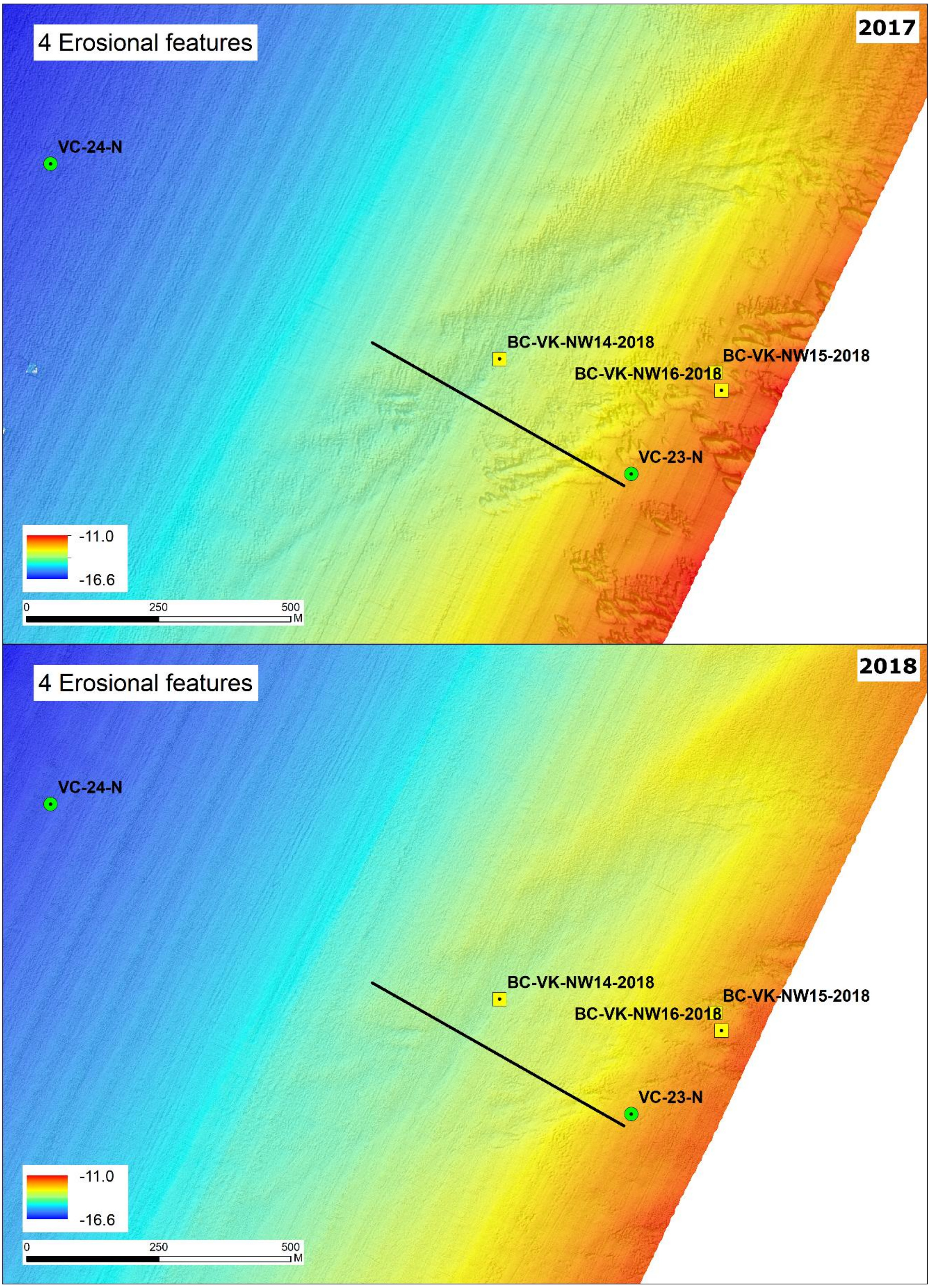


Figure 3.20 Erosional features on the shoreface off Noordwijk of the same area in 2017: upper panel and 2018: lower panel.

3.4 Backscatter Ameland

The bed classification of the 2017 Ameland data resulted in an initial, high-resolution acoustic bed classification (ASC) map (Figure 3.21), showing 4 classes (i.e. the optimal number of classes calculated in the Bayesian method). The map still displays across-track variations in classes and a few abrupt changes in classes. For example, the bundle of tracks that are black and yellow in the west and yellow-blue in the east (indicated in Figure 3.21 as double black arrow), also shows up as a bundle in the bathymetry dataset as slightly shallower. The result of the ASC map thus is in the measured data and could be caused by different conditions during the surveying. Another abrupt change is visible in the center of the map, where the sudden change from class 2 and 3, yellow and blue, respectively, runs across several tracks (indicated by the red ellipse in Figure 3.21). This may be linked to an RTK positioning error or lack of the RTK signal, although these artefacts still have to be investigated further. However, despite the artifacts in the data, a pattern of the four classes stands out in the area offshore Ameland, with class 3 (blue in Figure 3.21) in the south-eastern and eastern part of the study area and the class 4 (red) within that area.

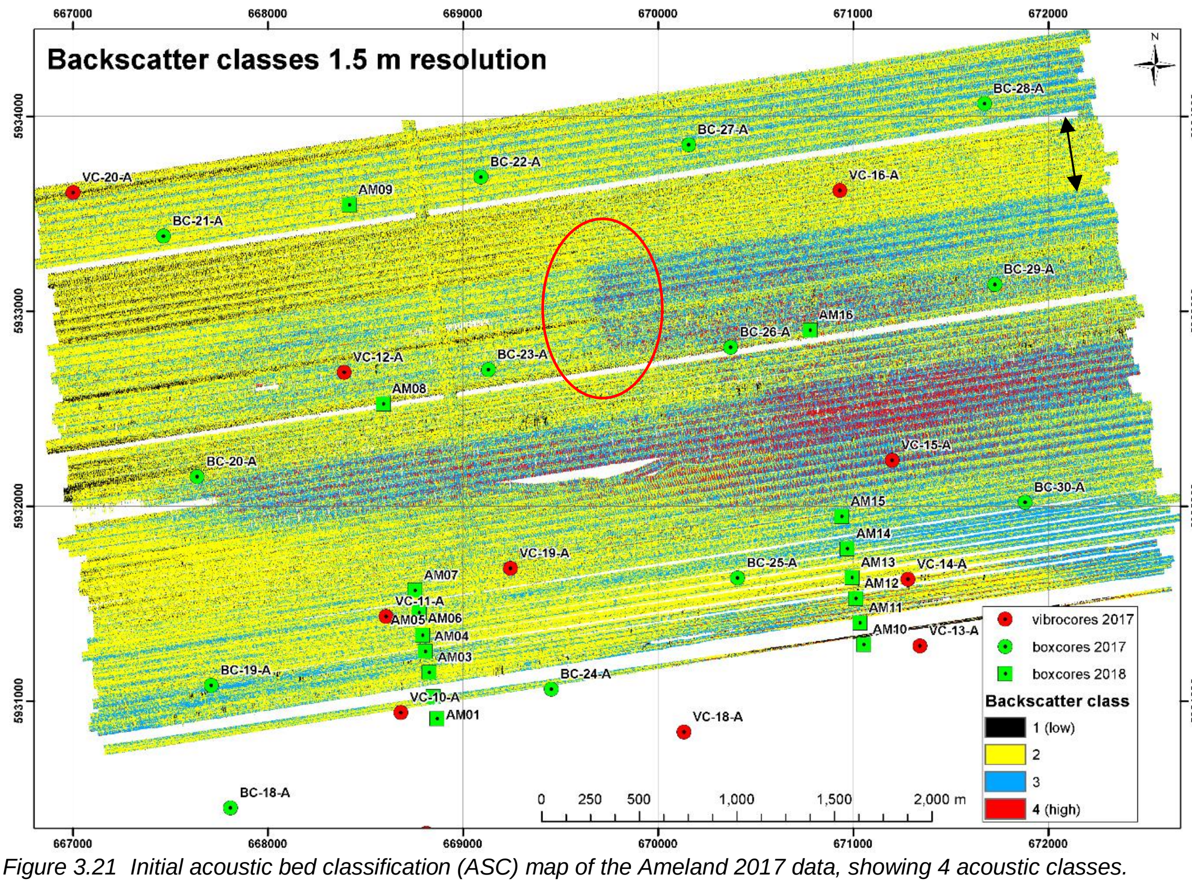


Figure 3.21 Initial acoustic bed classification (ASC) map of the Ameland 2017 data, showing 4 acoustic classes. The locations of box cores and vibrocores of both 2017 and 2018 are indicated. The double black arrow and red ellipse indicate sudden changes in classification, as for now attributed to data artefacts. Despite these artefacts, the bed classification shows a pattern of classes 3 and 4 that would not have been revealed by the bed samples only.

A lower backscatter intensity is thought to correspond to a finer grain size, and the higher backscatter intensity to coarser sediment, although some studies show that for coarser sediments the backscatter strength can decrease again (e.g. Gaida et al., 2018a, and references therein). Also, the shell content of the sediment at the surface or protruding fauna may affect the backscatter intensity.

Coupling these classes to sediment types found in the bed samples would then make the acoustic bed classification map into a seabed sediment map (for an example of the Cleaver Bank, see Snellen et al., 2018). Linking the ASC map of Ameland to sediment characteristics as established from the bed samples entails more consideration (e.g., comparing non-simultaneous sampling and sounding, samples were not taken in locations to correlate to acoustic classes (unknown at the time), look at shell content or mud drapes and macrofauna, and whether or not to incorporate both 2017 and 2018 samples) and was beyond the scope of this project. Ideally, the sampling locations are tuned to the class distribution in the ASC map.

The interpretation of this map is therefore preliminary, with relatively coarser sediments or sediments with a higher shell content in the red zone (class 4), finer sediments in the blue zone (class 3) and yet finer sediments in the yellow zone (class 2). The initial comparison of 2017 ASC classification results to the median grain sizes (D50) of the 2017 and 2018 boxcores and vibrocores suggests that the subtle differences in sediment characteristics can be picked up in the bed classification. It also shows that median grain sizes do not provide sufficient explanation for the patterns as observed in the ASC map, indicating that other characteristics, such as shell content, grain-size sorting or protruding organisms, may play a role. This was also established in the recent SPA project of the Maasvlakte 2 sand pit (Van Dijk et al., 2019).

The advantage of using MBES-backscatter data, collected simultaneously with bathymetry data and thus not an extra surveying effort, in comparison to the existing method of sediment mapping is that the high-resolution information from multibeam backscatter provides *(i)* area-covering data (as opposed to sparsely distributed point data of bed samples), *(ii)* measured data (as opposed to filling in the maps of samples by interpolation) so that it thus results in a more truthful, high-resolution map based on observations, potentially with less sampling effort (see the next section on comparison of the acoustic mapping versus the classical way of mapping).

Comparison of acoustic bed classification to the established seabed sediment mapping method

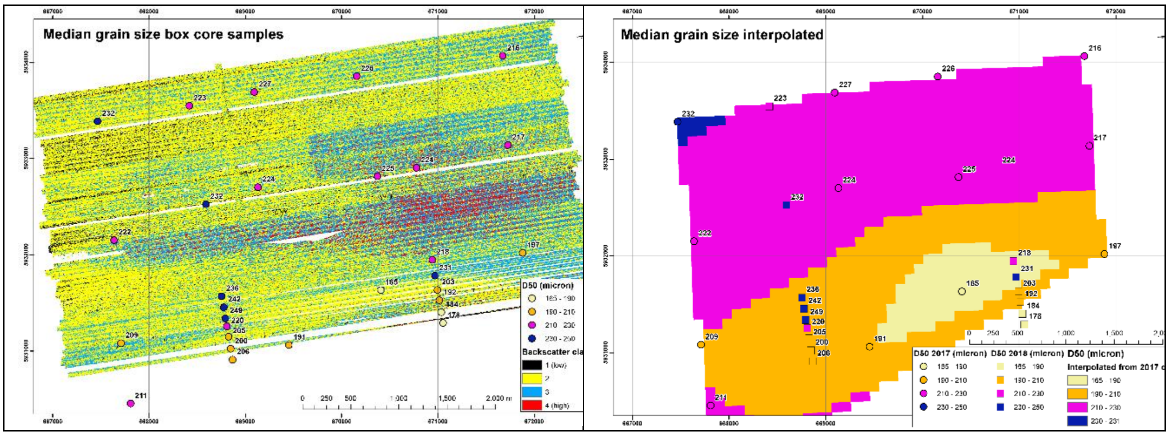


Figure 3.22 Left: preliminary acoustic bed classification map displaying classes of 2017 data. Median grain sizes (D50) of 2017 and 2018 samples (box cores only) are plotted on the map. Right: median grain size (D50) map, as achieved by the established (classical) method of interpolating the median grain size from sampling in 2017 (box cores only). The D50 of the samples (box cores of both 2017 (circles) and 2018 (squares)) in which matching colors show that the 2018 sampling does not correspond with the 2017 D50 map. Also, mapping units are grossly simplified due to the low data density.

When comparing the preliminary acoustic bed classification map based on backscatter data to the interpolated map of the Kustgenese 2 project based on sampling (Figure 3.22) the high-resolution ASC map reveals the distribution of sediments from observations and the pattern of classes can be used to map the extent of different sediment types. The interpolated map exhibits simplified zones of median grain size.

The preliminary comparison of the ASC map to the median grain sizes of the samples, is not conclusive at this moment. A correlation of D50 and bed class should reveal how well the correlation can be made to either 2017 or 2018 samples, or both. Also, for the interpolated map, median grain sizes of 2018 box cores do not match with the 2017 map, as might be expected due to the observed changes in the area.

The acoustic data result in a different sediment map (different extent of units) and show a level of detail that cannot be achieved by sampling and interpolation. Especially in heterogeneous areas, the acoustic bed classification method, coupled to sediment characteristics from box cores (ground truthing), is expected to sharply improve the seabed sediment mapping. Furthermore, applying this method to the other backscatter datasets in Kustgenese 2 (the two other areas and both years) this method is expected to provide valuable (quantitative) results on the surface sediments of the lower shoreface and changes over time therein (see also Ameland ZW results, submitted to be published). In the acoustic method, bed samples are used to verify (ground truth) the bed classification results and should potentially lower the number of samples required for a much higher-quality sediment map (Gaida et al., 2018a).

4 Interpretation and Discussion

4.1 Ameland

The main feature of the Ameland study area is that it consists of a deeper offshore and the higher delta lobe of Ameland Inlet. The deeper offshore is dominated by tidal currents which follow a stretched ellipse. Here large ripple patterns develop, which are oriented perpendicular to the tidal motion and to the coast (Figure 3.3). Towards shallower reaches waves become more influential. Such waves will deform the tidal bedforms to three dimensional patterns or even obliterate such forms completely (Figures 3.4 & 3.5). The depth on which this occurs depends on the wave lengths. If these vary the depth of the bottom patterns will vary. In 2018 more or less coast-perpendicular large ripples can be observed in deeper waters up to water depths of ca. –15m and changing in flat bed. In 2017 large ripples give way to irregular three-dimensional bedforms at -18m, which change in -14.5m.
The differences might well be explained as caused by the differences in the wave climate. Before and during the multibeam observations of 2017 the wave height was higher than before and during the 2018 survey. In 2017 the significant wave height was mostly above 1m and exceeded 2m two times in the two weeks before the measurement and shortly during the measurement. In 2018 the significant wave height was mostly around 0.5m and exceeded 1m only shortly during two times in the two weeks before the measurement and one time during the measurement. Also wave peak periods were longer in 2017 than in 2018. The direction of the waves was mostly between north and west in both years, with slightly more waves coming from the west in 2018 than in 2017.

In 2018 the tidal large ripples show a more irregular pattern than in 2017 in deeper water. The reason for this is not clear.

Higher up on the shoreface, other forces are relatively more important, such as (storm) wave action and the tidal flows via the ebb-tidal delta. That the latter might be important, is also suggested by the lack of 3D bedforms in the centre of the area (at the right side of subarea 3 and directly east of it), where the ebb-jet leaves the back-barrier area. Furthermore, the decrease in depth from 2017 to 2018 at the east side of the ebb-tidal delta lobe and the erosion at the west side of it, can be explained by the observed eastward shift of the ebb-delta lobe.

4.2 Terschelling

4.2.1 General

The observation that tidal large ripples are largely lacking in the major part of the area in water depths of less than -18m in both 2017 and 2018, although tidal currents are high enough to form them, is difficult to explain. The 2017 observation were done after a series of storms; the 2018 observations were made after a prolonged period of -relatively quiet weather when compared to 2017, but still quite energetic. Apparently, in both cases waves were able to rework bedforms into the hummocks which cover a large part of the area. From the thin layer of active sediments on top of older channel sediments, in front of the coast of Terschelling (see Oost et al., 2019) it might be concluded that the either energy was not enough to entrain sediments over larger depths or that a part has been removed during storms.

4.2.2 Linear bedforms with deep troughs -18.1 to -19.3m

In 2017 at the North Side of the area, the widely separated crests with their broad troughs indicate that insufficient amounts of sand were available to form a complete ripple field. Two box cores taken in the area show at least 25 cm thick massive shell layers approximately half-way between the top of the large ripples and the bottom of the troughs. Probably the separated ripple-crests are so-called sediment starved large ripples, which do not receive enough sediment to maintain a full cover of the whole surface. The shell layer will be incapable to deliver enough quantities of sands.

The steep troughs observed in the survey of 2017, might be scoured out where the shell layers were missing or eroded away. During the period of the multibeam survey strong waves and storms have occurred. Given the large water depths it is not fully clear how such scour, for which normally current velocities over 1.1 m/s are needed, can be brought about. Most likely the shell layers which are present nearby function as hard objects, enhancing scour. From the 2017 data it appears that these bedforms are in the direction of the lineament features discussed below, but it is not known if there is any relation between both. In 2018 more tidal ripple forms are present suggesting a relatively larger role for tidal currents, as was to be expected given the milder conditions during and before the 2018 survey. An alternative explanation might be that also here (see 4.2.5) shallow gas has been expelled during severe storm conditions, enhancing erosion of the troughs. The ripple features with deep scours are reminiscent of similar features encountered by Krämer et al (2017) near Helgoland, but have larger dimensions.

4.2.3 Tidal large ripples and probably hummocks -18.4 to -19.1m

Also, the presence of the hummocks in 2017 can be understood as the combination of oscillating flow which is caused by large storm waves and unidirectional flow on depths of -18.4 to -19.1m and were most likely due to the storms at the end of 2017. Hummocks in 2018 should probably be attributed to the September storms which occurred just before the survey and perhaps to those which occurred before July 2018. The vague bedforms of 2017 and 2018 perpendicular to the coast were most likely brought about by coast parallel tidal currents forming large ripples. The ones subparallel to the coast cannot be explained but must have been brought about by currents.

4.2.4 Lineament feature -14.9m to -17.3m

A remarkable feature was the 4 km long lineament feature observed in 2017 but had largely vanished by 2018. The observations indicate that fair weather wave conditions led to morphological infill of the floor of the lineament feature. It suggests strongly that the lineament itself may well have formed or been activated during higher energy events such as the series of storms preceding the multibeam survey of the Terschelling area in 2017. The reason for the observed differences in erosional behaviour between the lineament and its surroundings are not known. Discussion led to the following hypotheses:

1) Presence of a different older sedimentary built-up near to the surface. An argument supporting this hypothesis is the observation that on many places older channel deposits are present (Oost et al. 2019), which may follow older ebb channel directions.
2) Leakage of deeper gas along a lineament leading to enhanced erodibility of the sediments. Arguments supporting this hypothesis are: A) the existence of the Elf-Petroland gasfield of which the eastern border is straddled by the lineament; B) the presence of shallower gas which accumulates under Holocene or Pleistocene clay or peat layers in the Wadden Sea and the North Sea coast (van Straaten, 1991); C) the likely presence of active pock-mark areas nearby, which are also formed by gas escape (see below).
3) Outflow of (fresh) water on larger depth leading to enhanced erodibility of the sediments.

4) A transport path downslope during storm conditions. Arguments supporting this hypothesis are: A) The fact that the lineament has been partly filled up after the survey of 2017 as can be observed in the survey of 2018 suggests that its genesis is probably partially related to storm conditions; B) the presence of layers in the feature's wall suggests erosion; C) the indications of possible levees and the lobe at the lower end of a similar feature suggest deposition; D) earlier observations of sediment-laden density currents in the inner German Bight (Aigner, 1984).
5) A combination of the above. That the lineament feature was fresher in the stormy year 2017 then in relatively quiet year 2018 makes it likely that erosion, as described under point 4), was the agent sharpening the feature. This, however, does not exclude the other explanations in combination. For instance: enhanced erodibility due to gas accumulation in sandy parts of older channel deposits, leading to erosion under storm conditions where retour currents in combination with waves and tides exert sufficient shear stress to erode the bottom.

4.2.5 Possible pockmarks -13.8 to -16 m

The small, mostly circular holes of 2-40m in cross section and with depths up to 6 dm which partially developed during the period between the 2017 survey and the 2018 survey are enigmatic. In some cases, the larger holes are clearly consisting of several smaller ones, suggesting that the larger holes might be generated by the formation of smaller ones. Some of the holes are characterized by a have a small outer rim of sand surrounding them. Discussion led to the following hypotheses:

1) The holes are pockmarks formed by gas efflux through the seafloor. Arguments supporting this hypothesis are: A) that shallow gas is a common phenomenon in the North of the Netherlands (van Straaten, 1991) and has been encountered at shallow water depths before (de Kleine & de Vries, pers. com.); B) that pockmarks have been observed both in the deeper waters of the North Sea (Hovland et al., 1984) as well as in relative shallow waters in the German Bight (-25 to -40m MSL; Krämer et al., 2017); C) the form itself which is comparable in dimensions to pockmarks in sandy sediments (usually in the order of 10m and less than 1m in depth; Krämer et al., 2017) and D) strongly suggest a sudden, vigorous escape of fluids from the seabed, given the sharp contours; E) the relative short period of genesis of 10-11 months. For the German Bight, Krämer et al. (2017) could prove that the pockmarks were formed in less than 3 months. An argument against it is the lack of methane-derived authigenic carbonate, often forming sandstone pebbles which are absent from the Terschelling beach (as far as information goes). It should be noted that, if these are pockmarks, there might be a small risk for fishing vessels which disturb the seabed, as this could trigger the release of methane or carbondioxide from the sediments, which might lead to the loss of equipment. Also, due to the shallow water depths, the gas would probably reach the water surface. It is recommended to investigate in some more detail whether these features pose a potential threat.
2) Scour marks around hard objects. Arguments supporting this hypothesis are: A) the general abundance of wreckage materials along the North Sea coasts. B) the apparent plane-like form visible in larger southern hole in 2018, suggesting the presence of a hard object. C) the disappearance of some holes which might be due to the coverage of the object by sand. Arguments against it are: A) the new formations during the a relatively quiet period, although scouring also happened at Noordwijk; B) the displacement of the larger holes and C) the marked differences between the observations around the wreck at Noordwijk. All in all, such an explanation seems improbable.
3) Migrating and deformation of larger holes. Arguments supporting this hypothesis are: A) the fact that the larger two holes have been displaced and deformed with between 2017 and 2018; B) observations show that in such water depths

disturbances of the sea floor will interact with hydrodynamics which leads to migration and deformation of larger holes.

At this moment it is not clear what causes these holes in relatively shallow water depths. Given the possibility that shallow gas is involved it is advised to investigate the matter. Furthermore, as argued with the lineament feature, gas or fluid pressure might enhance the erodibility of the bed.

4.3 Noordwijk

4.3.1 General

The morphological features in 2017 and 2018 are in general remarkably comparable. This is due to the presence of large features such as sand waves and shoreface-connected ridges which do not change rapidly.

Important seems to be the lack of large ripples in the area between the shore-face connected ridges and the shoreface of Noordwijk, although tidal currents ought to be sufficient in the narrow opening to generate them. Furthermore, morphological indications of wave action are relatively scarce. Perhaps the shore-face connected ridges provide shelter from the waves. This is supported by the observations that trawling traces are still visible after one year.

Another interesting feature which can clearly be observed in the 2017 multibeam observations are the erosional features in the form of southsoutheast oblique landward scouring and deposition features and southsouthwest oriented channel-like features down slope. It seems likely that wave set-up has brought about these phenomena.

4.3.2 Sand waves -18.5 to -21.4m

In 2017 this is an area characterised by sand waves. The orientation indicates that these bedforms are generated by the tidal flow along the north-south oriented coast for Holland. Their steepest flank is to the north, but migration directions vary. Smaller bedforms present on the sand waves are much stronger developed in 2018 indicating that these have developed during the quiet period since 2018. As quiet weather conditions also occurred before the storms of 2017 it seems likely that the smaller bedforms were “flattened” by the storms. It is not clear to what extent the formation of a stronger connection between the sand waves and the shoreface-connected ridges which formed from 2017 to 2018 might also be a (partial) reaction to storm driven changes of 2017.

4.3.3 Shipwreck at ca. -14m

The strong changes in bed height observed over the period 2017-2018 around the ca. 40m long ship of -4 to +2m indicate that on these water depths shear stresses, brought about by currents and stream contraction suffice to cause considerable erosion around hard objects even under relatively calm weather conditions.

4.3.4 Fishery traces -15.2 to -17.8m

The fishery traces are caused by fishing equipment which is dragged over or through the seabed. This includes fishing for bottom-dwelling flatfish and shrimp fishing where beams are dragged over the seabed, so that fish can be caught after it jumps up. In contrast to the strong currents scouring sediments around the sunken ship it appears that the fishery traces of 2017 can still be observed vaguely in the multibeam observations of 2018. It indicates that morphological changes are quite slow. Alternatively, it might suggest that, once the bed is disturbed its erodibility has changed, slowing recovering to an undisturbed situation.

4.3.5 Erosional features on the slope -11 to -14m

In this part of the area 0.2-0.7m deep scoured structures and, at their southsoutheast side, sediment accumulations strongly suggest that storm waves are the likely cause of these local features. These may locally remove the sediment and deposit it in a more shoreward position. Comparable observations were done at the Noordwijk site by van der Meene et al. (1996). The underlying sediments with their rough surface structure observed in 2017 suggests that clay might be present at the surface. Indeed, boxcore samples taken in 2018 show the presence of consolidated clays covered with only a thin veneer of sands (see Oost et al., 2019). The clays may be older deposits of the Old Rhine delta (see van Heteren & van der Spek 2005).

The erosion structures merge partly into elongated shallow “gullies” which go downslope under an angle to the coast (south-south-west orientation). One of these gullies continues to depths of -14m. More to the south the trenches end up halfway on the slope. These shallow structures may point to sediment transport to deeper water downslope. All structures visible in 2017 have largely been obliterated and smoothened out in 2018, after the prolonged relatively quiet period, supporting the idea that in 2017 the structures were formed under higher energy conditions.

5 Summary and conclusions

5.1 Introduction

This chapter summarizes the relevant findings of the multibeam surveys in paragraph 5.1. It gives answers to part of the research questions in paragraph 5.2.

5.2 Summary

Within the areas studied it appeared that the shorefaces had different morphological structures. The Ameland area was steep as it was part of the terminal ebb-delta lobe. The Terschelling area was gradual and characterized by special sedimentary features, such as deep ripples, lineaments and possible pockmarks. The Noordwijk area was relatively steep and characterized by sand waves in deeper water and shoreface connected ridges in shallower waters.

There is a deeper zone maximal up to -14m, which during fair weather conditions is mainly dominated by coast parallel currents, resulting in bedforms which are oriented perpendicular to the coast and migrate along the coast (Terschelling, Ameland) or are steady (sand waves at Noordwijk). Under storm conditions the bed up to a depth of at least -22m, may be eroded or deformed (hummocks) by a combination of waves and tidal and storm-driven currents. This is concluded from the changes between 2017 and 2018 in the three areas and is also confirmed by the earlier boxcore study (Oost et al., 2019). At several locations it cannot be excluded that the older sedimentary units present just below or at the surface influence present-day development of the shoreface.

In general, it is observed that bedforms brought about by coast-parallel tidal currents dominate in deeper water. Along the Holland coast these are sand waves (present up to ca. -14m NAP) and superimposed large ripples. Along the Wadden coast these are large ripples oriented roughly perpendicular to the coast up to water depths of -15m. From this it can be concluded that under quiet conditions coast parallel tidal currents are dominating the sediment transport on the deeper part of the shoreface (<-14m). Although it might be expected that tidal currents are also important in shallower waters, this cannot be proven from the sedimentary structures visible on the multibeam. However, infill in the period 2017-2018 at Terschelling of some of the scours and lineaments, locally accompanied by large ripples, points to sediment transport related to currents. The slow coverage of shallow fishing traces at Noordwijk in the same period indicate that there sediment transports in the zone between -15 and -18m are small.

At shallower depths bedforms become more irregular under the influence of (storm) waves resulting in irregular three-dimensional bedforms at the Ameland Inlet site and in hummocks above -18m at the Terschelling site. The 2017 observations were done after a series of storms; the 2018 observations were made after a period of quiet weather -relatively to 2017-, but conditions still have been quite energetic. Apparently, waves were able to rework bedforms into the hummocks which cover a large part of the area to substantial depths. Morphological developments in this zone are relatively fast, due to strong processes. For instance, the observation that at the Ameland area straight crested tidal large ripples end in 2018 (after fair weather conditions) around ca. –15m, and at -18m in 2017 (after rougher weather conditions), is attributed to the differences in wave climate and perhaps outflow via the Ameland inlet.

At even shallower water depths flat beds are present which is attributed to even stronger wave influences. In shallower parts of the lower shoreface waves may even lead to erosional features. There are indications that, during extreme storms, locally waves may erode the bed severely (example Noordwijk, 2017) and bring about localized retour currents over the seabed which occur in a shore-oblique offshore direction (Noordwijk and Terschelling, 2017). If this interpretation is correct the currents might be envisioned as storm-related rip currents in deeper water. They may transport sediment to deeper water.

Other structures make clear that the built-up of older deposits is locally of influence on the recent sedimentary development. Two examples are: 1) the starved large ripples at the Terschelling site at -20m NAP occur partially on thick shell layers which cannot deliver sufficient amounts of sediments; 2) the erosional features at the coast of Noordwijk where underlying older clays surfaced.

Furthermore, also structures were encountered in front of Terschelling which are not well understood. These consist of large linear features over many km, the afore-mentioned deep ripples of 2017 and small circular holes at relatively shallow water depths. As all structures might possibly be caused or influenced by shallow gas or outflowing water, it is recommended to study this in more detail.

The preliminary acoustic bed classification map reveals seabed sediment patterns of coarser sediments in the south-eastern area of the Ameland site. This high-resolution mapping of sediments when applied in time series may reveal the changes in sediment composition over time.

5.3 Conclusions

Based on the multibeam research the following questions can be partially answered as follows:

ZB110: What is the sedimentary built-up of the coast, in terms of bedforms, sedimentary structures, bottom profiles and grain size distributions?

In general, it is observed that bedforms oriented perpendicular to the coast dominate in deeper water, which are brought about by nearly coast-parallel tidal currents. These bedforms are sand waves with superimposed large ripples along the Holland coast (up to ca. -14m NAP) and large ripples along the Wadden coast. Along the Wadden coast ripples have irregular three-dimensional forms in shallower depths, under the influence of storm waves resulting in irregular three-dimensional bedforms at the Ameland Inlet site and in hummocks at the Terschelling site. At even shallower water depths flat beds are present which is attributed to even stronger wave influences and (Ameland) perhaps the outflow via the inlet. Along the Holland coast at ca. -17m water depth (4-5 km off the shore) shoreface-connected ridges are present.

On many locations older deposits are present at or just below the surface and influence the local recent development. The extent of this influence is not yet understood. An example are the sturdy early Holocene clay layers at Noordwijk which clearly limit sediment erosion during storms. It is hypothesized at the Terschelling site natural gas or water outflow in the sediments may be present, leading to formation of pockmarks or enhancing erodibility which may help formation of lineament features. However, further research is needed to confirm or reject this hypothesis.

ZB 120: Which processes determine the exchange of sediment between the shoreface and the deeper shoreface and what is their frequency of occurrence and their contribution?

At all water depths a combination of wave action and currents influences the bottom during storm conditions. During fair weather conditions coast-parallel (tidal) currents could be shown to be important to -14/-15m at Ameland and Noordwijk sites and -18m at Terschelling, given the coast-normal bedforms. In shallower reaches of the shoreface the current directions are less clear. Storm waves locally have a strong influence on the development of the deeper shoreface at Terschelling as indicated by hummocks at water depths of -18.4m to -19.1m and at Noordwijk as shown by erosional features on the slope -11 to -14m.

ZB140: In which subareas (or zones) can the coastal profile be subdivided, which are similar in (stability) of the profile, sedimentary built up and dynamics?

The deeper zone goes up to maximum -14m, which during fair weather conditions is mainly formed by coast parallel tidal currents, resulting in bedforms perpendicular to the coast. Under storm conditions the bed may be eroded or deformed (hummocks) by a combination of waves and tidal and storm-driven currents.

Between the lower zone and the upper zone there may be an intermediate zone, which is not characterized by more three-dimensional forms or flat beds. Sedimentation and reworking seem to be rather slow in this zone.

Above ca. -14m waves may exert a strong influence on the development of the local morphology. During fair weather, such features are altered, and erosional traces are filled up.

6 Recommendations

The multibeam observations taken after fair weather periods and after stormy periods provide a wealth of valuable data which shed more light on the morphodynamics of the shoreface. The erosional, channel-like features can be very relevant for coastal maintenance, but very little is known about them. It is recommended to routinely carry out dedicated multibeam surveys to study these features and to understand the genesis of the deeper shoreface.

Older deposits sitting at or just below the surface may locally influence the sedimentary development of the deeper shoreface considerably (see also Hijma, 2018). Also, to that end it is recommended to carry out multibeam surveys and combine the information with sedimentary data from cores.

At the Terschelling area, the large linear features over many km, the deep throughs of ripples and small circular holes at relatively shallow water depth are not well understood. As both structures might possibly be caused or influenced by shallow gas, it is recommended to study this in more detail. An extra reason is that these might pose a risk to shipping safety.

The initial results of the multibeam backscatter study need further improvements in the tuning of the acoustical settings for optimal results. Furthermore, it is recommended to couple the acoustic bed classification to sediment characteristics. Further study of the other backscatter datasets of Kustgenese 2 (the other areas and both years) is expected to give valuable results on the seabed sediments of the lower shoreface, both in distribution and over time.

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