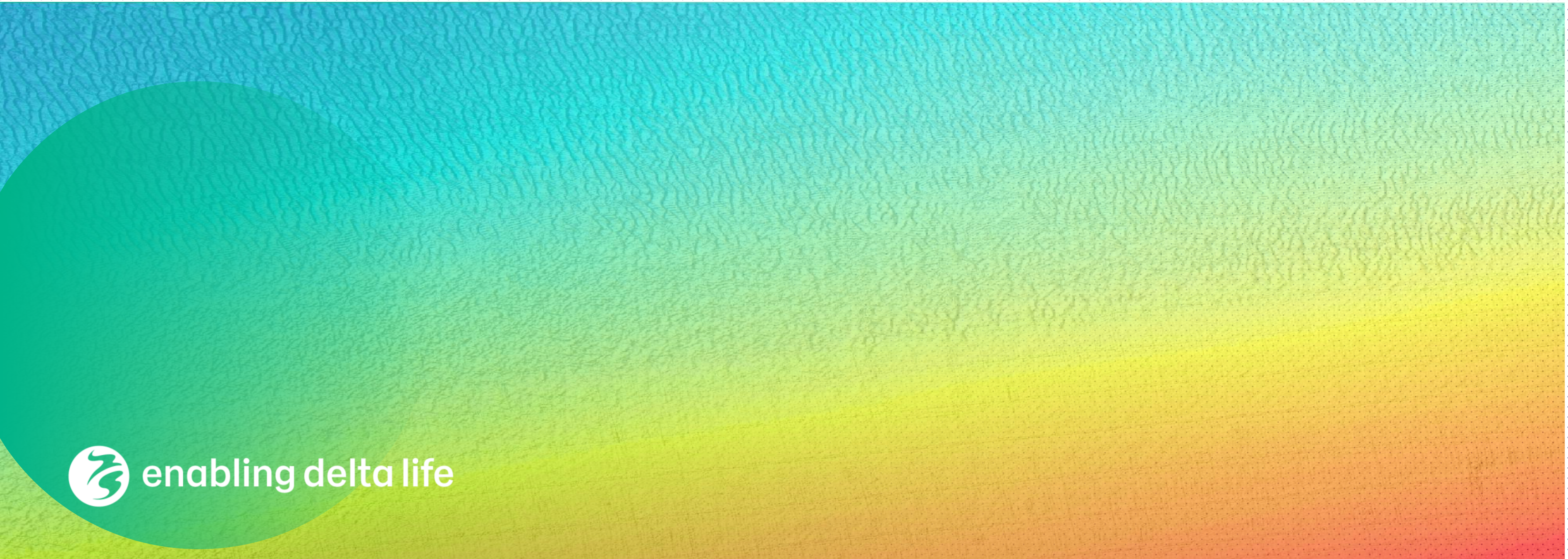
Deltares

The Kustgenese 2.0
Atlas of the Dutch Lower Shoreface

Final Version – February 2020



The Kustgenese 2.0
Atlas of the Dutch Lower Shoreface

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enabling delta life

Summary

From February 2017 to February 2020, Deltares carried out research into the long-term development of the coast as part of Rijkswaterstaat's Kustgenese 2.0 program. In this research, the morphodynamics and sediment transport on the Dutch lower shoreface were one topic next to the sediment transport to the Wadden Sea, the development of ebb-tidal deltas and the subsidence in the coastal zone.

The research had two overall objectives: 1) to increase knowledge, and 2) to answer specific policy questions. For the Dutch lower shoreface, the policy question related to the seaward position of the coastal foundation.

The Kustgenese 2.0 research on the Dutch lower shoreface consisted of a literature survey of available knowledge, an extensive field campaign by Rijkswaterstaat followed by data analysis, and modelling. The research has been reported in several reports and publications and the policy question has been answered in a technical advice.

This Atlas provides an accessible summary and synthesis of the present-day understanding of the Dutch lower shoreface. The focus is on the new Kustgenese 2.0 data and knowledge, although relevant prior knowledge is included as well.

The Atlas contains maps, as any atlas does, but is much broader in giving insight by other types of visualizations as well.

Summary - continued

- The Kustgenese 2.0 Lower Shoreface project comprised both data collection in the field and numerical modelling. Sediment cores and multibeam sonar surveys provided information on the geology, geomorphology and sediments of the lower shoreface of the Dutch coast. Instrumented frames placed at the seabed collected a wealth of process data. A detailed hydrodynamic and sand transport model of the Dutch lower shoreface was built and validated with the field measurements. The new information gives a more detailed picture of the lower shoreface.
- The variation in shoreface composition and morphology is larger than anticipated previously. The large-scale morphology of the lower shoreface seems rather stable. Decadal time series show an erosional trend. Small-scale bedforms can change over an interval of days to weeks.
- The multibeam surveys revealed unexpected details such as geology-based shoreface irregularities between -15 m and -18 m that probably act as conduits for downslope currents and sand transport. After a wave event (storm?), more erosional features that suggest seaward sand transport were discovered.

Summary - continued

- The field measurements showed that wave orbital velocities at 20m depth can be larger than 1 m per second.
- The model results show that the tidal velocities are slightly asymmetric offshore the Westerschelde mouth, the asymmetry increases towards Texel and decreases again towards Schiermonnikoog. The alongshore-directed sand transport is much larger than the cross-shore transport. The largest transports at the 20m-depth contour occur between Wijk aan Zee and Texel. Here, transport is parallel to the coast or directed to deeper water. Transports at 20m depth along the other parts of the coast are directed to shallower water.
- The modelled landward sand transport is *c.* 3 million m^3 per year over the -20m contour and *c.* 5 million m^3 per year over the -15m contour. This suggests a yearly erosion of 2 million m^3 at these depths, which is, depending on alongshore transport gradients, an average increase in depth of 2 mm per year. Storms seem to increase the cumulative long- and cross-shore sand transport per year considerably.

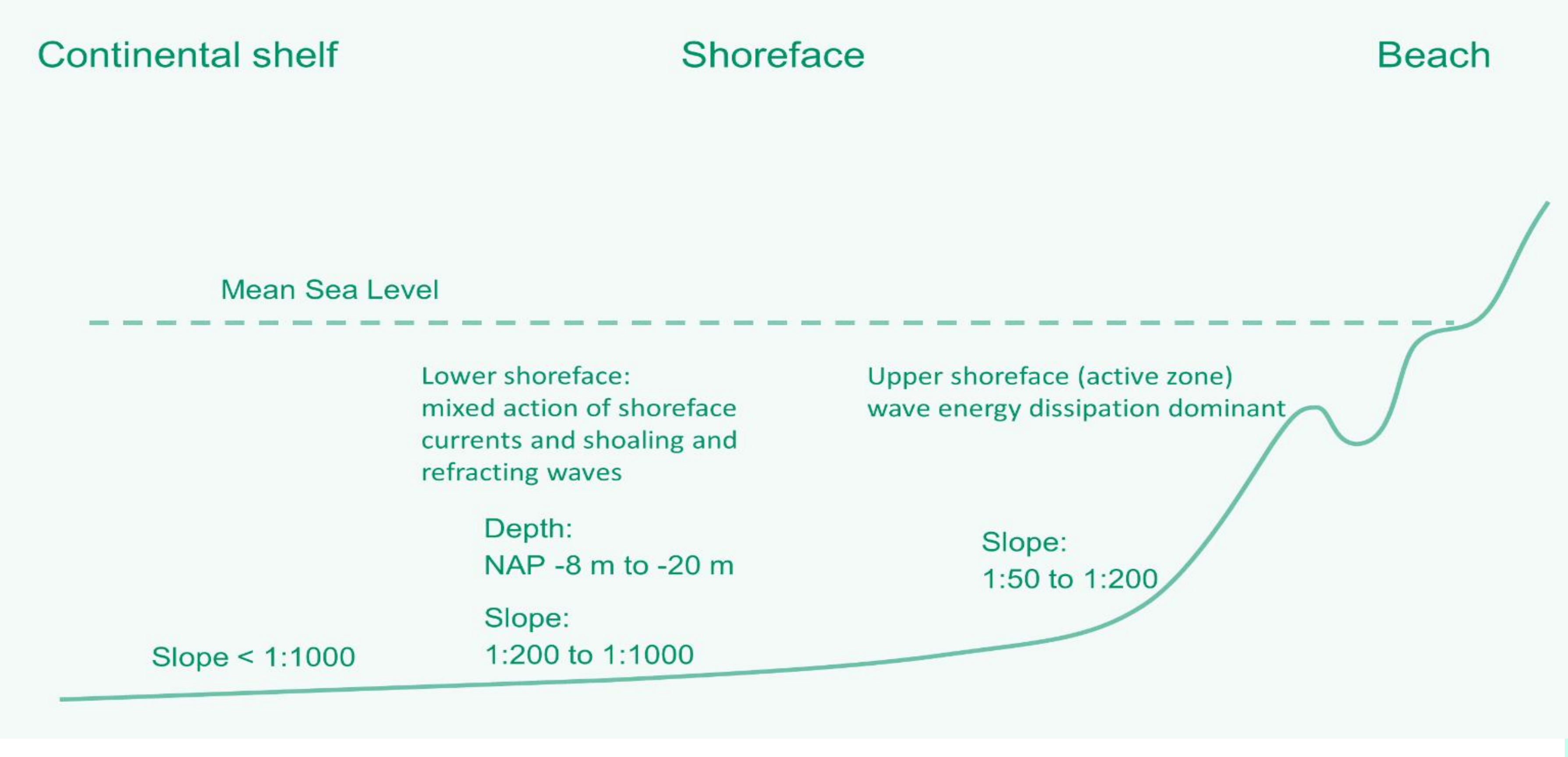
Version	Author	Reviewer	Approver	Publish
5.1	Ad van der Spek	Robert McCall	Toon Segeren	

1. Introduction

The Dutch lower shoreface

- The shoreface is the area seawards of the low water line that is under the influence of waves and tidal currents. The surfzone is called the upper shoreface. Along the Dutch coast, the lower shoreface is defined as the zone between approximately the -8m and -20m depth contours, with typical bed slopes between 1:200 and 1:1000. The lower shoreface is the zone below the fair-weather wave base, where tidal currents and storm waves dominate (see slide 6).
- The knowledge about the Dutch lower shoreface is limited. It remains unclear what the relative importance and interaction is of marine processes such as tides and waves. This knowledge gap is mainly caused by lack of observations and data.
- The Kustgenese 2.0 programme included extensive field measurements at 3 locations in 2017 and 2018. Analysis of these data and model simulations helped to fill this gap.
- ***All depths in this report are given with reference to NAP (Dutch Ordinance Level), which is approximately mean sea level.***

The lower shoreface



Background information and detailed description of definitions can be found in the literature study of the KG2 Lower Shoreface subproject (Van der Werf et al., 2017).

The Kustgenese 2.0 project

- The Dutch coastal policy aims for a safe, economically strong and attractive coast. To achieve this, the coastline position and the shoreface sand budget are maintained with sand nourishments. The nourished maintenance zone is called ‘coastal foundation’, its offshore boundary is set at the -20m contour.
- In 2020 the Dutch Ministry of Infrastructure and Water Management will reconsider the annual nourishment volume. The Kustgenese 2.0 (KG2) knowledge development programme aims to improve our understanding of the coastal system to support this decision making process.

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The Kustgenese 2.0 Atlas of the Dutch Lower Shoreface

- This Atlas of the Dutch Lower Shoreface is compiled as part of the KG2 project. It combines new information generated in the KG2 programme with existing information. The new data consists of seabed morphology, seabed sediment composition and grainsize distributions and net sand transport along the Dutch coast based on field data and numerical modelling
- It is an extension to the description of the Dutch shoreface by Van der Werf et al. (2017) and depicts the dominating processes and resulting dynamics of the shoreface. Moreover, it provides estimates of the net sand transport at the lower shoreface of the Dutch coast.
- More details and in-depth information can be found in the technical reports by Oost et al. (2x), Schrijvershof et al. and Grasmeijer et al. An overview of the field data and the deployed equipment is given by Van der Werf et al. (Full references on slide 84).
- **The aim of this Atlas of the Dutch Lower Shoreface is to visualize and describe the Dutch lower shoreface morphodynamics.**
- **The most-important questions to answer are: How dynamic is the lower shoreface? and How large are the net sand transports and what is their direction?**

Set-up of the Atlas

The following chapters subsequently discuss:

2. the study areas,
3. the geological architecture of the shoreface,
4. its geomorphology based on multibeam sonar surveys,
5. shoreface sediments,
6. shoreface processes and sand transport based on field measurements and numerical modelling,
7. and finally the shoreface evolution at decadal scale.
8. The Final Remarks summarize the most important findings of this study.

- The Atlas concludes with a description of the methodologies that were used to collect the results.

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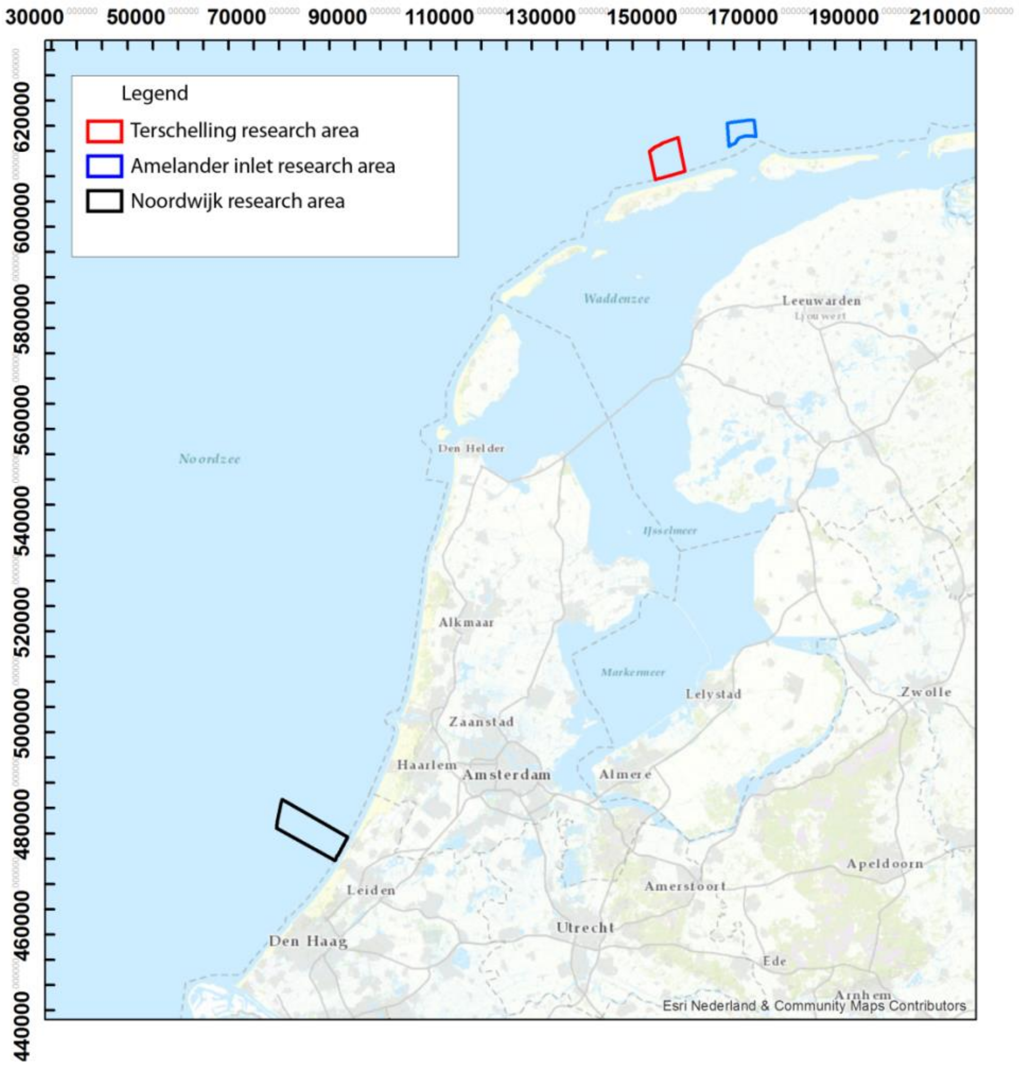
2. The study areas



- To get an impression of the alongshore variation, 3 study areas with different characteristics were selected : Ameland Inlet, Terschelling and Noordwijk aan Zee.
- The Ameland Inlet study area is situated directly offshore the northern part of the ebb-tidal delta of this inlet and includes the depositional area of the main ebb channel in this delta. Moreover, it links up to the site of the KG2-Seawad 2017 field campaign to its south.
- The Terschelling study area is located directly offshore the central part of the island of Terschelling. The shoreface of the barrier islands of the Wadden coast is comparatively unknown.
- The Noordwijk study area represents the north-south trending Holland coast. In general, this stretch of coastline differs from the Wadden coast. Moreover, this area has been studied in detail in the past (see e.g., van Heteren et al., 2003).
- As part of the KG2 programme, extensive field campaigns were organized. All study areas were surveyed in 2017 and 2018 with multibeam echosounders. Moreover, vibrocores and boxcores were collected and fully equipped frames were deployed for measuring flow velocities, suspended sediment concentrations and small-scale seabed dynamics.

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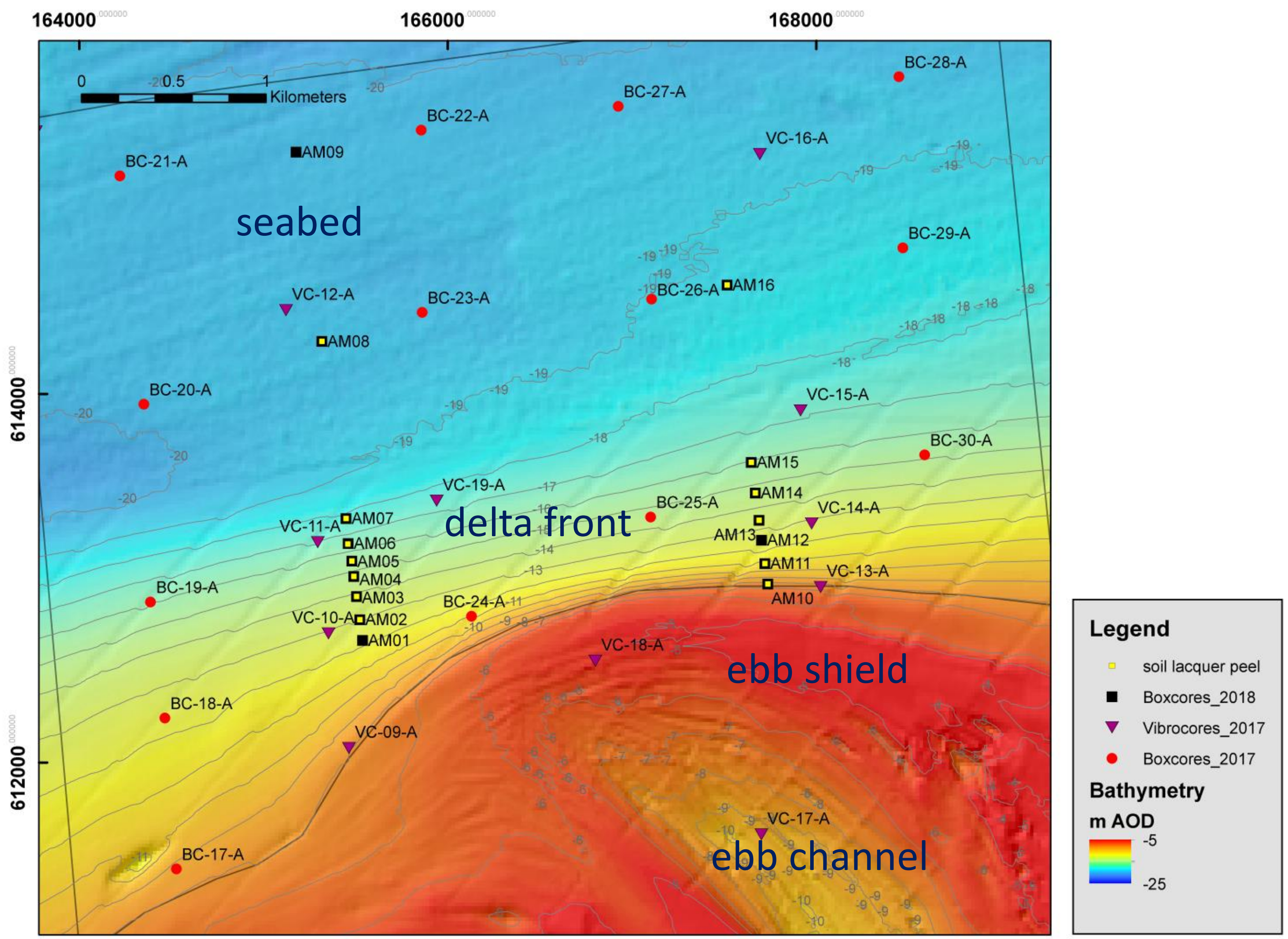
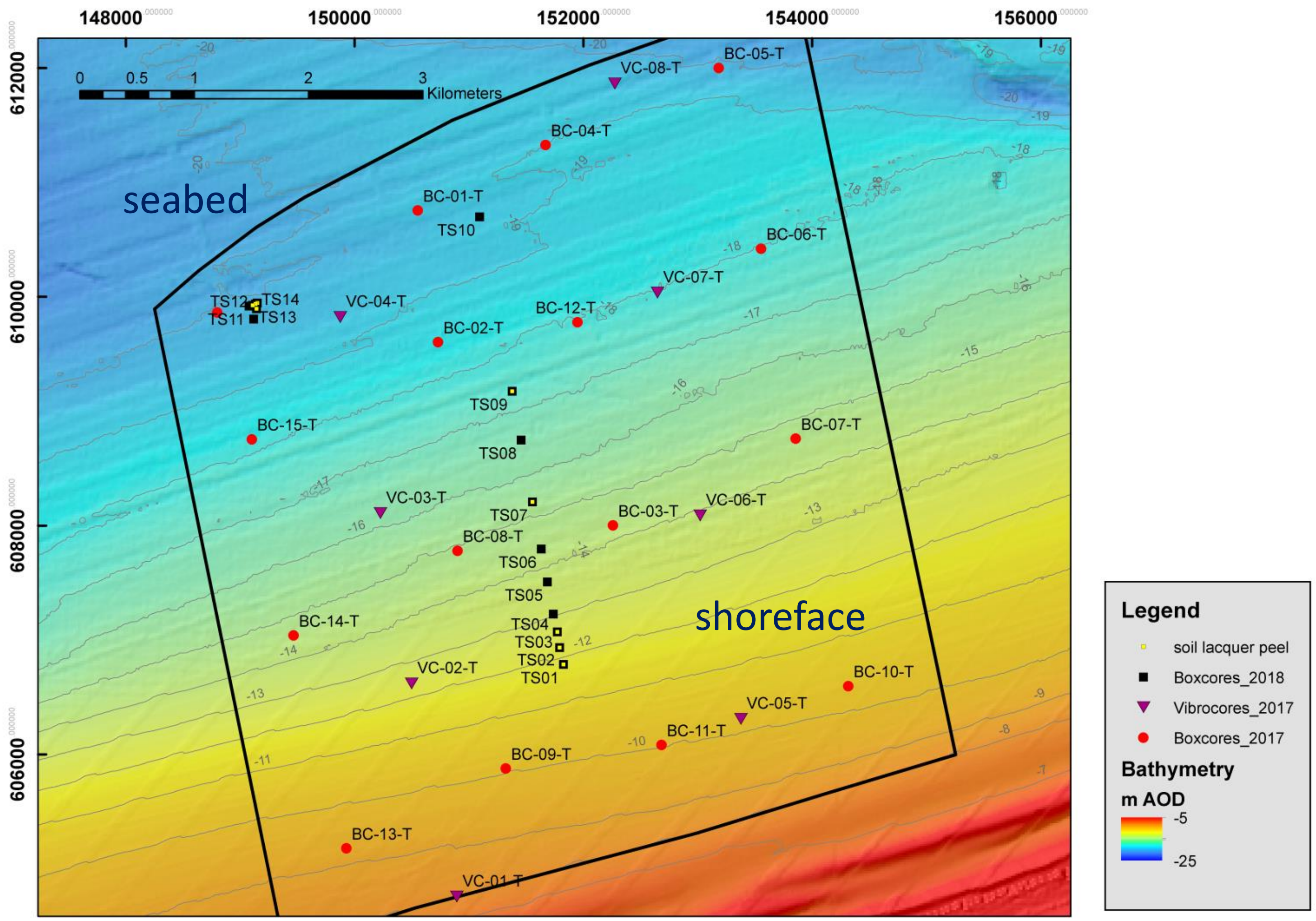
Study area Ameland Inlet



- The Ameland Inlet study area is situated directly offshore the northern part of the ebb-tidal delta of this inlet and includes the depositional area / ebb shield of Akkepollegat, the main ebb channel in the Ameland Inlet ebb-tidal delta. The study area is a seaward extension of the sampling sites of the Kustgenese 2.0 / Seawad September 2017 field campaign in the inlet.

- The area comprises the steep front of the delta in the south and the approximately flat seabed with megarippels in the north. The study area measures *c.* 5 km x 4 km, the depth ranges between -8 m and -20 m.

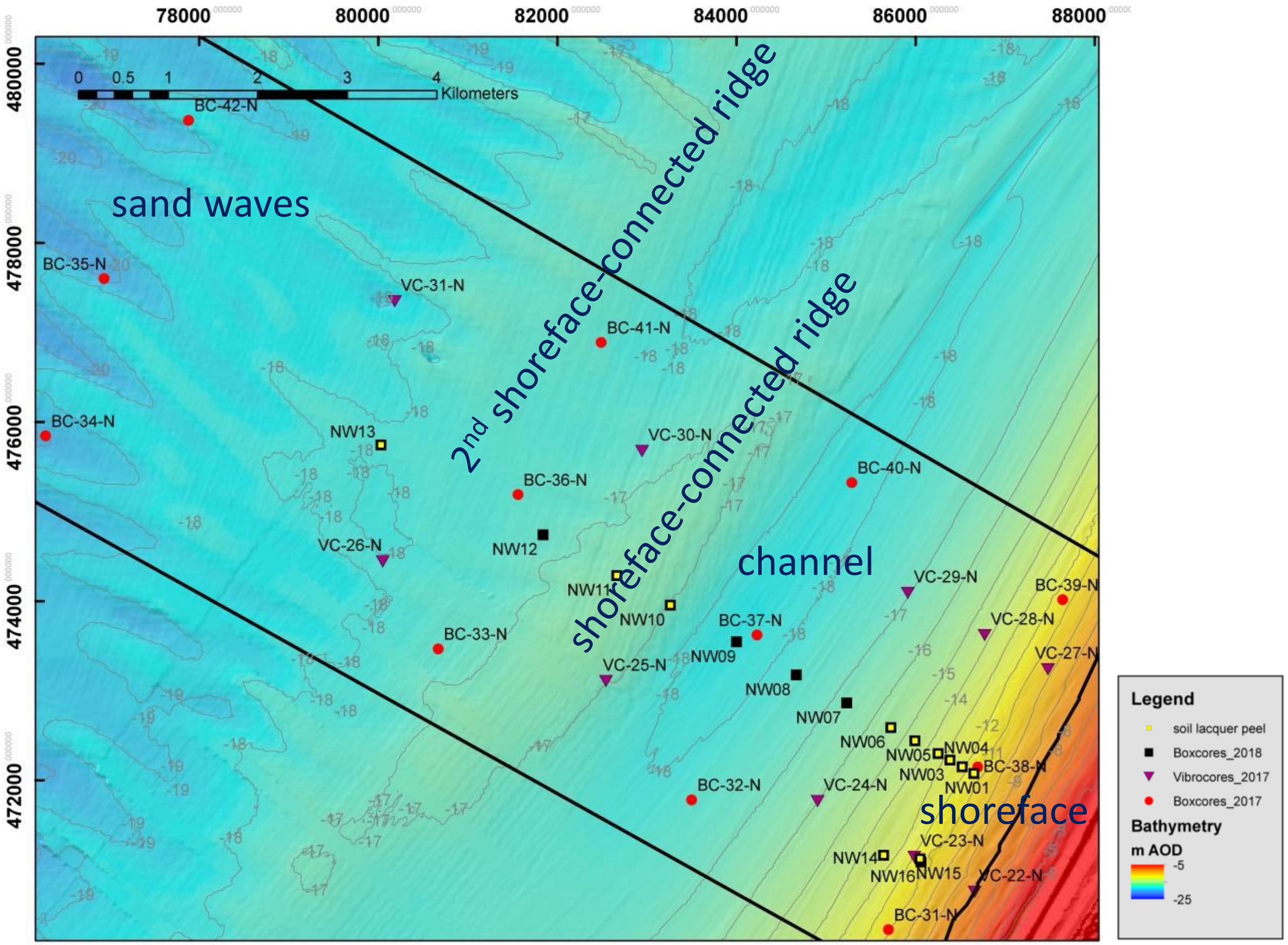
Study area Terschelling



- The Terschelling study area is located directly offshore the central part of the barrier island of Terschelling along the Wadden Sea coast. It shows a low-gradient coastal profile and excludes the sand bars of the surf zone. This area is situated outside the region of direct influence of tidal inlets and is part of the approximately west-east oriented Wadden coast.

- The study area measures *c*. 6 km x 6 km, the depth ranges between -8 m and -20 m.

Study area Noordwijk



- The Noordwijk study area represents the Holland coast. An over -18m deep channel separates the steep shoreface from a series of approximately shore-parallel shoreface-connected ridges. The second, seaward ridge gives way to a field of shore-normal sand waves.

- The area measures *c*. 13 km x 5 km, its depth ranges between -8 m and -20 m, which excludes the sand bars of the surf zone.

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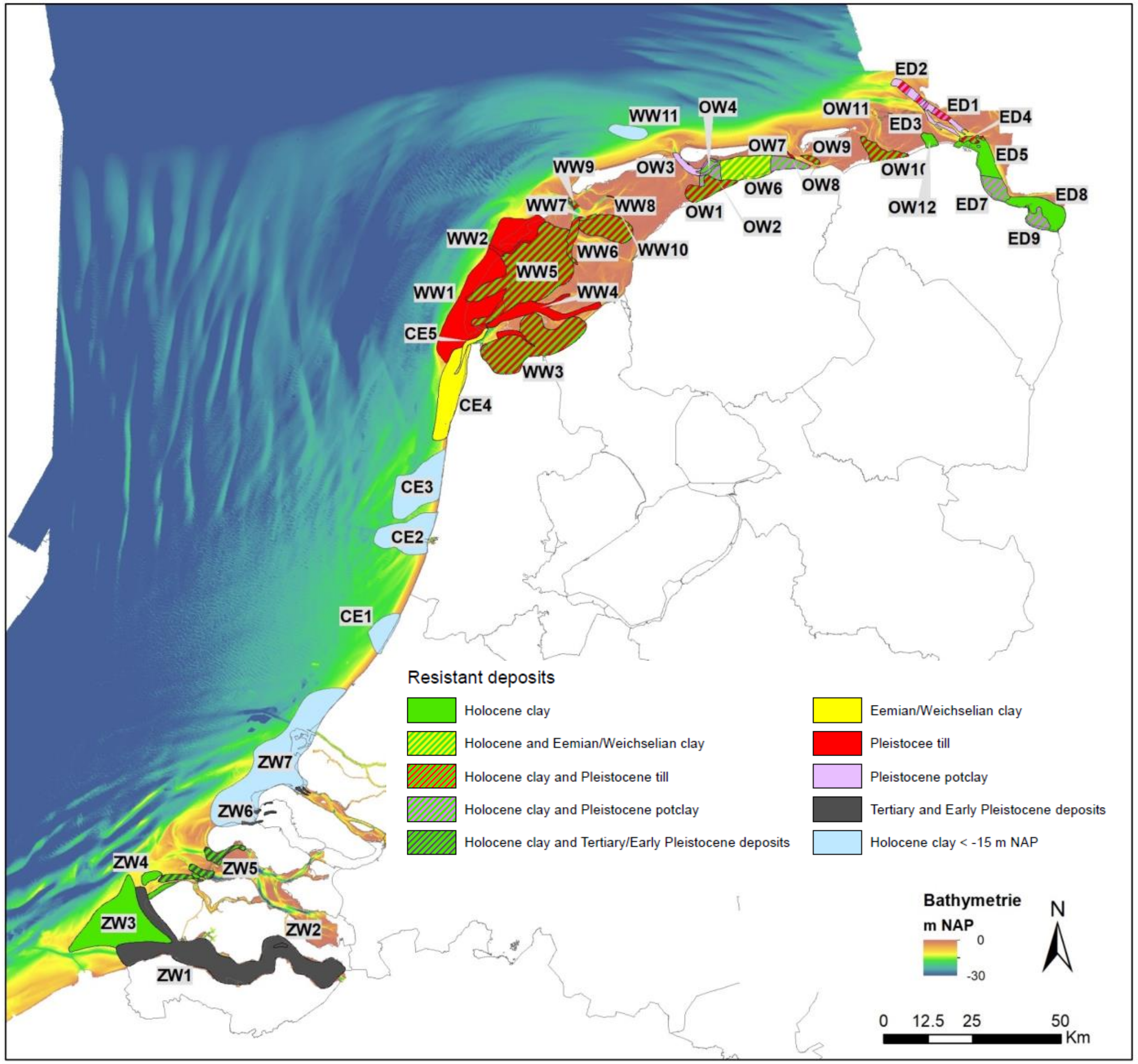
Field campaigns study areas

- In the KG2 study areas the bathymetry was surveyed and vibrocores and boxcores were collected in 2017 and 2018.
- Instrument-bearing frames measured hydro-morphological processes at -10 m/-12 m, -14 m/-16 m and -20 m depth between November 2017 and May 2018.
- An overview of the collected field data is given by Van der Werf et al. (2019).

	2017							**2018**											
	June	July	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Cores		vibro/box														box			
Multibeam				Ameland		Terschelling									Ameland	Noordw	Terschel		
					Noordwijk														
Frames						Ameland		Terschelling 1		Tersch. 2	Noordwijk								

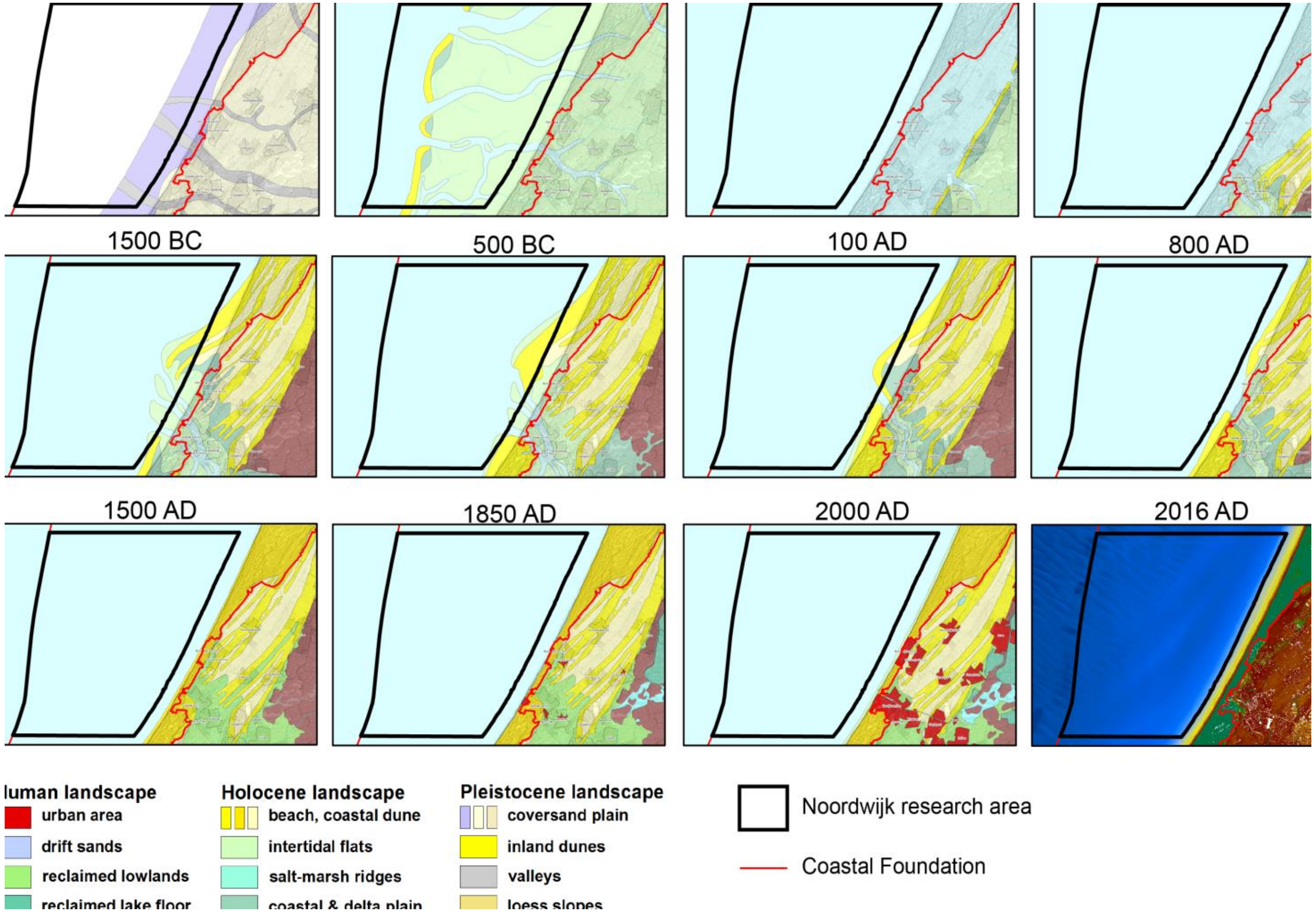
3. Geology of the shoreface



- Subsurface sediments determine the local sea-bed sediment composition. Beside that, erosion-resistant layers influence the morphodynamics of the shoreface.
- The figure shows the deposits in the subsurface of the coastal zone that potentially influence the evolution of the sea bed. Especially deposits with strongly deviating grainsize distributions or erosion resistance influence developments. In the northern part of the Netherlands these are Pleistocene glacial deposits, in the southwest Pleistocene and Tertiary deposits. Moreover, Holocene deposits exposed by the retreating coast can act in a similar way.

Source map: Hijma, 2019

Holocene coastal evolution causes geological variation – *example Noordwijk*



Source: Oost et al., 2019a

- These maps show the evolution of the coastal zone near the Noordwijk study area. Around 9000 years Before Christ (BC) river channels were crossing this area. Around 5500 BC the area had changed into a tidal basin. The coastline migrated eastward and the tidal basins disappeared. Between 1500 BC and 500 BC the river Rhine built a delta that later on eroded.
- Each of these phases produced specific deposits (called *sedimentary environments*) that can be traced in the subsurface.

Deposits study areas

- The 23 vibro cores contain deposits that were formed in different environments, each with specific conditions.

Ameland Inlet

- The 9 cores from Amelander Zeegat comprise deposits of migrating tidal channels, chaotic layers typical for rapid deposition of sand, presumably supplied by an active ebb channel, and offshore seabed deposits (1 to 2 m thick). In all cores, these deposits are overlain by 0.2 to 0.6 m sand of the active layer.

Terschelling

- The 6 cores from Terschelling consist of deposits possibly laid down by migrating tidal channels. However, the sediment does hardly contain shells or -fragments, except for core 7 that contains an abundant number of shells. Moreover, the sediment colour deviates from the normal range of colours. Active-layer sands 0.1 to 0.6 m thick cap these deposits.

Noordwijk

- The 8 cores from Noordwijk contain fluvial and estuarine deposits laid down by distributaries of the river Rhine with tidal-channel deposits on top. Between -13 m and -17 m in the shoreface, a featureless sand layer occurs that is possibly deposited by the Oude Rijn estuary. The offshore sand ridges consist of seabed sediments, up to 3 m thick. All deposits are covered by 0.3 to 0.8 m of active-layer sands.

- See Oost et al. (2019a) for more information.

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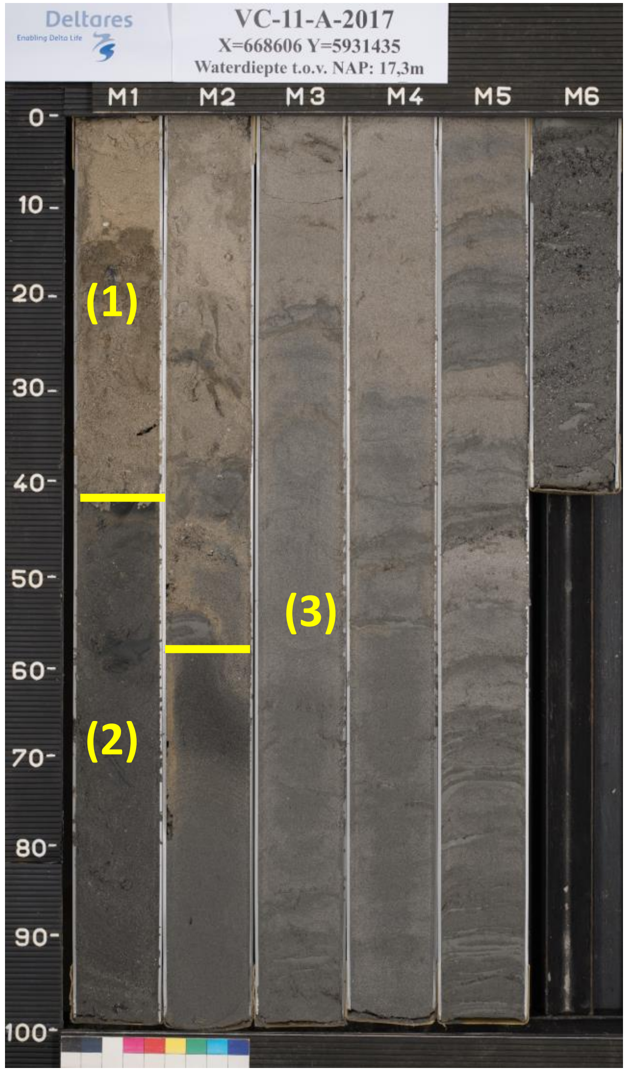
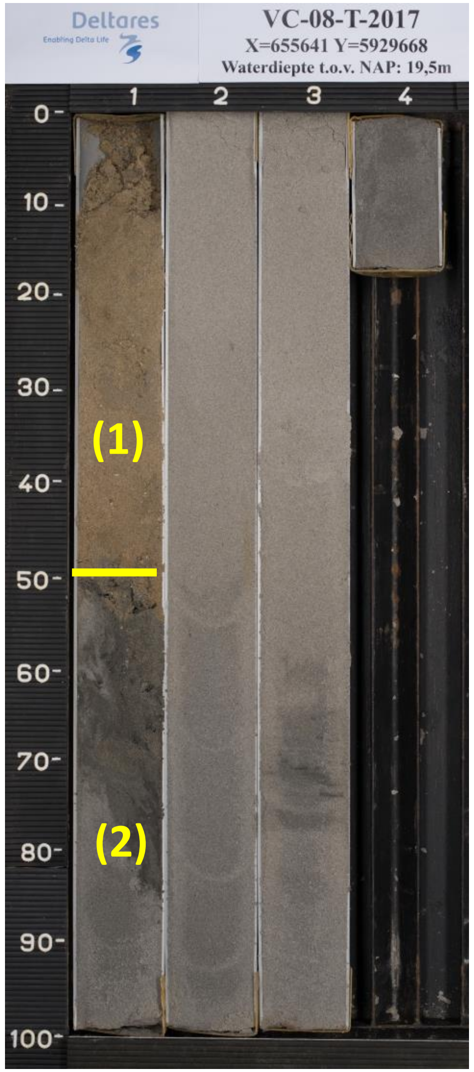
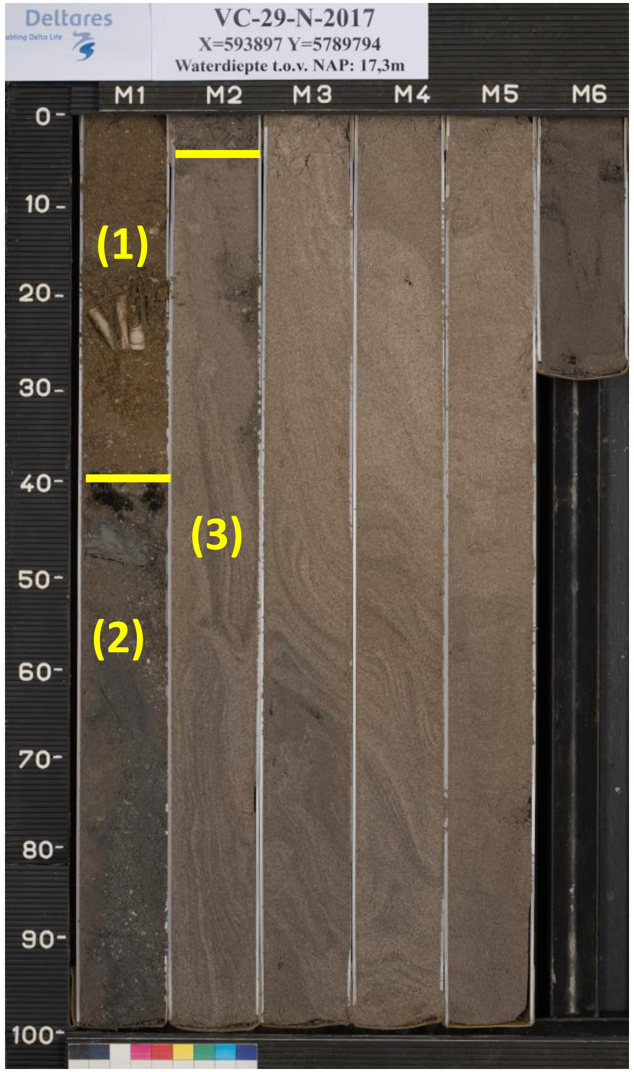
Examples of vibro cores





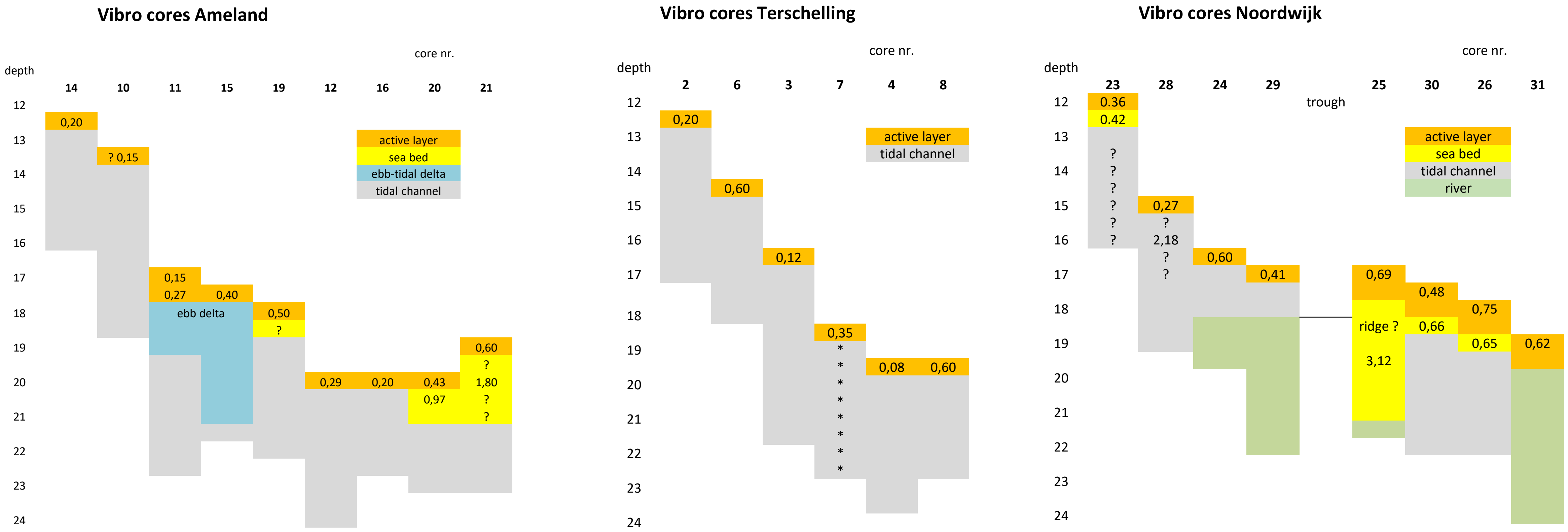


Core VC-11-A
Ameland Inlet: shoreface sand (1) on chaotic ebb-shield deposits (2) on tidal channel deposits (3)

Core VC-08-T
Terschelling: sea-bed sand (1) on tidal channel deposits (2)

Core VC-29-N
Noordwijk: shoreface sand (1) on tidal channel deposits (2) on river deposits (3)

Sedimentary environments study areas



Schematic representation of the sedimentary environments distinguished in the vibro cores.

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Sedimentary environments

- Based on the vibro cores, deposits from different sedimentary environments can be distinguished:

Lower shoreface and sea-bed deposits; active layer

- Shoreface and seabed deposits consist of fine to coarse sand, varying in colour between yellow, brown and grey. They typically contain many shells and shell fragments and in some cores some clay layers. The base of these deposits is often sharp, indicating their erosive nature. These deposits recently were formed by reworking and transport of the underlying Pleistocene and Holocene deposits. In some cores stacking of two or more generations can be distinguished .

Tidal channel deposits

- Migrating tidal channels deposit sediments in their inner bends that consist of brown-grey and grey sand, usually with abundant (thin) clay layers and sometimes peat clasts and fine organic material. The base of these deposits is often sharp. Tidal channels can be found in tidal basins, inlets and ebb deltas. These deposits are found in all study areas.

Ebb-shield deposits

- Ebb-shield deposits consist of brown-grey and grey sand with clay clasts and typical tidal-basin shells, often showing a chaotic arrangement. These deposits formed due to the transport and fast deposition in the tidal delta of a precursor of Ameland Inlet.

Fluvial deposits

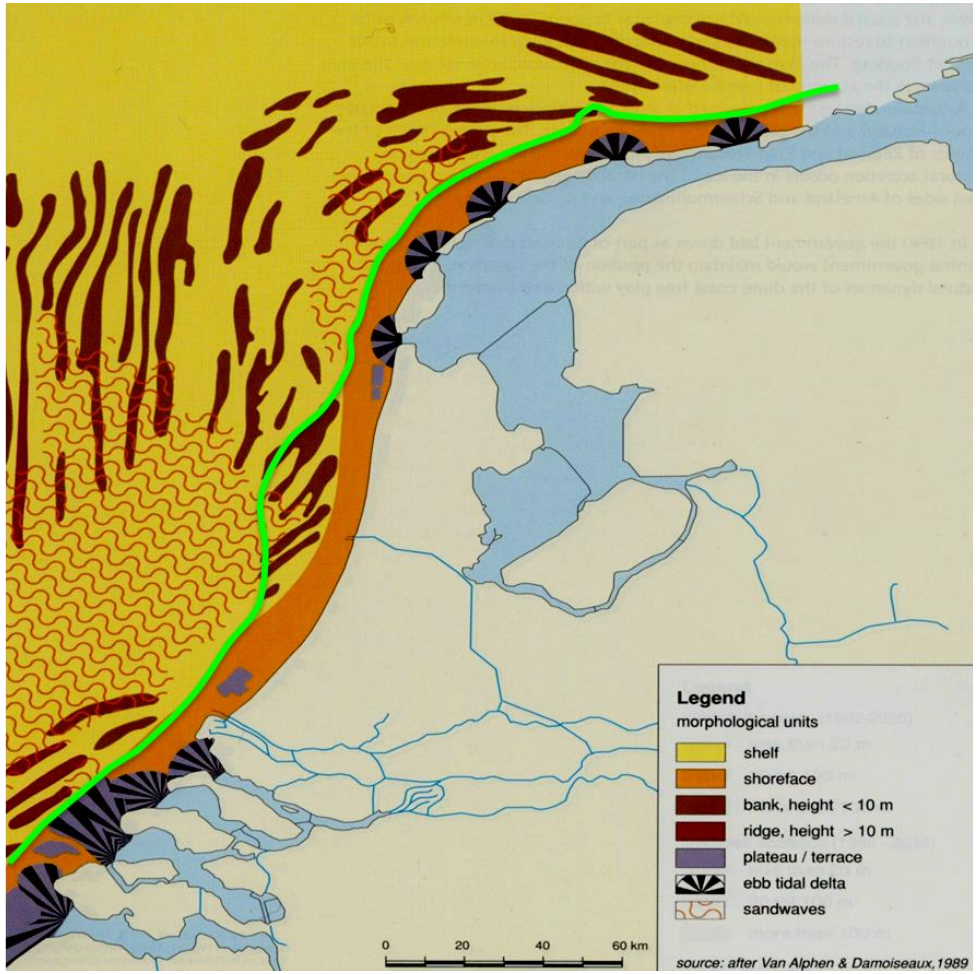
- Fluvial deposits are found only in the Noordwijk area and consist of brown-grey to red, cross-laminated sand without shells. These deposits were formed by Pleistocene and Early Holocene distributaries of the river Rhine.

4. Morphology of the shoreface

Geomorphological map of the shoreface

- In 1987, Van Alphen & Damoiseaux published a geomorphological map of the Dutch coastal zone. It shows the geomorphology of the shoreface and the bounding North Sea floor, based on a series of 77 profiles, about 25 km long and collected in 1984. They distinguished the shoreface and the seabed on the basis of slope: shoreface slopes are steeper than 1:1000, the seabed less. This so-called ‘dip’ in the slope appears approximately at the -20m contour.
- The shoreface includes ebb-tidal deltas, sand ridges, plateaus and smaller-scale features (see maps; slides 23-25).

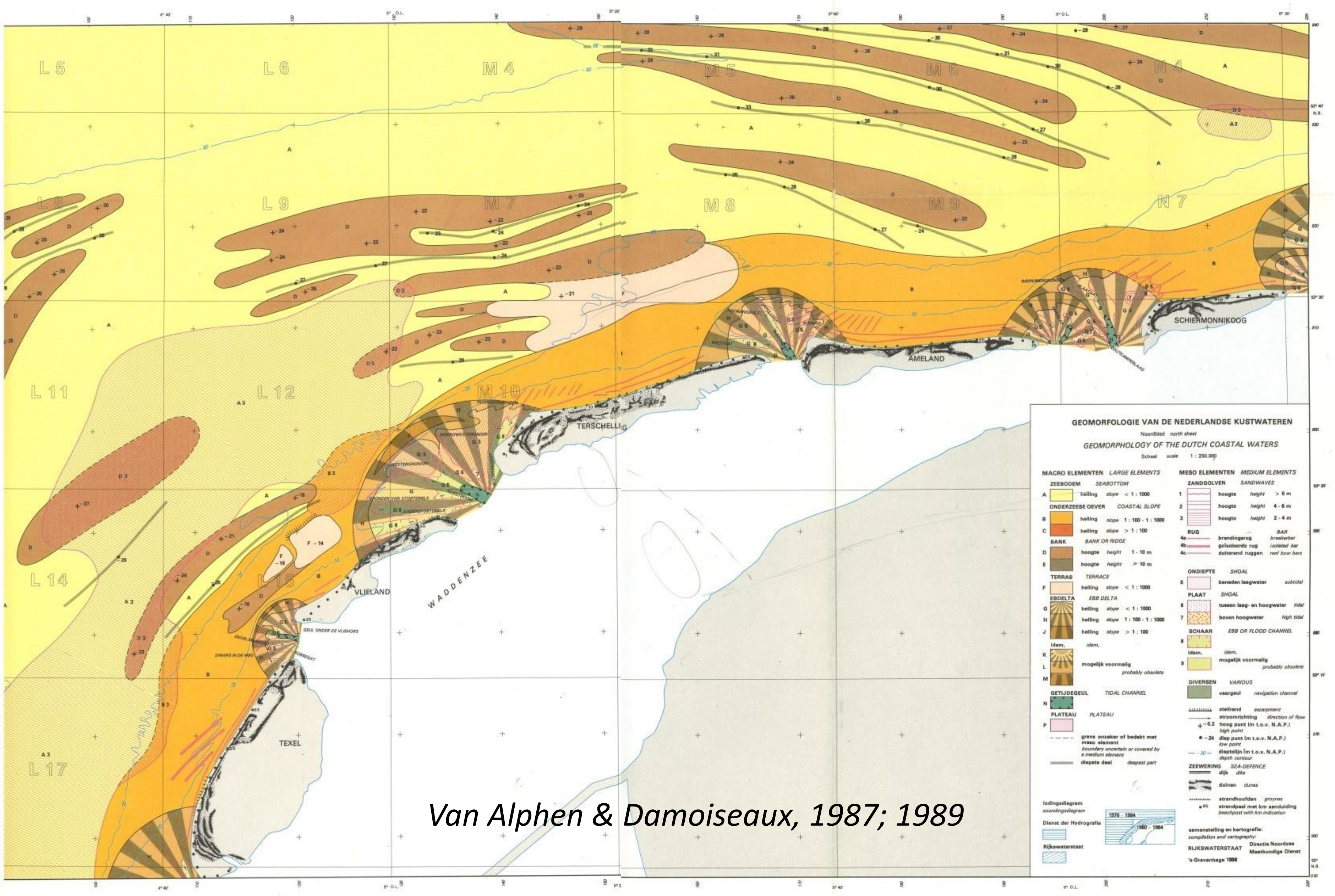
Lower boundary of the shoreface



- The -20m contour (green line) was assumed to be the lower, seaward boundary of the shoreface. Later on, a smoothed version of this contour line was adopted as the seaward boundary of the 'coastal foundation', the management concept describing that part of the coast that supports the functioning of the system.
- However, the set of profiles shows a wide variety in slope morphologies (see slide 26) and, hence, it is not clear if the -20m contour is really the active lower boundary of the shoreface.
- Therefore, the validity of the -20m contour as lower boundary of the 'coastal foundation' can be questioned and needs further study.

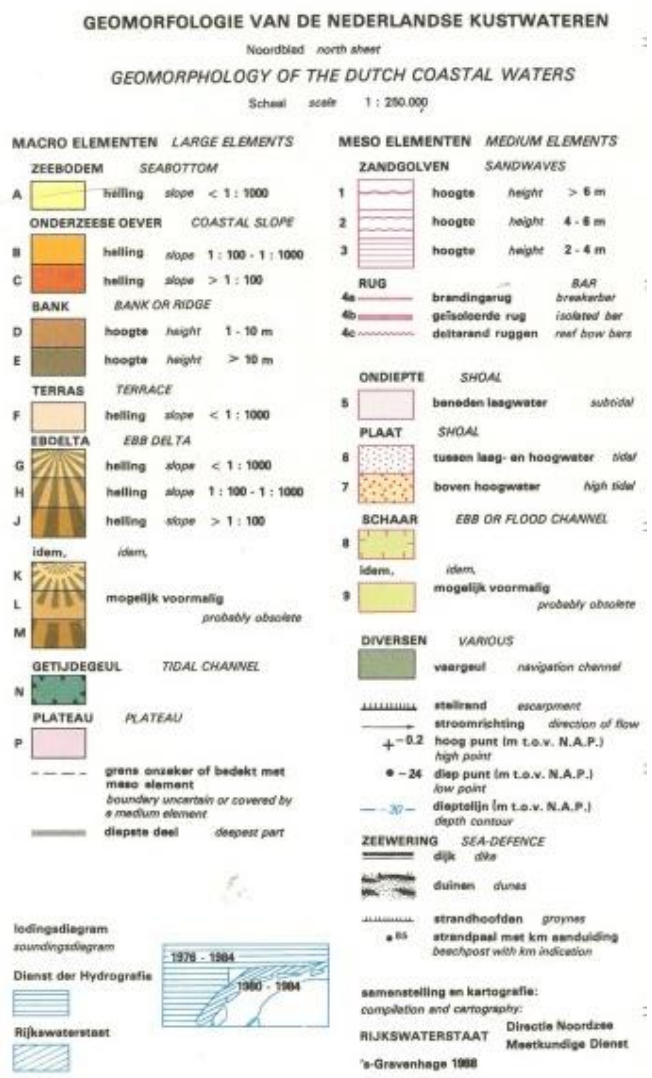
Source figure: Van der Werf et al., 2017

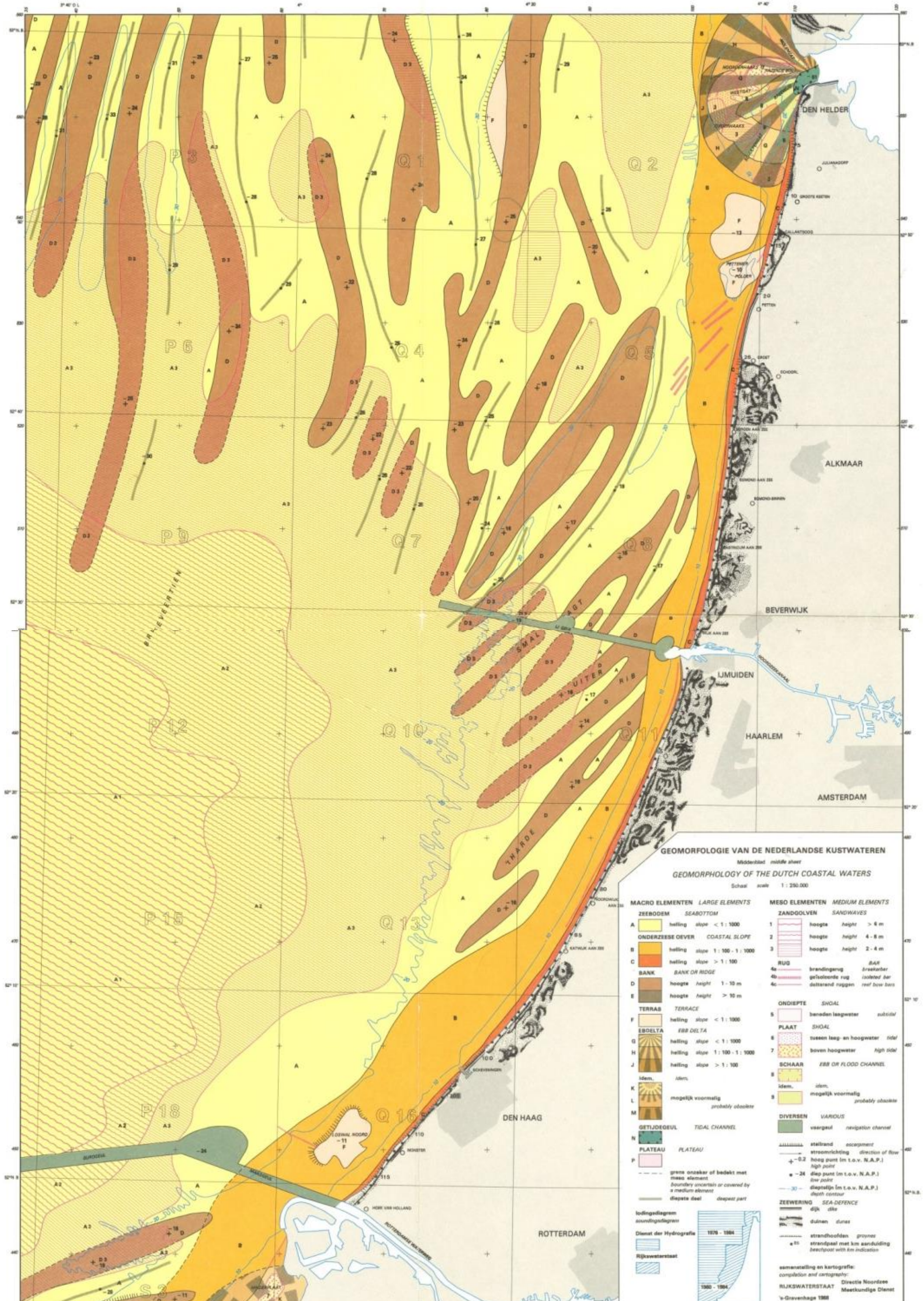
Geomorphological map shoreface Wadden



Van Alphen & Damoiseaux, 1987; 1989

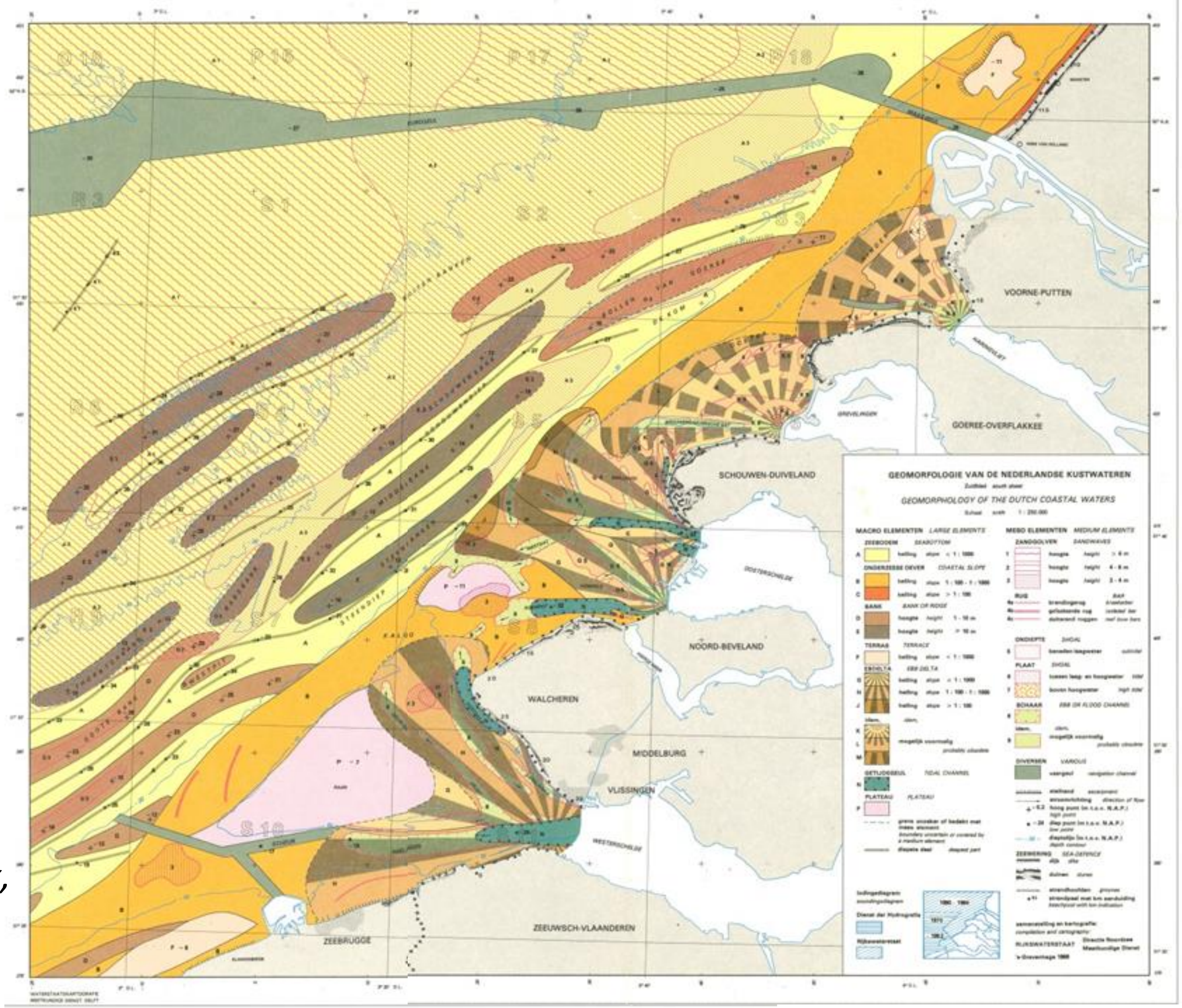
Geomorphological map shoreface Holland





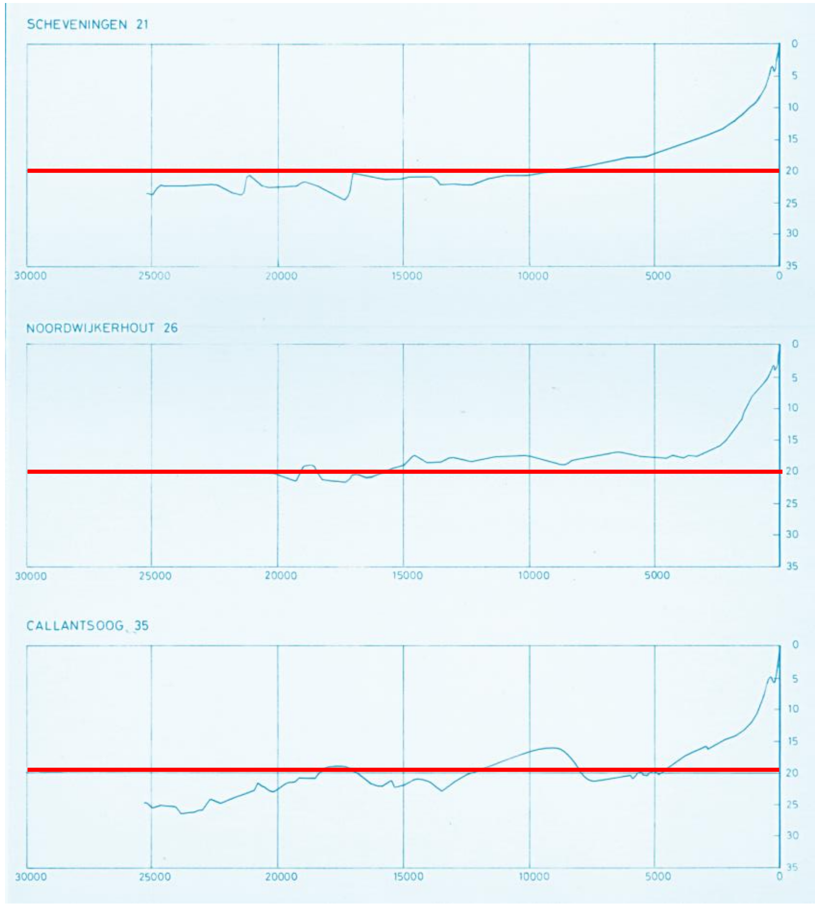
Van Alphen & Damoiseaux, 1987; 1989

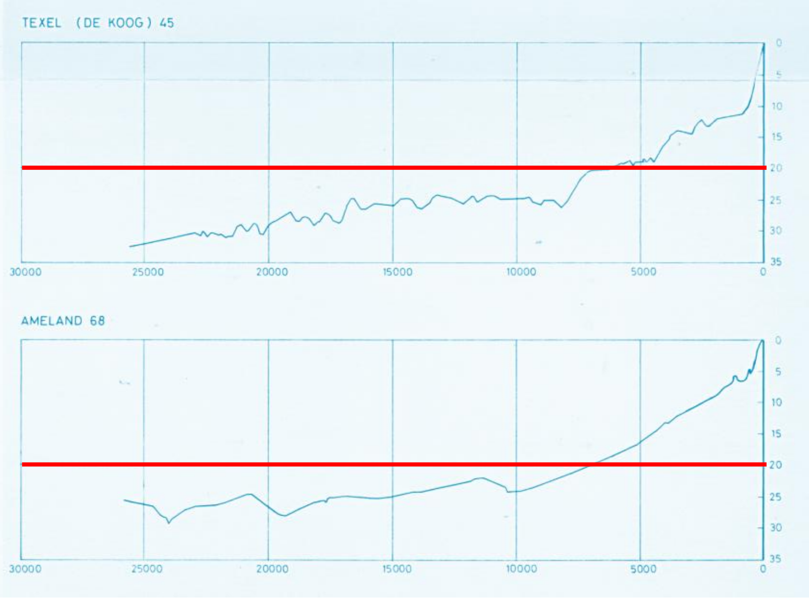
Geomorphological map shoreface Delta



Van Alphen & Damoiseaux, 1987; 1989

Coastal profiles Kustgenese 1984





- 77 profiles
- c. 25 km long
- spacing c. 5 km
- red line indicates -20m level

See Van Alphen & Damoiseaux, 1987; 1989

Multibeam sonar surveys 2017-2018

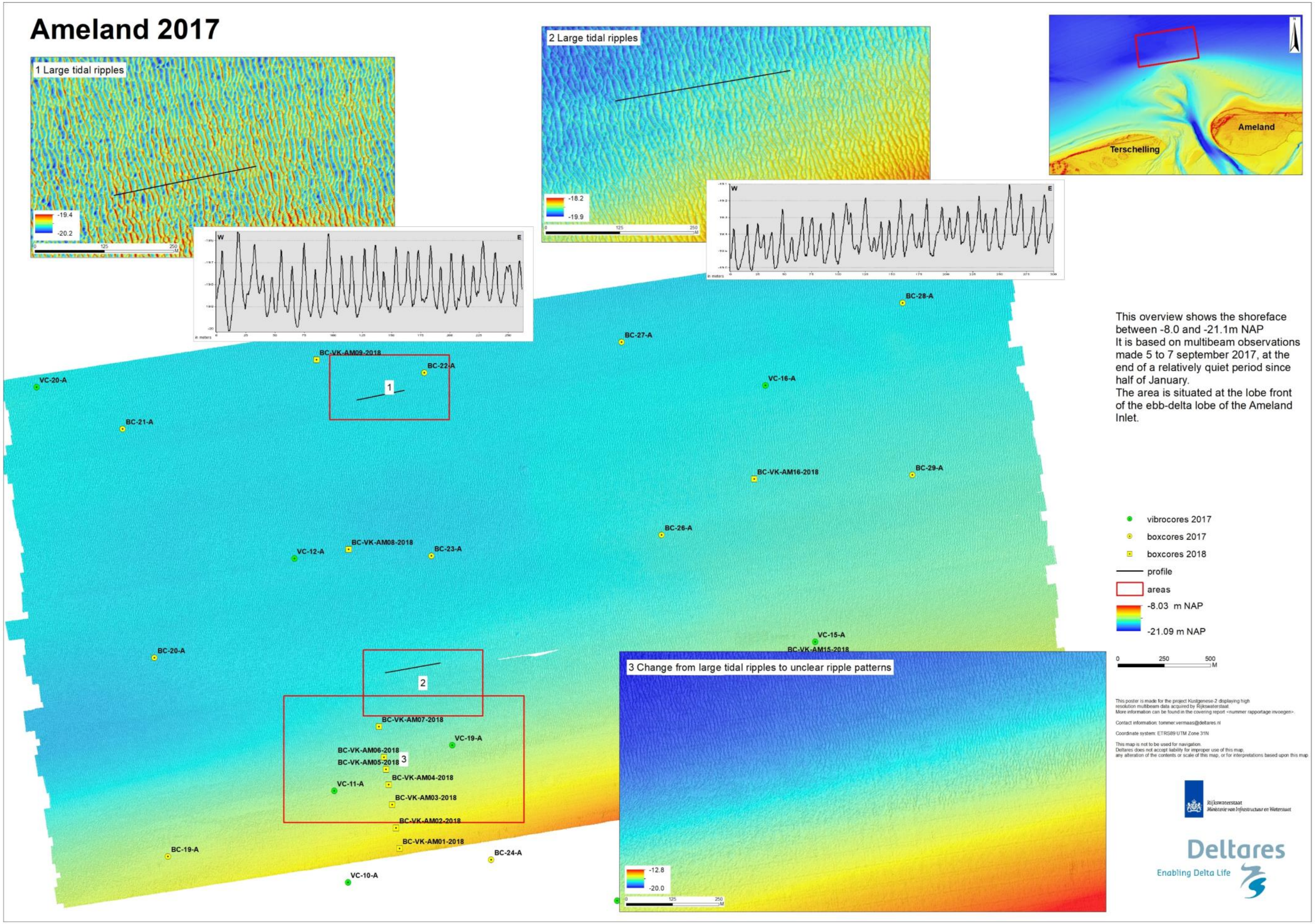
- In order to get more detailed information and complete areal coverage, the study areas were surveyed using multibeam echosounders in late summer to fall 2017 and in the same season in 2018. Varying meteorological conditions preceding and during the surveys caused different smaller-scale morphological phenomena. Comparison of the surveys shows the morphological variability on a yearly scale.

- At the lower shoreface, bedforms created by tidal flow, by wave orbital motions and by their combined effect can be expected. Tidal currents tend to form megaripples that migrate in the direction of the dominant current. Orbital motions caused by waves deform existing megaripples at the seabed. Besides that, the combination of tidal flow and wave orbital motions triggers the formation of a different, more three-dimensional ripple type.

- See Oost et al. (2019b) for details on the multibeam surveys.

Multibeam Ameland Inlet 2017

- The 2017 Ameland Inlet survey (slide 29) shows the slope of the ebb-tidal delta in front of the main ebb channel Akkepollegat, between *c*. -9 m and -18 m, and the North Sea bed offshore of it. The latter shows a regular pattern of linear megaripples with their crests oriented in north-south direction.
- In the direction of the ebb-tidal delta, around -18 m, the ripple pattern becomes more chaotic and less continuous, the ripples become smaller and more three-dimensional and from -16 m upwards the ripples disappear altogether.
- The megaripples (length ≤ 10 m; height ≤ 0.45 m) have been formed by the tidal currents and are asymmetrical in the direction of the dominant flood current, which means that their eastern sides are steeper than their western sides. The transition from regular and continuous two-dimensional to irregular and three-dimensional ripples around -18 m when going in landward direction, shows the increasing influence of waves on the sea bed. The absence of megaripples shallower than -16 m is caused by waves dominating the sand transport at the sea bed.

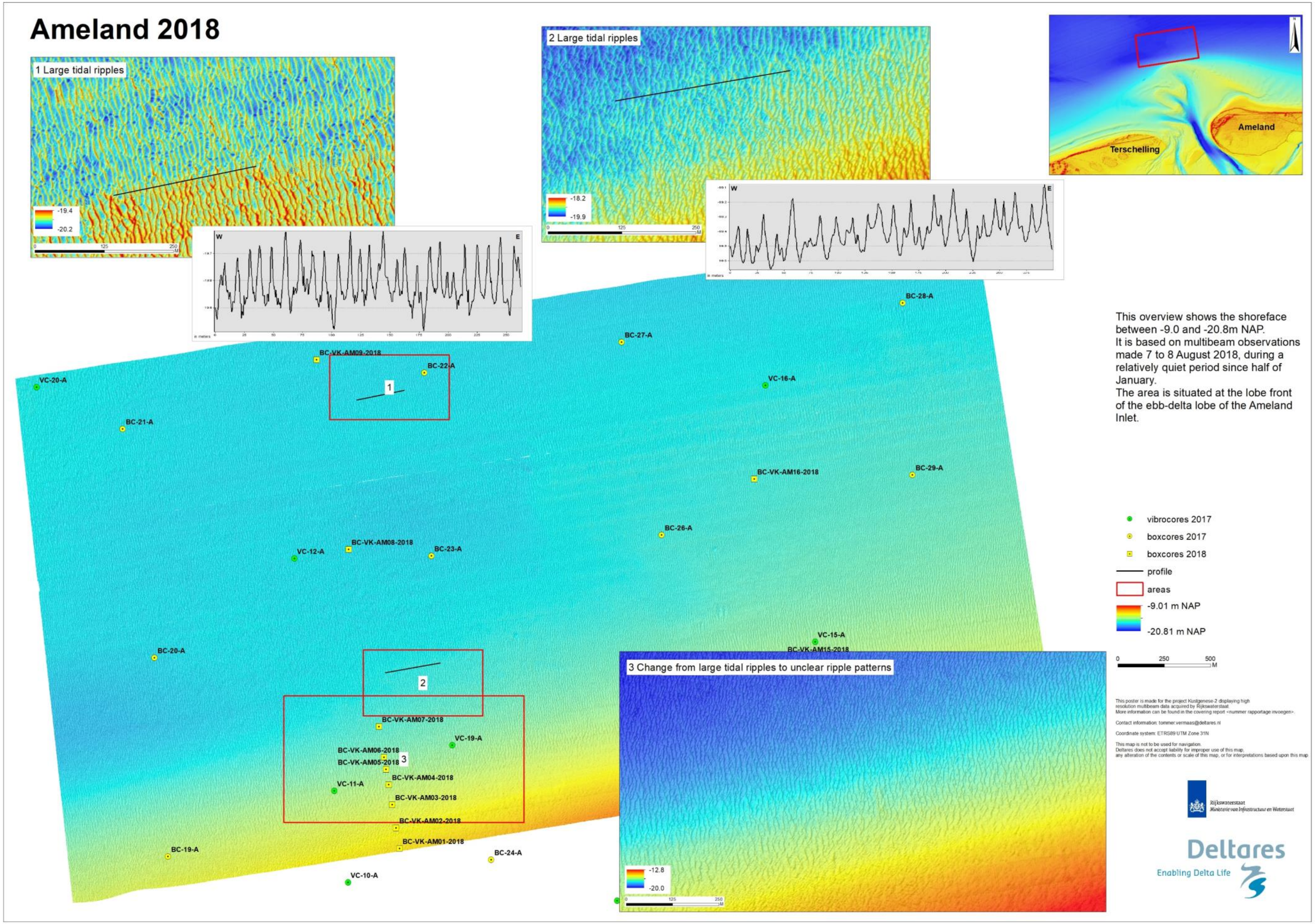


Multibeam Ameland Inlet 2017

Details:
1,2; large tidal megaripples (length ≤ 10 m; height ≤ 0.5 m)
3; change from regular ripples to irregular patterns

Multibeam Ameland Inlet 2018

- In 2018 the study area shows a similar pattern with small differences: the megaripples are less regular and slightly lower (length ≤ 10 m; height ≤ 0.3 m) and the ripples disappear around a depth of -15 m. In the south-eastern part of the study area the transition shows a different pattern: the megaripples become higher, their wave length increases and the pattern is interrupted by ripple-less (smooth?) spots (slides 32, 33). The change to a flat bed occurs over a short distance.
- The differences in megaripple pattern and dimensions were most likely caused by varying tidal currents since the grain-size ranges are similar. The upward shift of the boundary between the rippled and the non-rippled area can be contributed to milder wave conditions preceding the 2018 survey when compared with 2017 (see slide 48). During mild conditions, the lower and shorter waves reach less deep, so the zone of wave domination extends less far seawards.



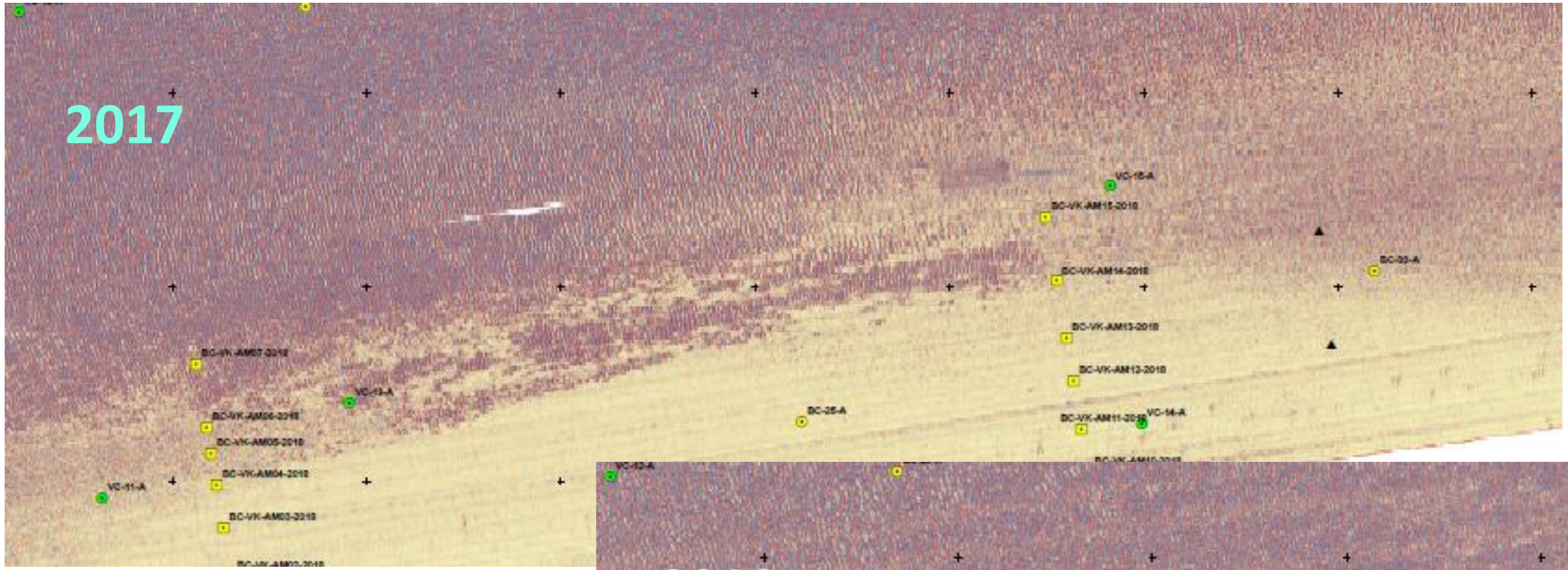
Multibeam Ameland Inlet 2018

<u>Details</u>:

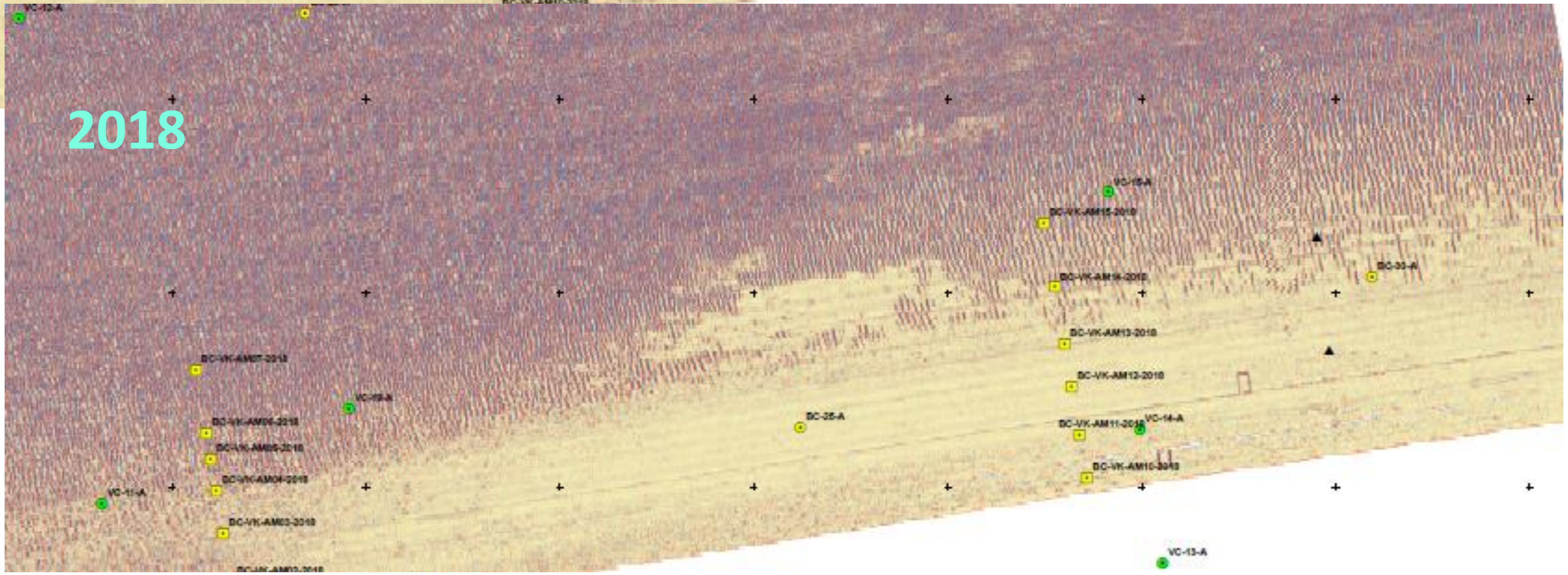
1,2; large tidal megaripples (length ≤ 10 m; height ≤ 0.4 m)

3; change from regular ripples to irregular patterns

Different ripple patterns Ameland Inlet 2017-2018

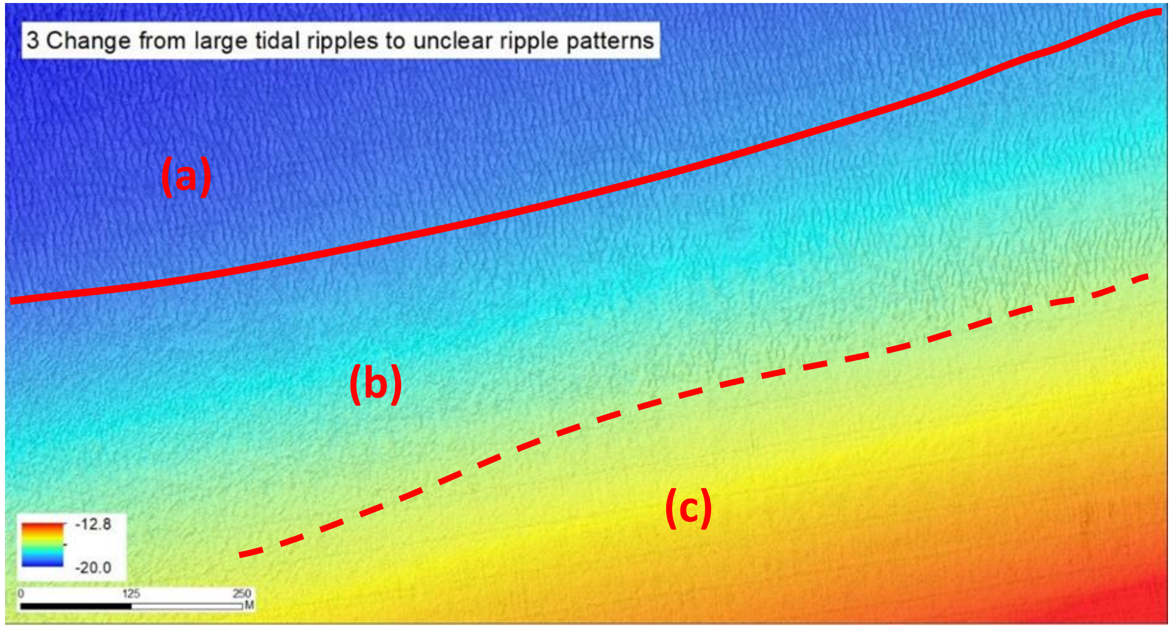


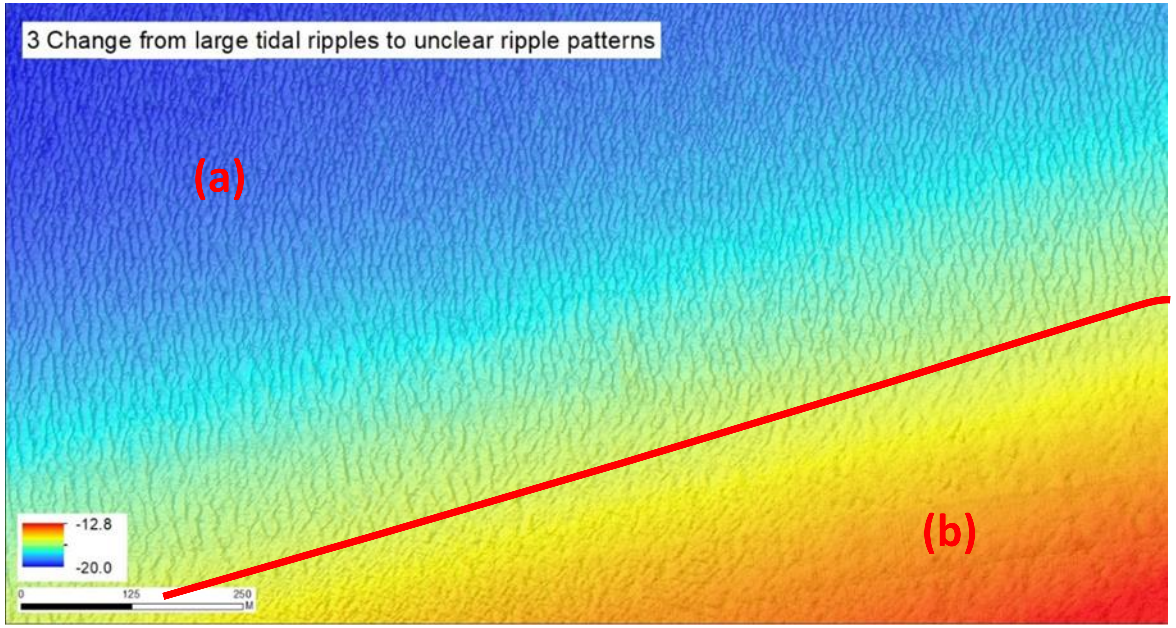
In 2017 the rippels became irregular when going in landward direction (to the bottom of the map). To the east they became smaller. Beyond -15 m they disappeared completely (white part map).



In 2018 the rippels became higher when going in landward direction (to the bottom of the map). In the east their spacing increased. Changes occur over a wider zone than in 2017.

Ameland Inlet shift transition 2D - 3D morphology





The depth of the transition from regular linear megaripples (a) to patchy, irregular 3D ripples (b) and finally a smooth seabed (c) varies with the wave climate. In 2017 (left), the transition occurred at -18 m, in 2018, during a quiet period, this occurred shallower (-15 m).

Multibeam Terschelling 2017

- In 2017, the Terschelling study area showed a gently sloping shoreface which grades into the North Sea bed between -18 m and -20 m. Megaripples at the seabed are small, occasionally irregular and their crests are oriented northnortheast-southsouthwest. The seaward part of the surveyed area shows less detail, possibly due to less favorable conditions during the survey.
- In the northwest corner of the area, deviant ripples are found. The ripples are higher and the troughs in between are deeper than in adjacent areas.
- At the shoreface at approximately -15 m, a distinct gully-like feature occurs that can be traced to the north-west into deeper water. The north-eastern side of the gully has a higher elevation than the south-western side (see slide 39 for details).
- Pockmarks (craters in the seabed) occur at the southwestern part of the shoreface at -15 m to -16 m depth.

Multibeam Terschelling 2017 - interpretation

- The grain-size distribution of the seabed sand offshore Terschelling is slightly coarser than that offshore Ameland Inlet (*c*. 230-300 µm vs. *c*. 215-230 µm respectively). However, this probably cannot explain the difference in megaripple dimensions. It is likely that the smaller ripples at Terschelling were caused by weaker tidal currents.
- The gully-like feature at the shoreface has not been reported before. It is likely caused by an erosion-resistant layer in the subsurface. Seismic profiles collected in the north-eastern part of the study area (Sha, 1989; Sha & De Boer, 1991) show series of stacked channel fills of mid to late Holocene age that were in part filled in with muddy sediments.
- It is likely that this gully acts as a conduit for seaward flows down the shoreface.
- Pockmarks are formed by gasses or fluids escaping from the subsurface. Since reservoirs of natural gas have been discovered at kilometer-depth underneath the island of Terschelling and the adjacent North Sea, the outflow of gas is the likely cause for pockmark formation.

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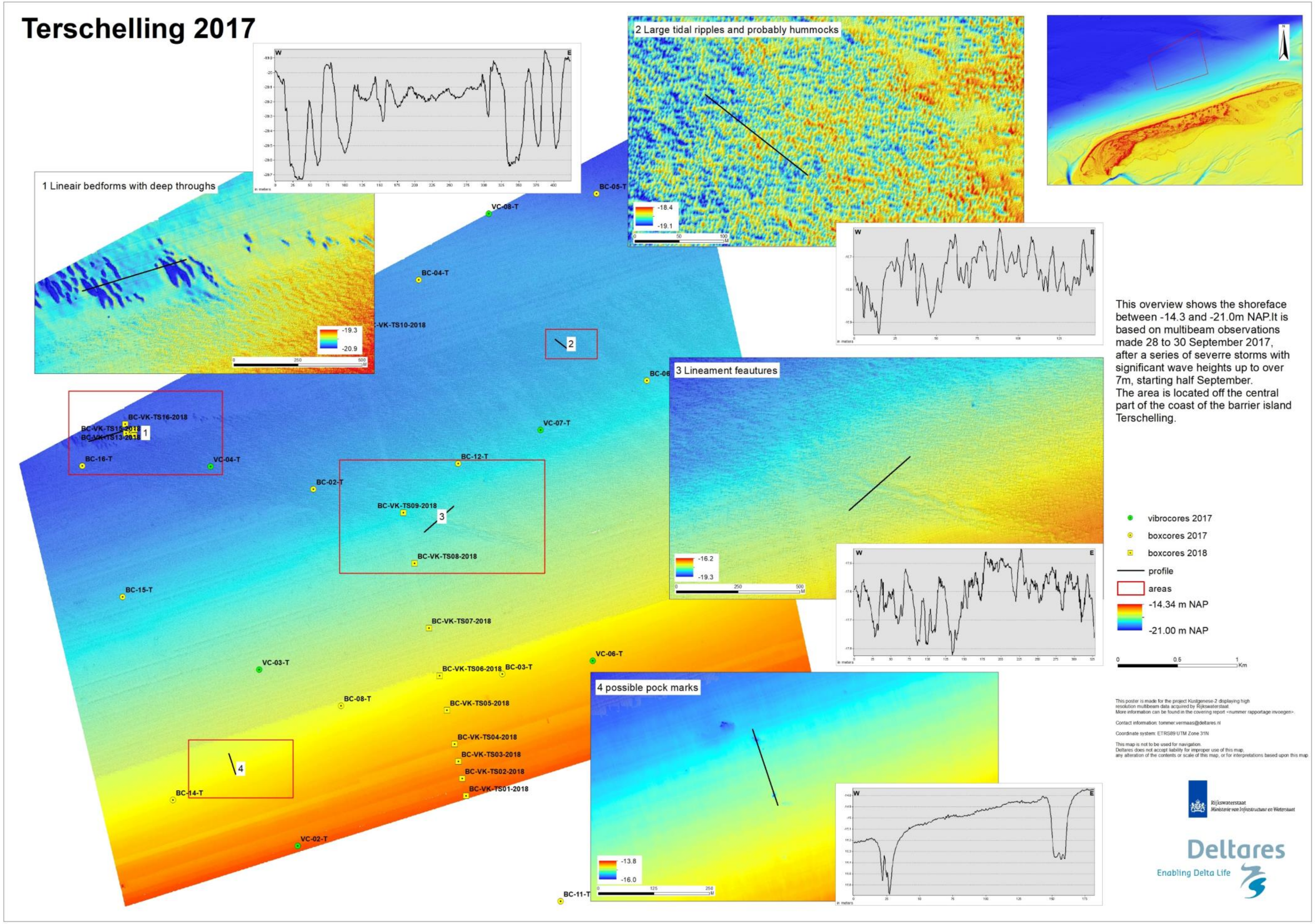


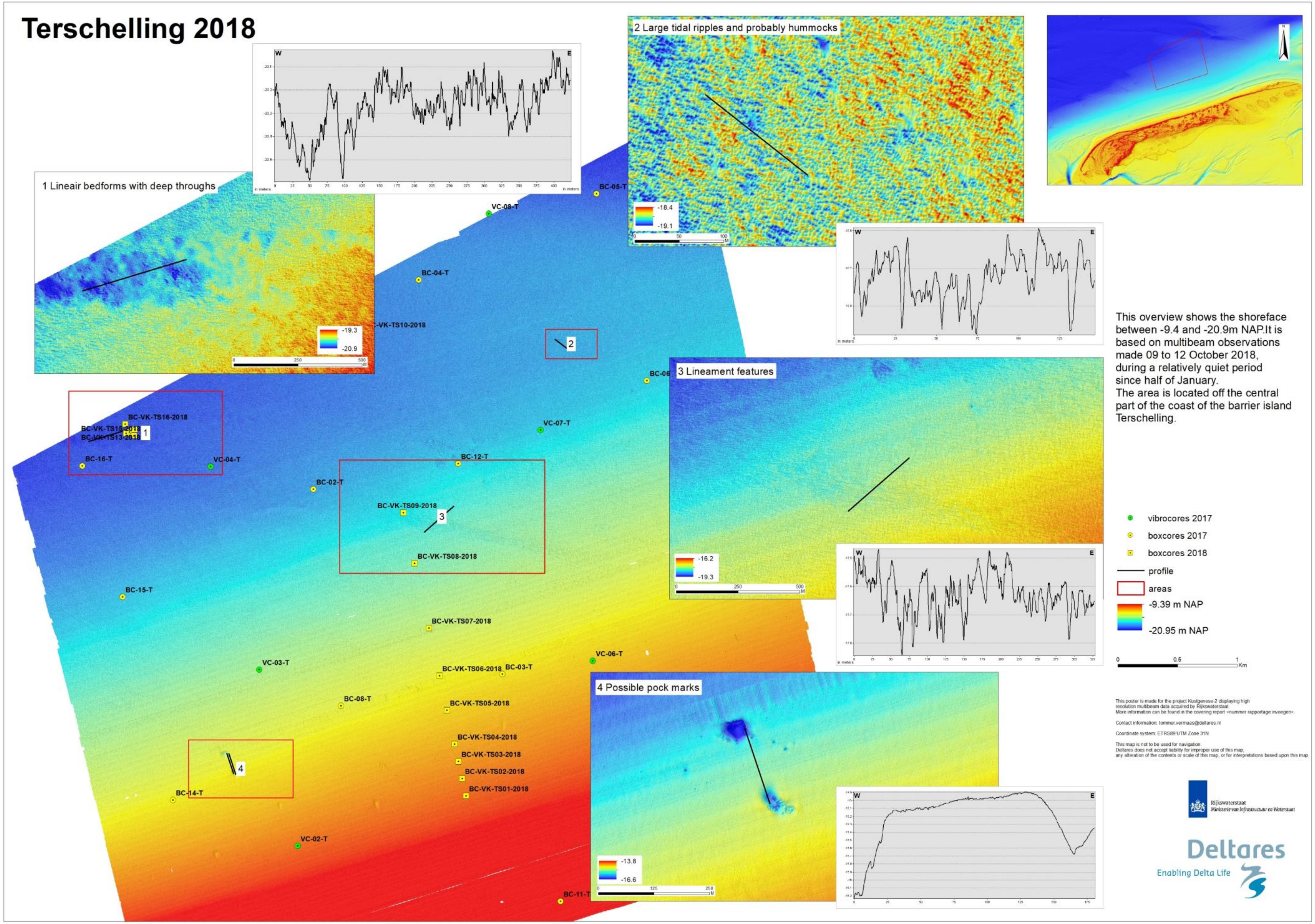
Multibeam Terschelling 2017

Details:

1; linear bedforms
2; large tidal megaripples
3; gully
4; pockmarks

Multibeam Terschelling 2018

- In 2018, the Terschelling study area showed a similar image as the 2017 survey.
- Meteorological and wave conditions were quiet during the survey and the preceding weeks (see slides 47, 48).
- Interestingly, the appearance of the gully was less prominent, possibly caused by deposition of sediments in and over it, which implies inactivity of the feature. On the contrary, both the number and size of the pockmarks had increased. The latter can be caused by reduced sand transport over the shoreface that would have (partially) filled in the craters formed by escaping gas.



Multibeam Terschelling 2018

<u>Details</u>:

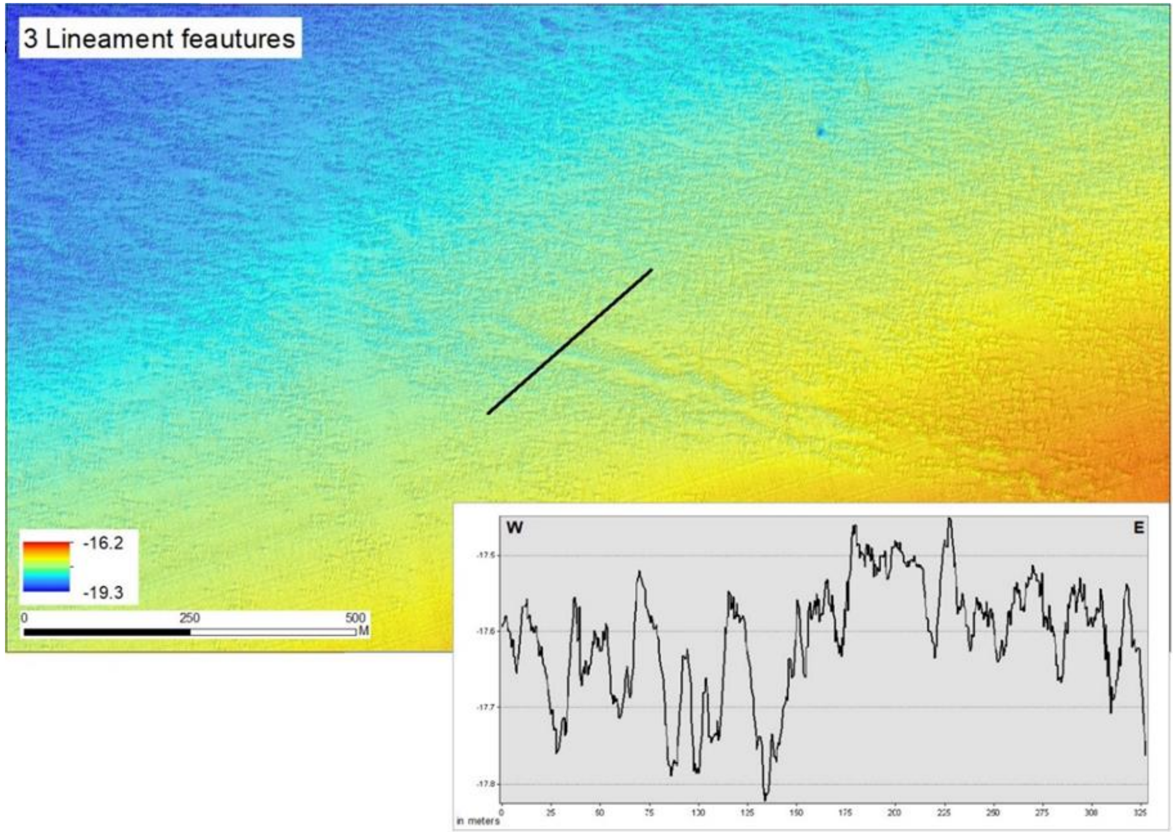
1; linear bedforms

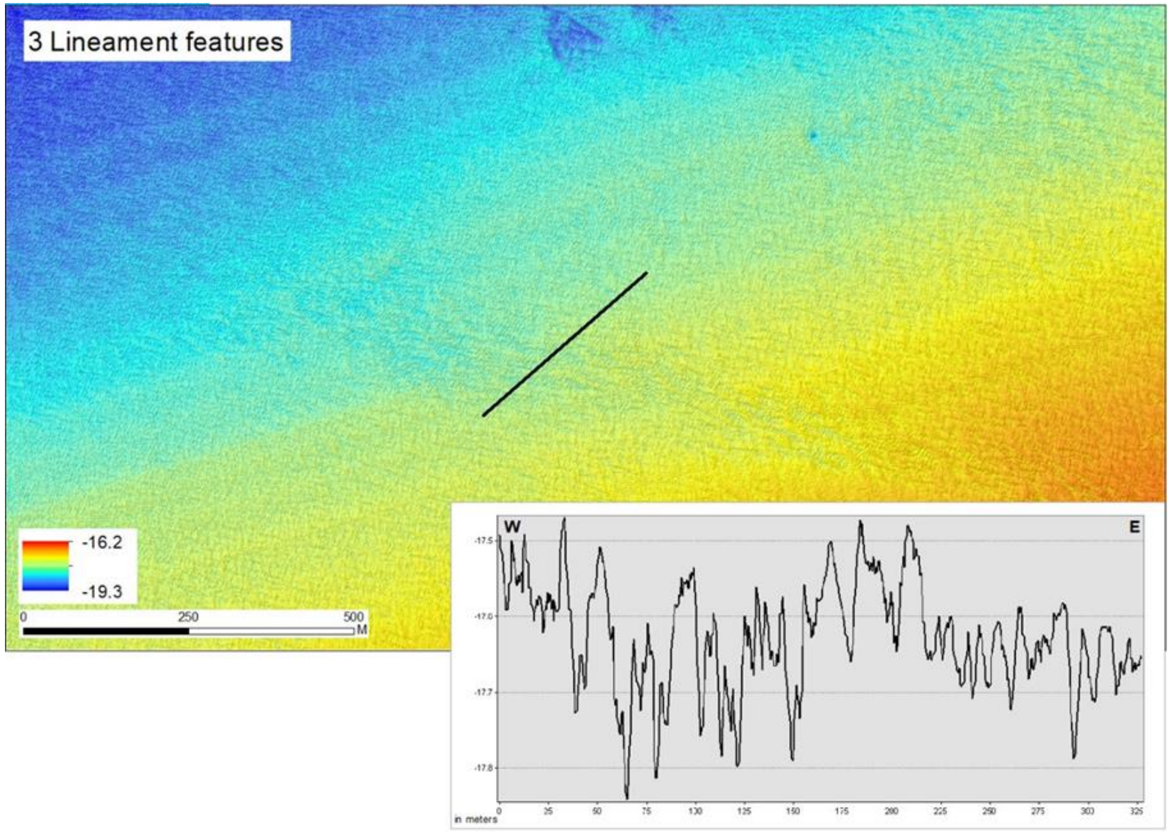
2; large tidal megaripples

3; gully

4; pockmarks

Terschelling – shoreface gully 2017, 2018





Gully found at the Terschelling shoreface between -15 m and -18 m. In 2018 (right panel) the gully was less distinct than in 2017, probably due to infilling with sand. The inset figures show cross-sections over the gully. This gully possibly guides seaward flowing currents over the shoreface.

Multibeam Noordwijk 2017

- The Noordwijk study area comprises several large-scale elements. Going seawards, the shoreface slopes down to -18 m after which the seabed comes up again to -16 m when crossing a shoreface-connected sand ridge. Going further seawards, depth increases slightly to -18 m when crossing a flat area that merges into a field of shore-normal oriented sand waves. Megaripples do not occur on the seabed at the toe of the shoreface.
- The shoreface shows a distinct spur-like extension to the southwest. Between the shoreface and the spur, a sinuous erosional path can be seen. Besides that, the shoreface shows typical small- and larger-scale depressions (0.2-0.4 m deep, tens of meters wide), especially at its southern half (see slide 46 for details). When the shoreface part of the multibeam data is detrended (which shows the deviations from the average cross-shore profile, see slide 43), it turns out that shore-normal features are encountered all along the shoreface between -11 m and -15 m.
- Additional features in the study area include a shipwreck at the toe of the shoreface at the northern boundary and parallel tracks that resemble cart tracks all over the area.

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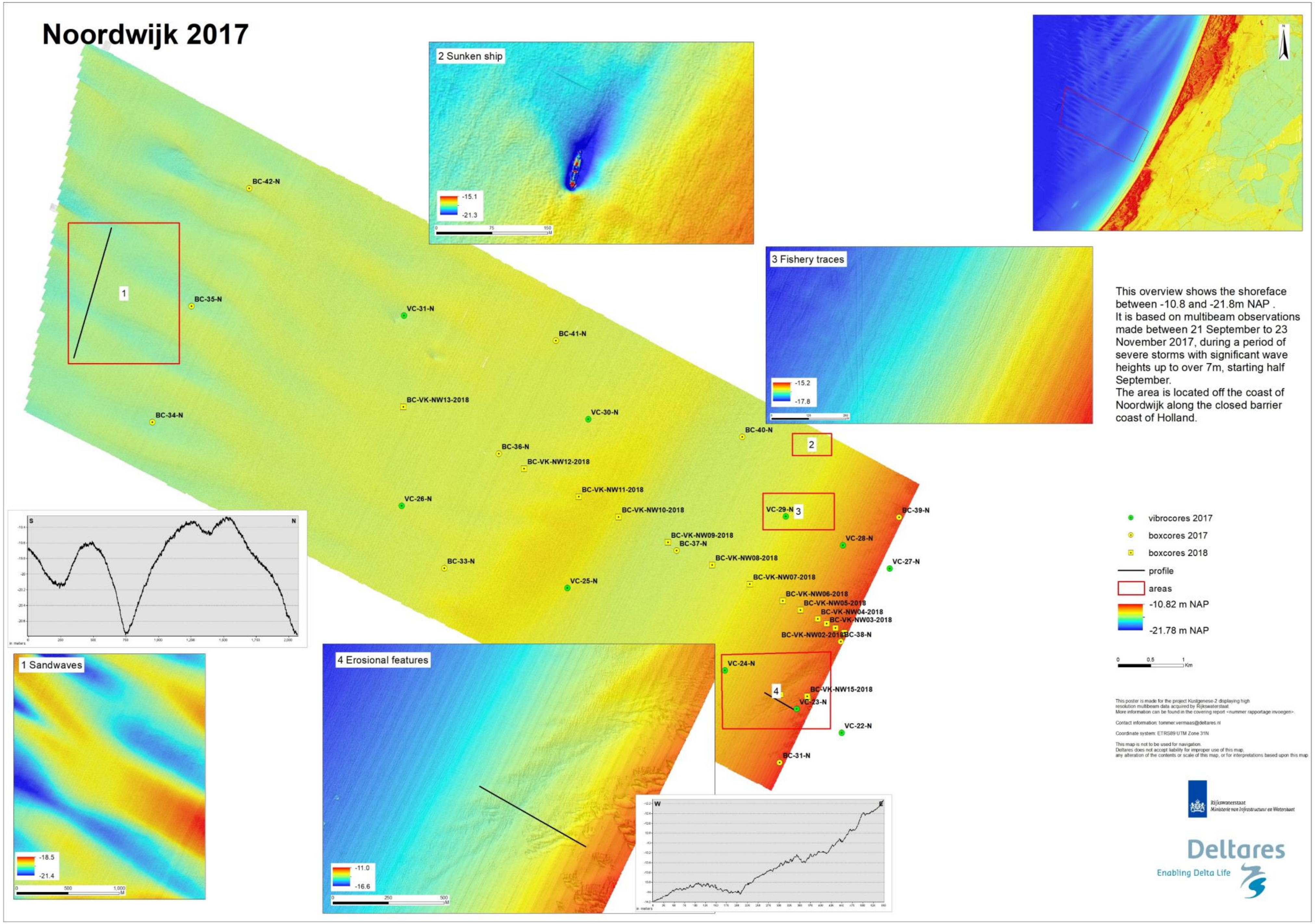
Multibeam Noordwijk 2017 - interpretation

- The shoreface-connected sand ridges are typical phenomena for the central part of the Holland coast. From south to north, four ridges are connected to the coast and more ridges are found further offshore (see the morphological map of the Holland coast; slide 24).
- It is unclear why megaripples are not formed in the shore-parallel trough between the shoreface and the sand ridge.
- The Noordwijk study area is situated at the location of the former mouth of the river Oude Rijn, the main distributary of the river Rhine that was active between *c*. 5000 and 800 years ago (slide 16). The fluvial deposits consist of clayey and loamy layers that are erosion resistant and can cause deviant morphodynamic behaviour.
- The mentioned spur is probably an outcrop of a clay or loam layer. Box coring of the small-scale shoreface depressions in 2018 showed the occurrence of compacted Holocene clays below a thin layer of sand (box cores NW14, NW15; slides 50, 52).
- Shore-normal trough-like features at the shoreface suggest downwelling currents, e.g. caused by undertow, that potentially will carry sand down the shoreface. These features have not been reported before!
- The parallel tracks at the sea-bed are made by fishermen using trawl nets.



Multibeam Noordwijk 2017

Details:

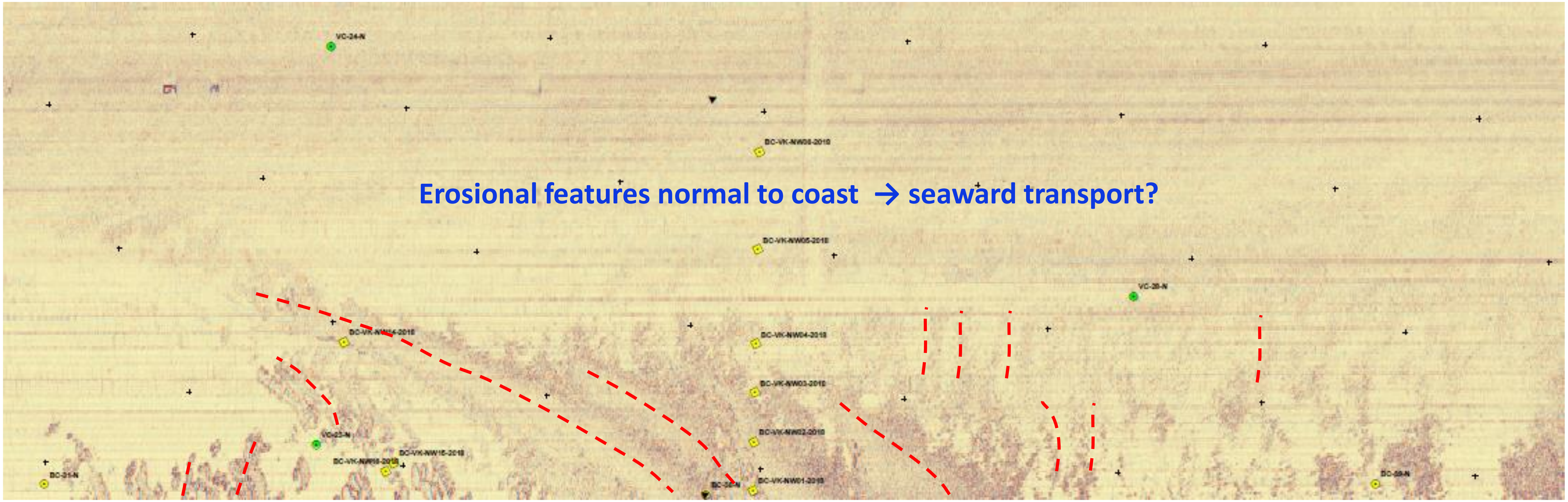
1; sand waves

2; shipwreck

3; trawling traces

4; erosional features

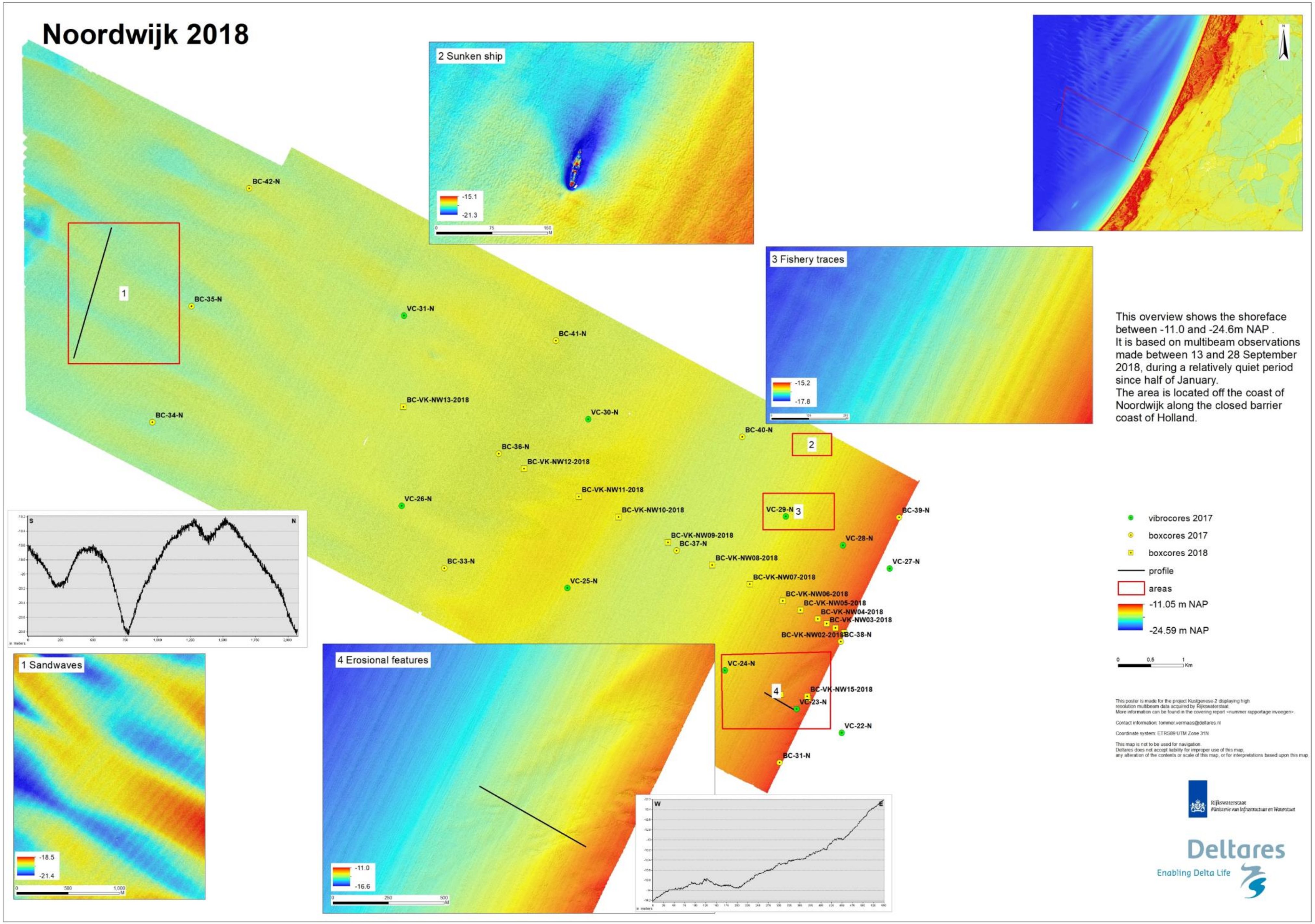
Shoreface Noordwijk 2017 – shore-normal depressions



Detail of the map in slide 42 (seaward is up); Erosional gullies running oblique and perpendicular to the coast, indicated by dashed lines. Note that not all features have been indicated with lines!

Multibeam Noordwijk 2018

- The 2018 multibeam survey shows an image comparable to the survey of the year before. The shore-normal trough-like features are less pronounced (0.05-0.4 m deep) and the sinuous erosional path between the spur and the shoreface is covered with sediment (see slide 45). The parallel tracks are more numerous, the wreck is still there.
- In 2018, the Noordwijk area was surveyed at the end of a quiet spell which can explain the contrast of the results with the 2017 survey that was interrupted by storms. The 2017 morphology shows shore-normal gullies which are much less distinct in 2018. The latter might be caused by sedimentation that fills in and levels out the gullies.



Multibeam Noordwijk 2018

Details:

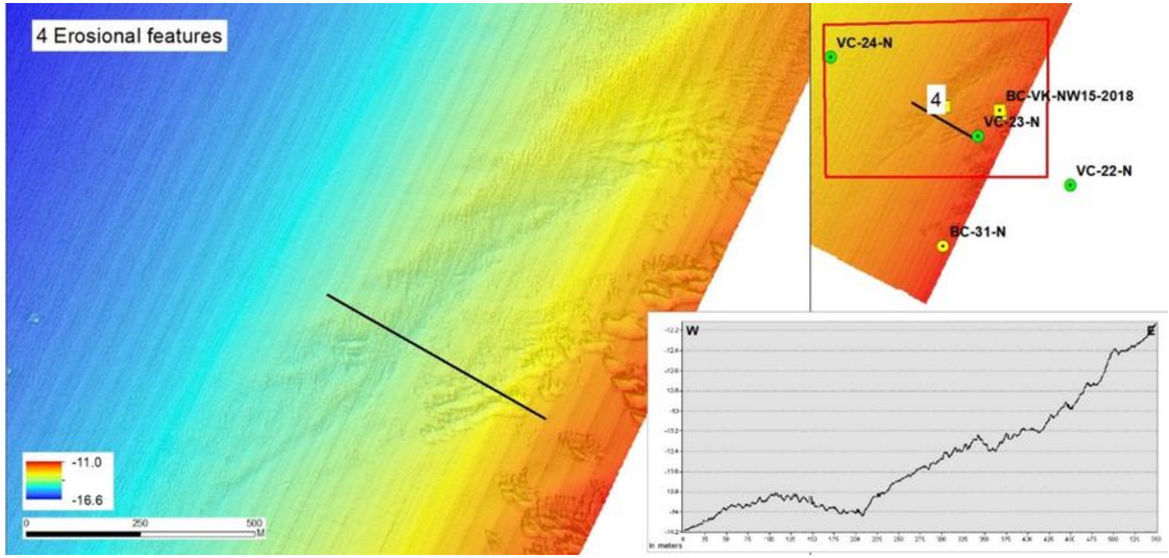
1; sand waves

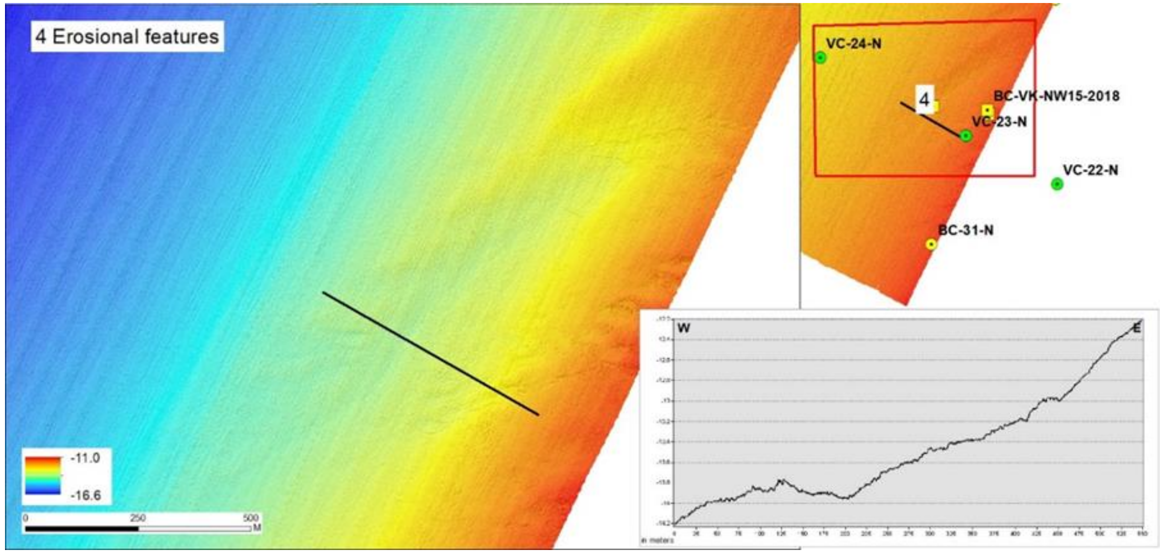
2; ship wreck

3; trawling traces

4; erosional features

Noordwijk – geology & erosion gullies





The spur-like extension and the ‘scars’ in the shoreface observed in 2017 (left panel) are less distinct in 2018 (right panel). Infilling with sand is the likely cause of the smoothing of the features.

Relationship between meteorological conditions and sea-bed morphology

Ameland Inlet

The 2017 survey shows a regular megaripple pattern. In 2018, conditions were calm during the survey, which resulted in a shift of the transition from current- to wave-dominated bedforms to shallower depth. The details of the megaripples were different too, which is likely caused by different tidal current velocities.

Terschelling

Both in 2017 and 2018 the conditions during surveying were calm after a preceding stormy period. In general, the resulting morphologies are comparable. It is possible that the observed morphologies were formed under these preceding conditions. However, in 2018 conditions were apparently less energetic what resulted in inactivity of erosional features and smoothing of the seabed relief.

Noordwijk

In 2017, the Noordwijk area was surveyed during a stormy period which caused serious delays. The shoreface showed clear erosional features. The 2018 survey met quiet conditions and the erosional features seemed not active. The were partly filled in with sand.

Relationship between meteorological conditions and sea-bed morphology

Study area	2017 survey	2018 survey
1. Ameland	5-7 September	7-8 August
weather conditions preceding survey	quiet months	quiet month, some events before
weather during survey	2 m waves	quiet
tidal ripples -19m -20m	present, linear	present, less regular, lower
tidal ripples -18m -19m	present, regular, smaller than in deeper water	present, less regular, higher than in deeper water
transition tidal to combined flow	boundary at -18m; change into flat bed at -16m	boundary at -15m
2. Terschelling	28-30 November-12 December	9-12 October
weather conditions preceding survey	2 stormy months	incomplete data, small-scale storm some weeks before survey
weather during survey	end of November quiet, increasing wave heigths thereafter	quiet
linear erosional bedforms -19m -21m	clearly present	less clearly present; overall image comparable
ripples (?) -18m -19m	irregular, no lineare rippels	comparable
erosional gullies -16m -19m	starting shallower than -17m, deposition c. -18m	less clearly present
pockmarks	some, at -15m to -16m	increased in size and number, no infilling
3. Noordwijk	21, 25-26 September/19-20, 23-24 October/13-16, 20-23 November	13-28 September
weather conditions preceding survey	storm 2 weeks before survey	September relatively quiet, small storm in June
weather during survey	interrupted by strong gales	started quiet, increasing waves turbulence from halfway
sand waves -18m -21m	present	no change
erosional gullies -11m -14m	from less than -11m to -15m	relief partly erased

5. Lower shoreface sediments

- Shoreface sediments have been sampled with box corers for analysis of sedimentary structures and grain-size distributions (see slides 11-13 for locations).
- In 2017, 42 stations arranged in transects normal to the coastline were cored with a cylindrical ‘box’ that does not allow for in-situ sediment observations. Hence, each core was sampled by pushing 3 pvc tubes (0.1 m diameter) into the sediment. Unfortunately, the quality of these sub-cores was poor, so no information on sedimentary structures could be retrieved.
- In 2018, a new series of 48 closely-spaced box cores was collected along one (Terschelling, Noordwijk) or two (Amelander Zeegat) coast-normal transects. These stations were sampled using rectangular boxes with a detachable side. The retrieved sediment sequence is shown after removal of the side plate and can be studied, photographed or lacquered, see slide 50. The latter action produces a cast of the sediment surface that enables the study of sedimentary structures in detail (slide 52). In total 33 box cores have been lacquered.
- See Oost et al. (2019a) for more information on box cores and grain sizes.

Box cores 2018

Box cores collected in 2018. Box core TS16 (Terschelling area; left panel) shows a coarse-grained shell layer. Box core NW14 (Noordwijk area; middle panel) shows a sand layer overlying a stiff blue-grey clay. Box core AM13 (Ameland Inlet area; right panel) shows a layer of brown, oxygenated sand on top of dark grey sand that is poor in oxygen. Directly left of the yellow label sits a razor clam that has dug itself in, probably in reaction to the penetration of the corer into the sea bed and its subsequent extraction.

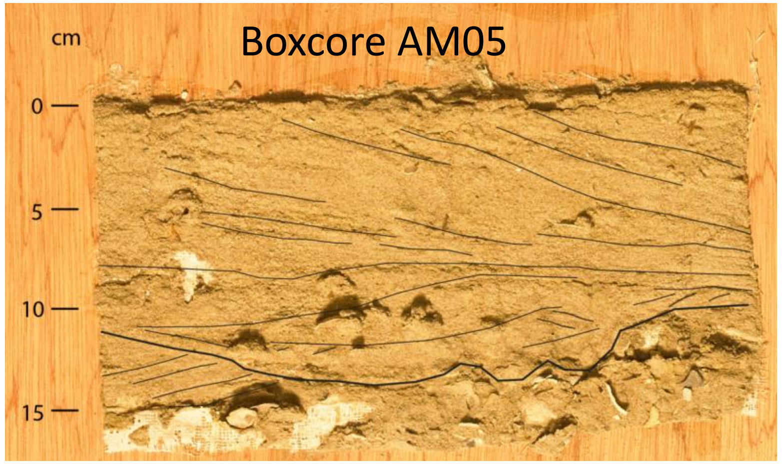
Sedimentary structures

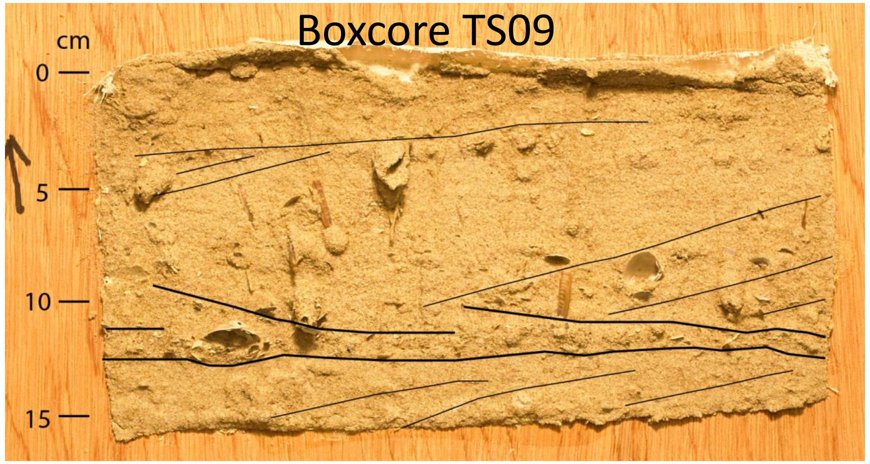
- Transport processes create typical structures in the deposited sediments. For instance, the orbital motion of waves and the migration of ripples under a uni-directional current produce specific but very different structures. Sedimentologists study these structures to reconstruct these forming processes. Burrowing animals tend to mix sediments and destroy sedimentary structures. The variation in sedimentary structures illustrates the variability in seabed processes in the study areas.

- The lacquer peels of the 2018 box cores show tabular cross-bedding, the product of migrating ripples, and a more ’swaley’ type of bedding that is formed by combination of a uni-directional current interacting with waves (see slide 52, boxcore NW01, lower and upper layer respectively). In some boxes, these structures are capped by a layer of homogeneous sand, often containing the molluscs that destroyed the structures by burrowing (e.g., core AM13).

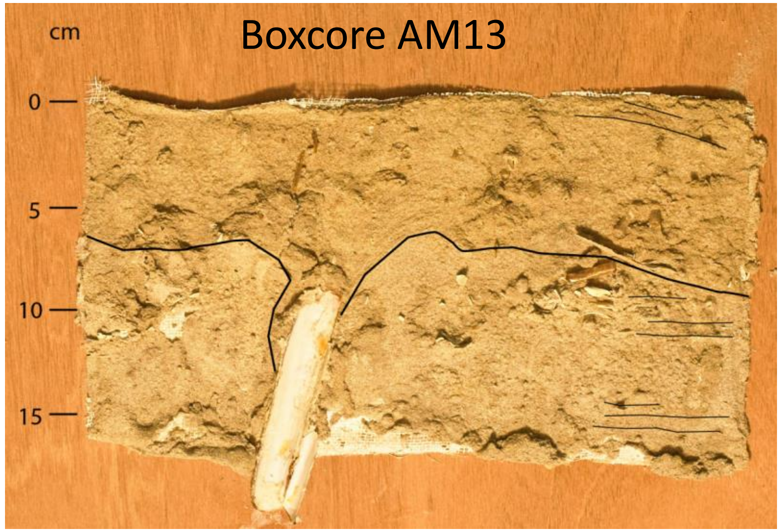
- The most abundant burrower is the ‘sea potato’ (*Echinocardium cordatum*), a sea urchin that migrates laterally through the sediment and thus erases the sedimentary structures (see photo right; grey-black circles).

Lacquer peels box cores 2018





Boxcore NW01



Boxcore TS14

Boxcore NW15

Grain-size distributions study areas

The **Ameland Inlet** study area can be divided into:

a. The offshore seabed with megaripples below -18 m that has a very small grain-size range (215-230 µm) and very low mud percentages (0-3%); and

b. The seaward slope of the ebb-tidal delta that shows a larger range (180-250 µm) and where the median grain size d_{50} in general increases with depth. The slope has higher mud percentages, especially in its eastern part.

The **Terschelling** study area shows:

a. Coarse offshore sea-bed sediments (230-300 µm) below -17 m and

b. Finer-grained shoreface sand (200-240 µm). In 2017 grain sizes increased with depth, in 2018 they did not.

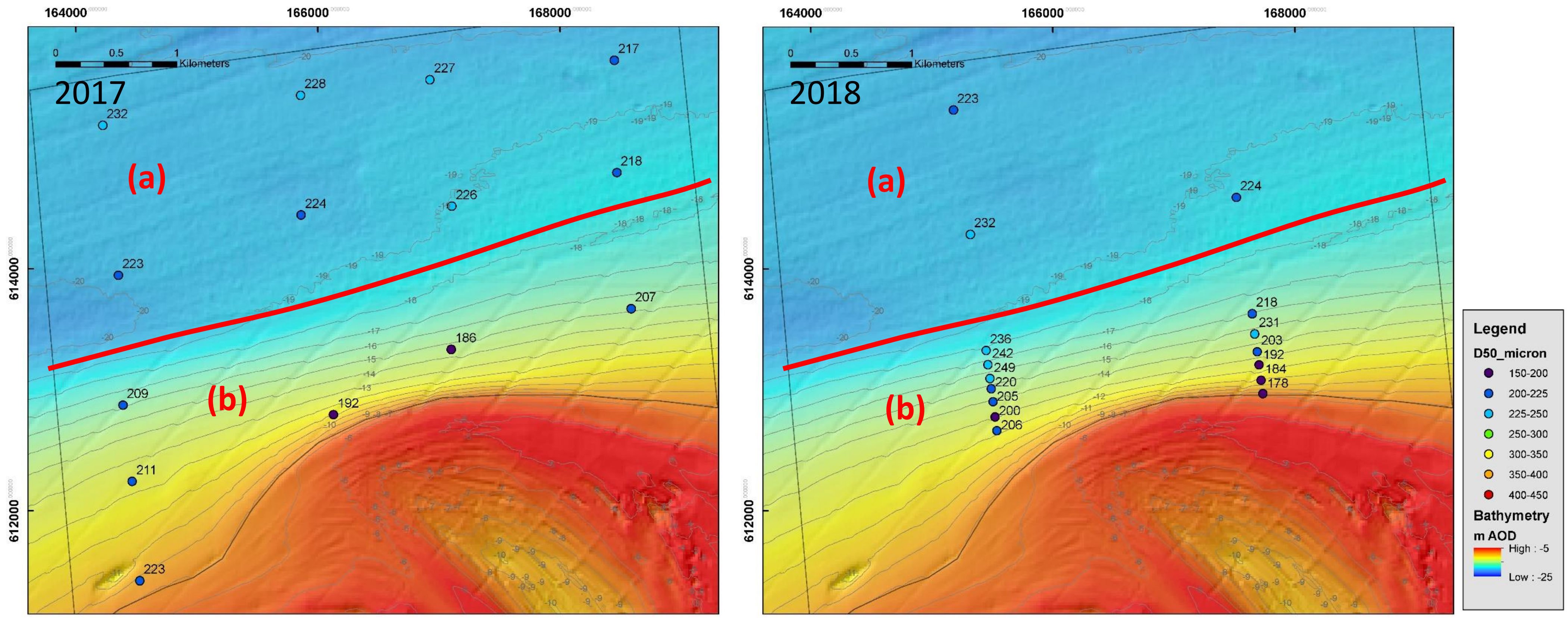
This area lacks mud in the seabed sediments.

Noordwijk: Grain sizes along the Holland coast are in general coarser than along the Wadden coast.

a. The offshore seabed is coarse-grained (330-415 µm) and usually lacks mud.

b. The shoreface sediments are finer grained (230-325 µm) and show no trend with depth. The coarsest sediments occur in the central transect at -11m/-12m depth. Mud percentages vary with depth.

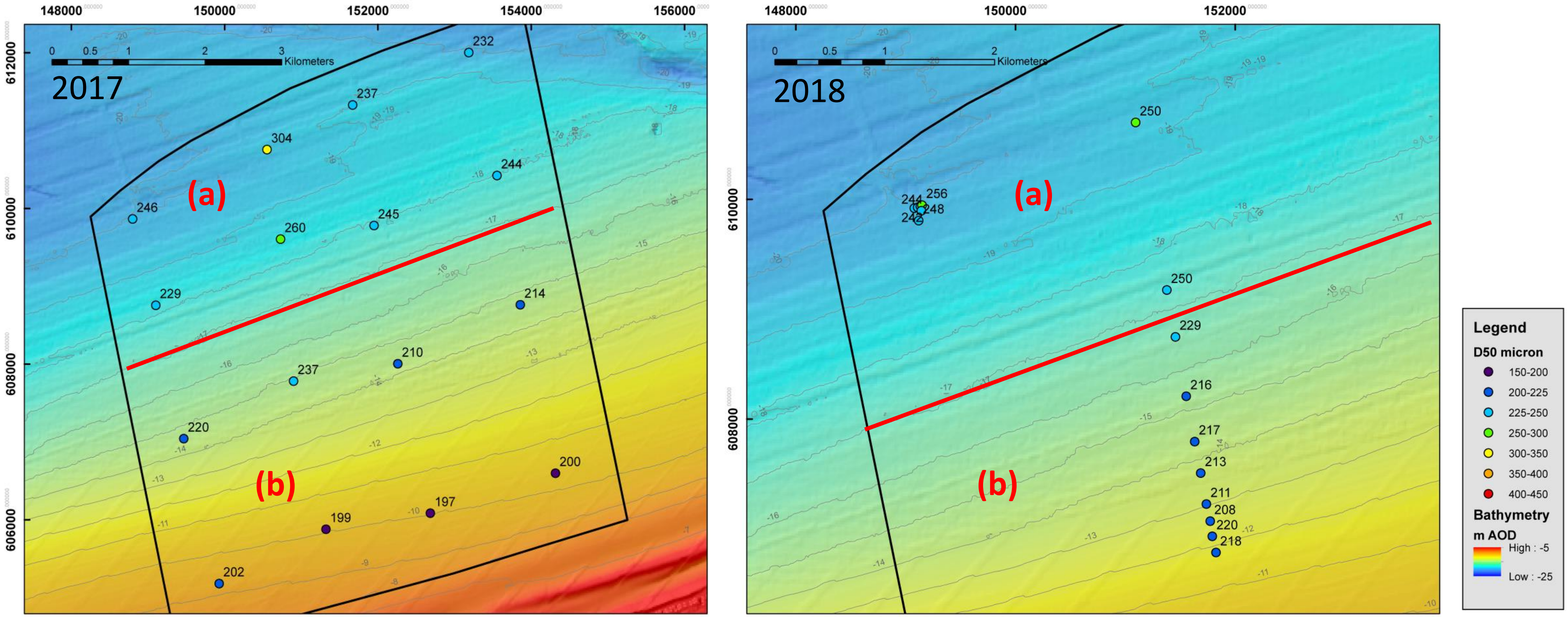
Median grain sizes Ameland Inlet study area



(a) offshore seabed; d_{50} **2017**: 217-232 µm; **2018**: 223-232 µm; **mud**: 0-3%

(b) seaward slope ebb-tidal delta; d_{50} **2017**: 186-223 µm; **2018**: 178-249 µm; **mud**: 2017: ≤17%; 2018: ≤7%

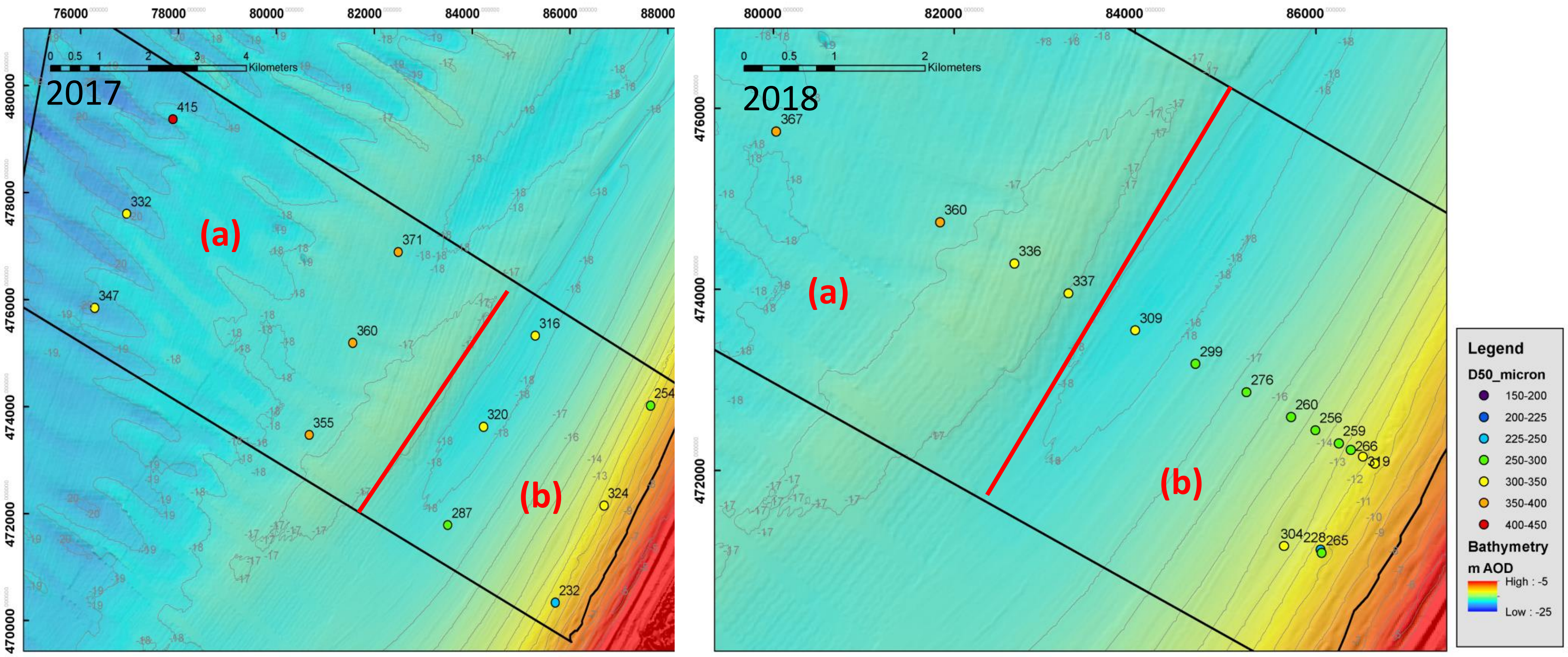
Median grain sizes Terschelling study area



(a) offshore seabed; $\mathbf{d_{50}}$ **2017**: 229-304 µm; **2018**: 230-256 µm; no **mud**

(b) shoreface; $\mathbf{d_{50}}$ **2017**: 197-237 µm; **2018**: 208-229 µm; no **mud**

Median grain sizes Noordwijk study area



(a) offshore seabed; **d_{50} 2017**: 332-415 µm; **2018**: 336-367 µm; no **mud**

(b) shoreface; **d_{50} 2017**: 232-324 µm; **2018**: 228-319 µm; **mud**: 2017: ≤7%; 2018: 2-12%

6. Shoreface processes and sand transport

- Both field observations and numerical modelling are used to highlight processes, such as tidal and residual flows and waves, and sand transport in the lower shoreface.
- Observations usually give an accurate picture of processes but are by definition limited in time and space. Models, on the other hand, generate a more complete temporal and spatial coverage but they are schematization of reality. However, models facilitate scenario studies, e.g., to assess the effects of a single storm.
- All field data were collected during the KG2 field campaigns in 2017 and 2018.
- A detailed hydrodynamic and sand transport model of the Dutch lower shoreface was built as part of the KG2 programme. It is based on the three-dimensional flexible-mesh Dutch Continental Shelf Model. The field measurements were used to validate the Delft3D numerical model.
- The following slides address tidal velocities, residual flows, wave heights, orbital velocities, small-scale bedforms and net sand transport.
- *For detailed information on the modelling, see Grasmeijer et al. (2019). For more information on KG2 field observations, see Van der Werf et al. (2019) and Schrijvershof et al. (2019).*

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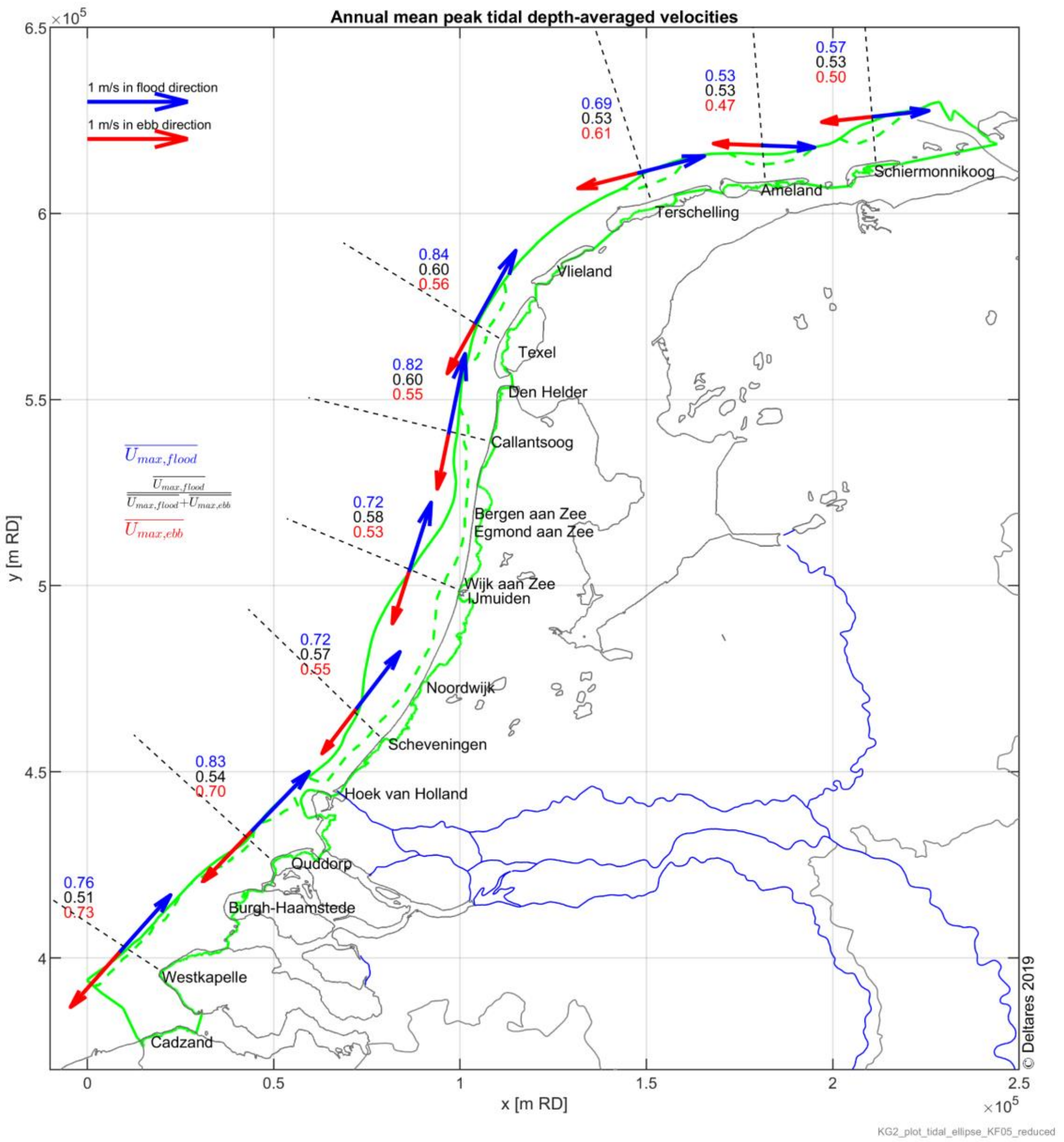
Peak tidal velocities at 20m depth contour



- These results are based on simulations with the KG2 lower shoreface model over the years 2013-2017. They show the mean of all depth-averaged peak flood and peak ebb velocities. The model performs generally well, but underpredicts the currents under high-wave conditions (not shown here).

✓ The largest mean peak flood velocity (0.84 m/s; blue vectors) is observed near Texel and decreases towards Schiermonnikoog.

✓ The largest mean peak ebb velocity (0.73 m/s; red vectors) is observed near Westkapelle and decreases towards the north-east.

✓ As a result: the tidal velocity asymmetry (black numbers) increases towards Texel and decreases towards Schiermonnikoog.

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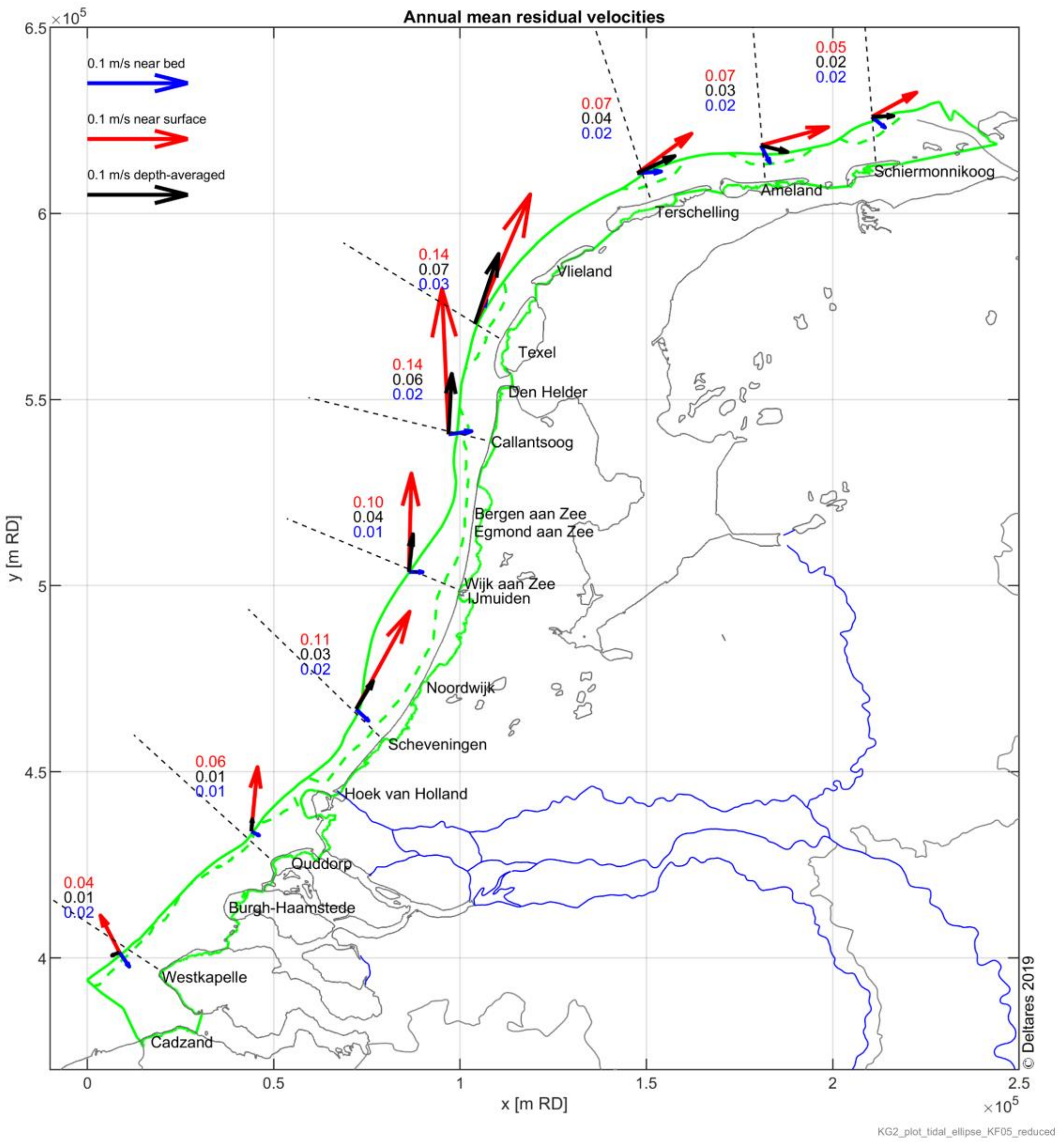
Simulated residual flow velocities at 20m depth contour



- These results are based on simulations with the KG2 lower shoreface model over the years 2013-2017, with real-time tidal and meteorological forcing and fresh water discharges (including salinity).

✓ The depth-averaged residual flow (black vectors) increases from 0.01 m/s near Zeeland to 0.07 m/s near Texel and decreases again to 0.02 m/s near Schiermonnikoog.

✓ The near-surface residual flows (red vectors) are more alongshore-directed with sometimes an offshore tendency.

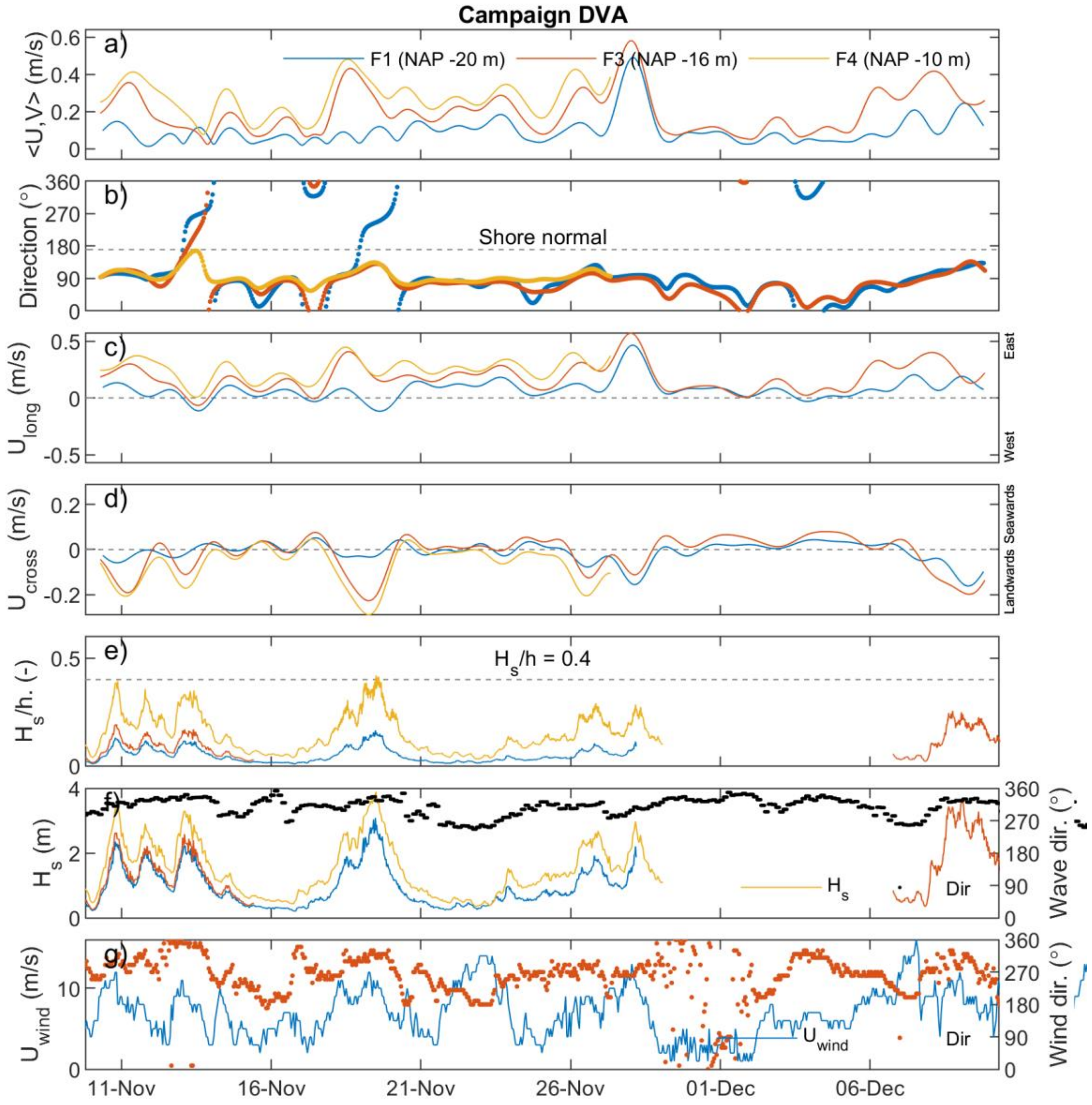
✓ The near-bed residual flows (blue vectors) show an onshore-directed tendency and are 0.01 to 0.02 m/s strong. Near Texel and Terschelling, this flow is shore-parallel.

Measured variation in residual flows

- These observations are based on depth-averaged and low-pass filtered Acoustic Doppler Current Profiler (ADCP) measurements at 20, 16/14 and 12/10 m water depth in the study areas. The following general statements can be made;

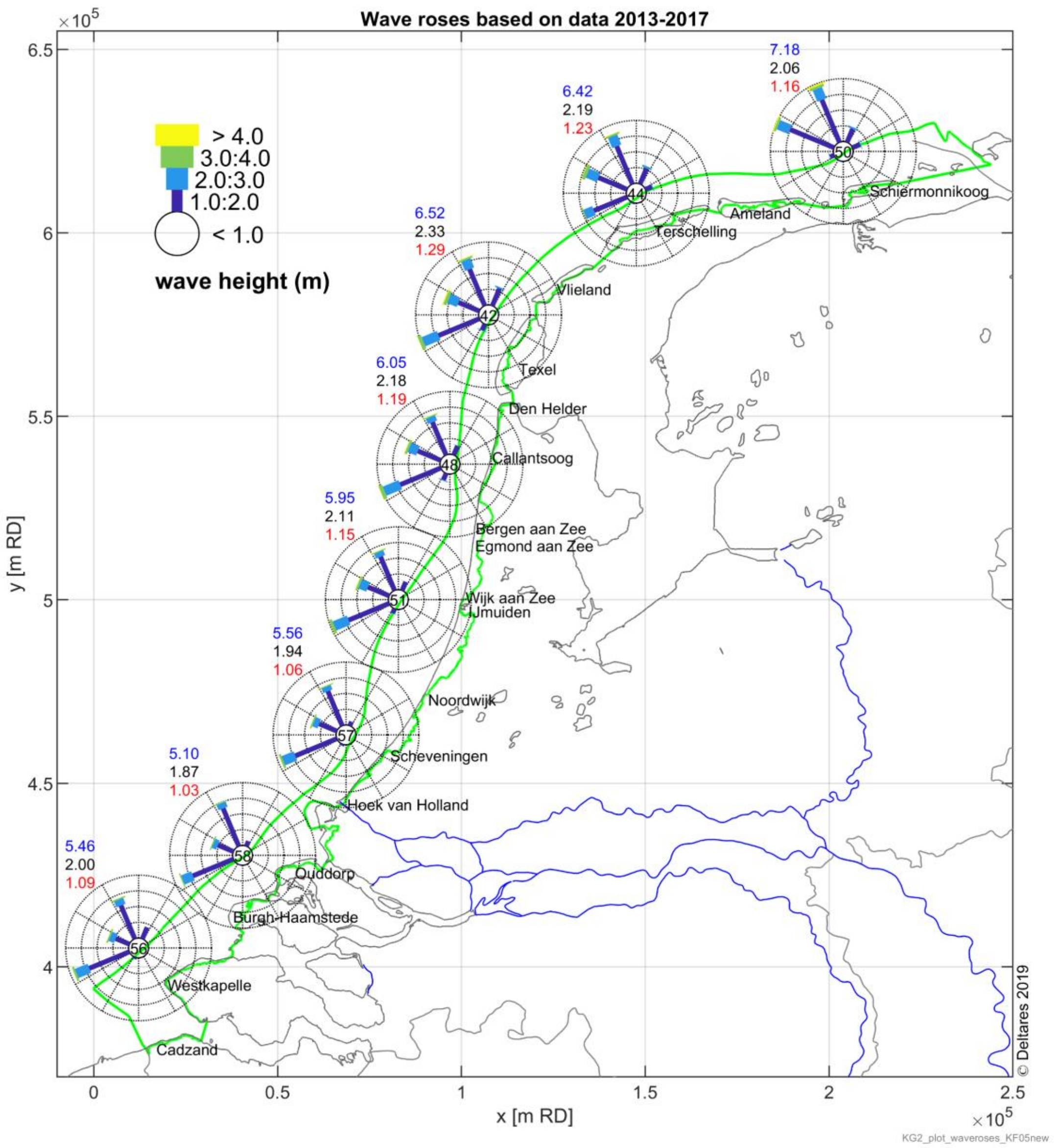
- Under mild conditions, residual flows are small.
- Residual flows increase in strength with decreasing water depth.
- Longshore residual flows (Ulong) are larger than cross-shore residual flows (Ucross).
- The direction of the residual flow depends on location and wave conditions and varies between places.

Effect of storm events on residual flow



- ✓ At Ameland Inlet (diagram), residual flows are typically eastward or seaward under mild conditions. During storm conditions (e.g., 20 Nov 2017; 4 m waves from NW), we observe an increased eastward or a landward residual flow.
- ✓ During the easterly storm with waves from north-east on 18 March 2018 at Terschelling, the residual flow was landward and westward.
- ✓ In the Noordwijk study area, the residual flow at -20 m does not show a strong response to the energetic event on 1 May 2018. Note that the frame at -20 m was located seaward of the second shoreface-connected ridge (see slide 13). Unfortunately, we have no data from the shallower frames during this event.

Wave climate at 20m depth contour



- The wave climate information is based on wave buoy measurements over the years 2013-2017 . These observations have been translated to the -20m contour for the entire Dutch coast using a wave transformation matrix. This method has been validated using wave data at Noordwijk and Ameland Inlet.

✓ The mean significant wave height Hm0 (red numbers) increases from about 1.1 m near Zeeland to about 1.3 m near Texel.

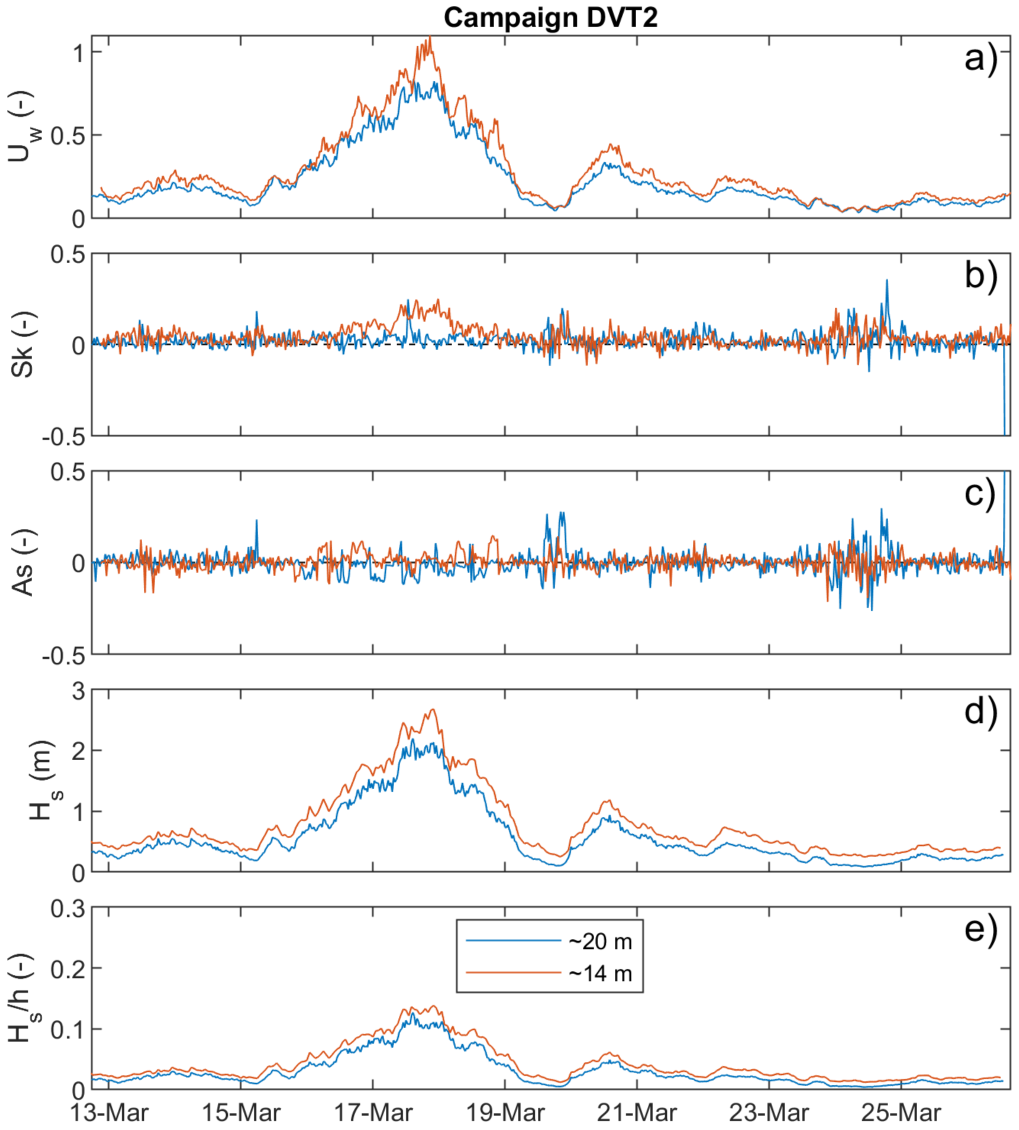
✓ In Zeeland, the significant wave height Hm0 was larger than 2.0 m during 10% of the observation interval (black numbers). Near Texel, this value is about 2.3 m.

✓ The maximum wave height (blue numbers) increases from about 5.5 m near Zeeland to about 7 m near Schiermonnikoog.

Measured orbital velocities

- Orbital velocities under waves were measured at the lower shoreface in the study areas using an Acoustic Doppler Velocimeter (ADV) at 20 m and 16/14/12 m water depth.
- The velocity skewness Sk is generally positive, which means that higher velocities occur in the direction of wave advance. This indicates a potential for wave-driven sand transport in landward direction.
- Orbital velocities increase with decreasing water depth.

Measured orbital velocities under high waves



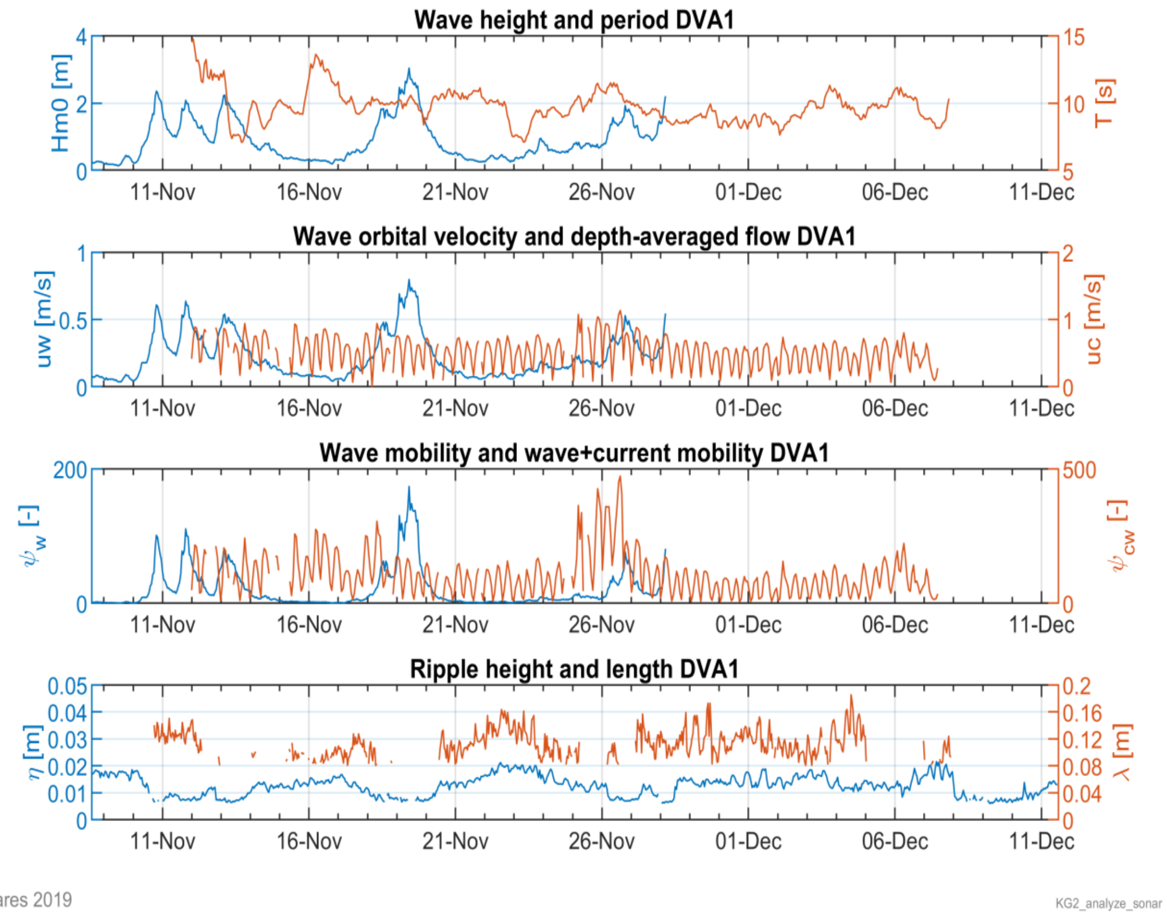
- The orbital velocity amplitude U_w exceeds 1 m/s (!) during high wave events at Ameland Inlet (e.g., 9 December; significant wave height Hs at -16 m c. 4 m). This indicates *high sediment mobility* under sheet-flow conditions at the seabed.

- At Terschelling (diagram), the orbital velocity amplitude U_w exceeds 1 m/s during high wave events (e.g., 18 March; significant wave height H_s at -14 m c. 2.5 m). This indicates high sediment mobility under sheet-flow conditions at the seabed.

- At the Noordwijk shoreface at -12 m , the orbital velocity amplitude U_w is about 0.1 m/s during calm conditions and goes up to 0.6 m/s under higher wave energy (5 April; significant wave height Hs c. 1.5 m). Unfortunately, there was no data recorded during the highest wave event on 1 May 2018.

Observed small-scale bedforms at the seabed

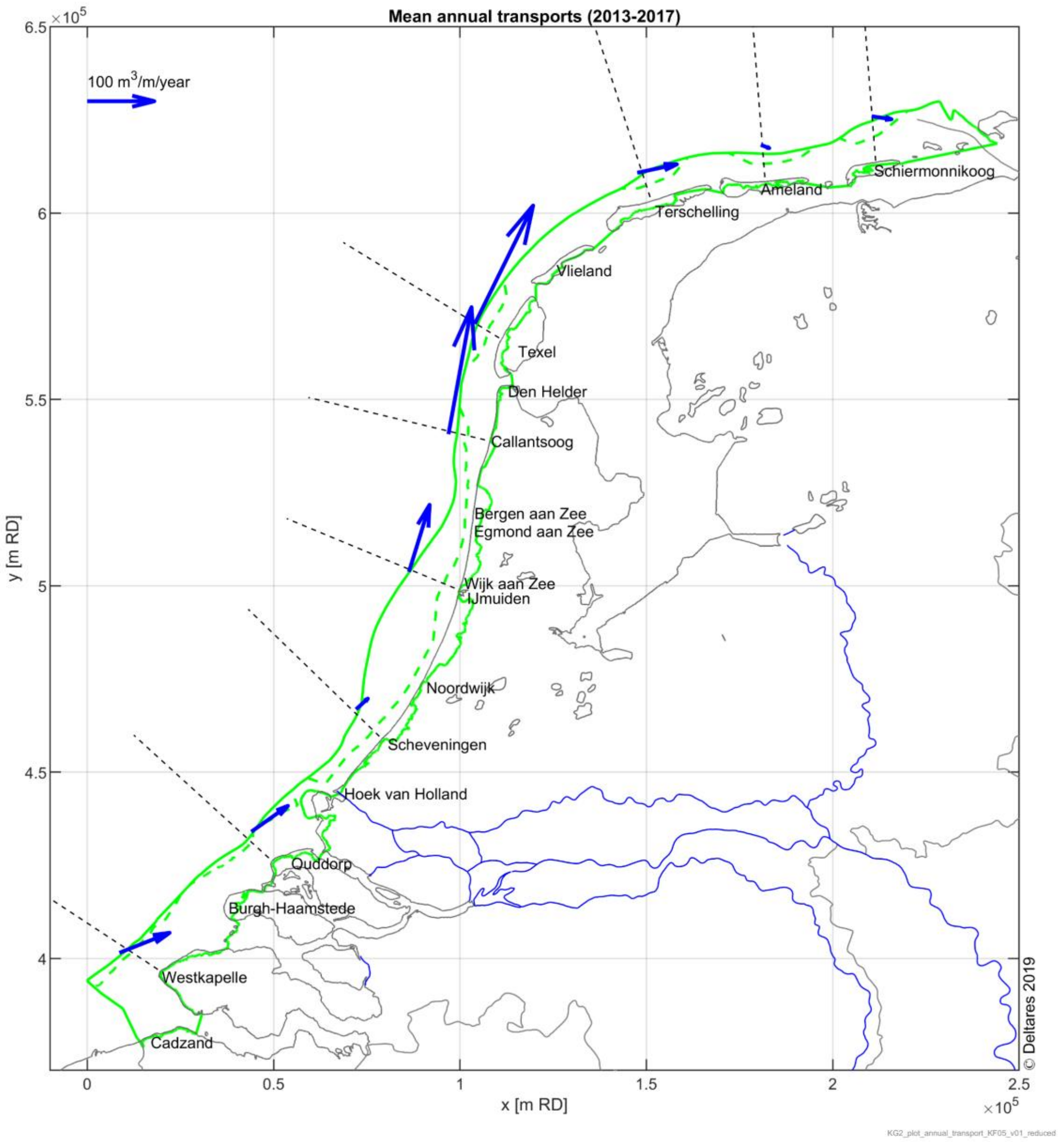
20m water depth



The dimensions of ripples at the seabed were measured with a frame-mounted sonar.

- Ripple dimensions mainly respond to variations in waves, not so much to variations in currents.
- At 20m waterdepth, ripple height (η) ranged between 0.01 m and 0.03 m. Ripple length (λ) ranged between 0.08 m and 0.20 m.
- During high-wave events, ripples were smaller and shorter (see, e.g., Ameland Inlet (diagram); 19 November 2017).
- At -20 m in the Noordwijk study area, ripple dimensions hardly varied under relatively calm conditions.
- At 10m water depth, ripples are a bit shorter than at 20 m. During storm events, ripples were absent or not measurable.

Mean annual sand transport at 20m depth contour



- These calculated transports are based on simulations with the KG2 lower shoreface model over the years 2013-2017, using a wave transformation matrix and the 1DV Van Rijn 2007 transport model (D_{50} = 250 µm; incl. pores).

✓ The largest transport occurs between Callantsoog and Texel.

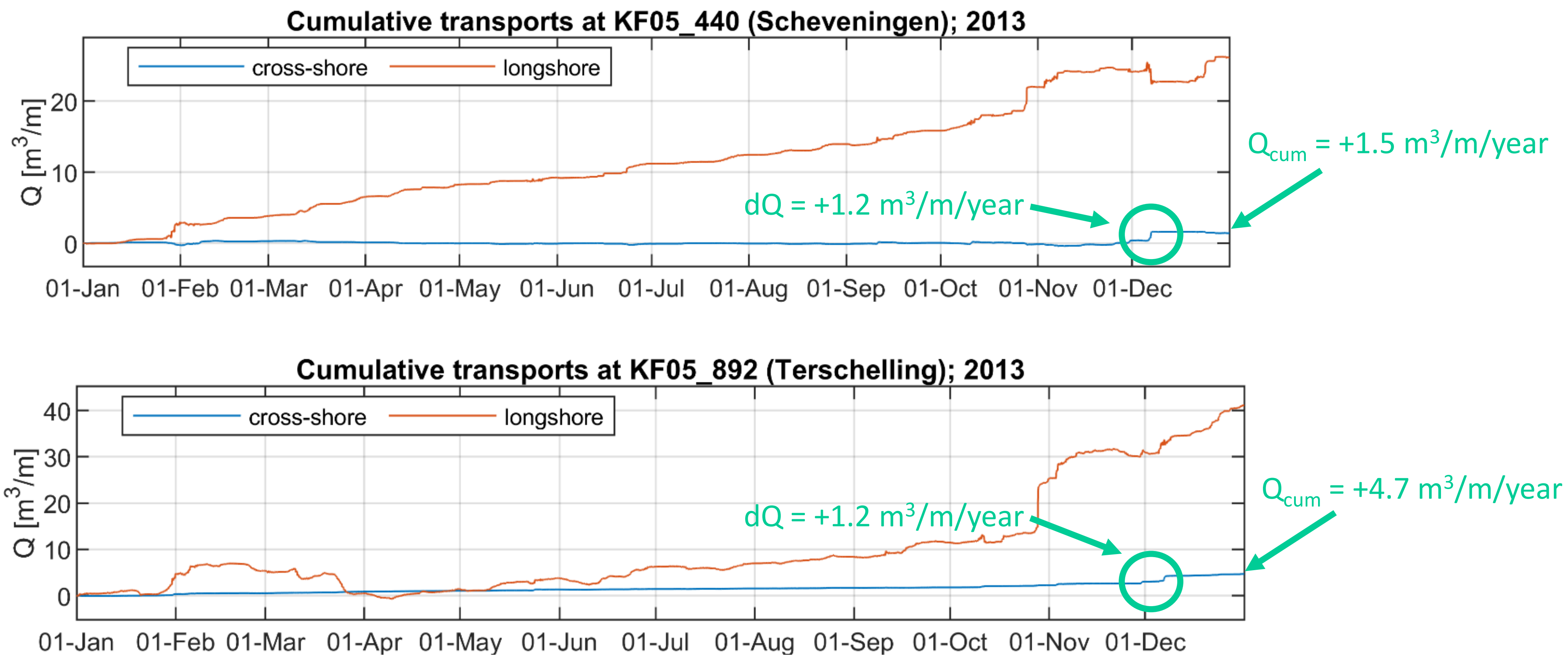
✓ The alongshore-directed sand transport is much larger than the cross-shore sand transport; *c*. 100 m^3/m/year and *c*. 10 m^3/m/year, respectively.

✓ The annual net sand transport is directed to the north-east due to tidal asymmetry and residual flow.

✓ Near-bed density-driven currents typically cause onshore-directed sand transport.

Modelling results from Grasmeijer et al., 2019

Storm effect on net sand transport



The "Sinterklaas" storm of 5 December 2013 makes a large contribution to the yearly net cross-shore sand transport: *c*. 80% at Scheveningen and *c*. 25% at Terschelling.

Total net annual cross-shore sand transport Dutch coast

Model setting	20 m depth	18 m depth	16 m depth	
Without return flow	+4 ± 3	+5 ± 4	+7 ± 5	M m^3/year

- ✓ Based on 3D DCSM-FM simulations 2013-2017, wave transformation matrix and 1DV Van Rijn (2007) transport model; see slide 66.
- ✓ Relative large band width due to uncertainties related to the applied model (e.g. the sand transport formula) and the model input (e.g., grain size).
- ✓ Near-bed density-driven currents typically cause onshore-directed sand transport.
- ✓ Cross-shore transports increase with decreasing water depth due to increased sediment stirring by waves and increased wave-related sand transport.

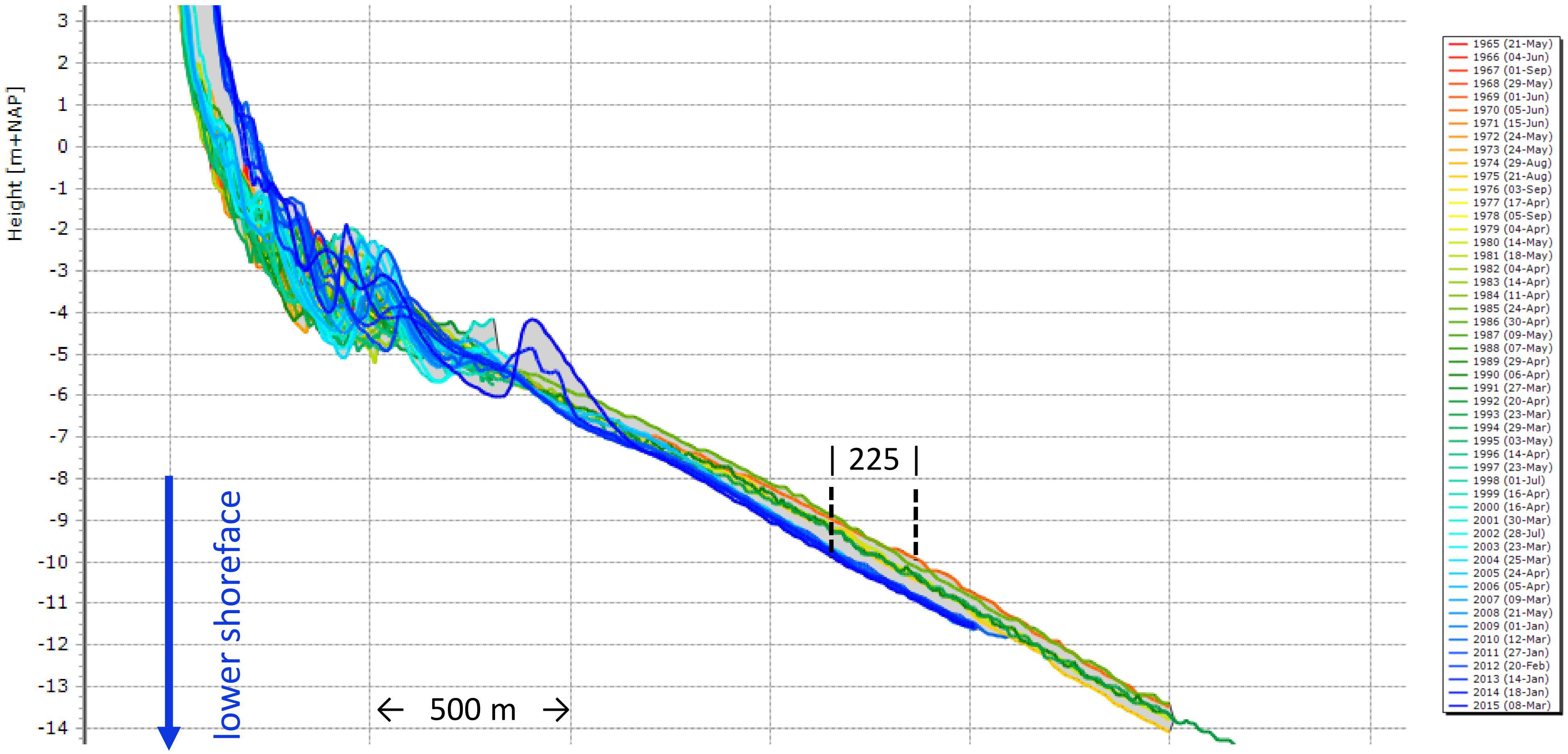
Disclaimer: these volumes do not include the potentially large effects of very large (NW) storms

7. Evolution of the lower shoreface

- The Jarkus data base of yearly shoreface profiles enables the analysis of shoreface evolution over 50 years.
- Plotting the yearly profiles shows the year-to-year variation, see slide 70. The variation decreases with increasing water depth.
- Jarkus profile 82.00 at Noordwijk (slide 70) shows a gradual landward retreat deeper than -7 m. Between 1965 and 2015, the -10m contour shifted c. 225 m landward. At the 1965 location of the -10m contour, the seabed has deepened almost 1 m.
- Most parts of the lower shoreface of the Dutch coast seem to be slightly deepening (slide 71).

1220339-000-ZKS-0068

Trend lower shoreface profiles slightly erosive



Noordwijk; Jarkus profile 82.00; evolution 1965-2015

Regional development trends lower shoreface

Development trends Dutch lower shoreface			
coastal section	***Lower shoreface***		***width zone***
	-8 → -12m	***-12 → -20m***	***-10 → -20m***
Western Scheldt mouth	(-)	(-)	wide
Eastern Scheldt mouth	(-)	(-)	variable
Ebb deltas Grevelingen, Haringvliet	(-)	0	wide
Maasvlakte	(-)	(-)	?
Delfland (HvH-Katwijk)	(+)	(-)	wide
Central Holland (Katwijk-Egmond)	(+)	(-)	narrow
Noord-Holland (Egmond-Groote Keeten)	?	(-)	wide
Ebb delta Texel Inlet	-	?	variable
Ebb delta Vlie Inlet	-	?	variable
Wadden – other ebb deltas	0	0	smal
Wadden – barrier island coasts	0	0?	very wide

(-)	slightly erosive
-	erosive
0	stable
(+)	slightly accreting
+	accreting
?	unknown / no data
na	not applicable

references:
Van Alphen & Damoiseaux, 1987
Elias et al., 2012; 2017
Van der Spek & Lodder, 2015

8. Final remarks

- The new information gives a more detailed picture of the lower shoreface.

Morphology and sediments

- The large-scale morphology of the lower shoreface seems rather stable. Decadal time series show an erosional trend. Small-scale bedforms can change over an interval of days to weeks.
- The variation in shoreface composition and morphology is larger than anticipated previously.
- The multibeam surveys revealed unexpected details such as geology-based shoreface irregularities between -15 m and -18 m.
- These irregularities ('gullies') probably act as conduits for downslope currents and sand transport.
- Moreover, the lower shoreface shows series of erosional features after a wave event that suggest large-scale seaward bottom currents and possibly sand transport.

Final remarks - continued

Processes and transport

- Even at 20m depth wave orbital velocities can be in the order of 1 m/s.
- The modelled total yearly sand transport over the 20m depth contour along the Dutch coast is *c*. 3 million m^3; over the 15m depth contour this is *c*. 5 million m^3. Both transports are in landward direction.
- This suggests, depending on alongshore transport gradients, a yearly erosion of 2 million m^3 between -20 m and -15 m, which is an average increase in depth of 2 mm per year.
- Storms increase the cumulative long- and cross-shore transports per year considerably.

9. Methodology

This section gives short descriptions of the methodologies that were followed in the analyses of observations and calculations.

For more detailed information the reader is referred to the following technical reports:

- Field surveys and equipment — *Van der Werf et al., 2019*
- Box and vibrocores: — *Oost et al, 2019a*
- Multibeam sonar: — *Oost et al., 2019b*
- Analysis field observations processes: — *Schrijvershof et al., 2019*
- Hydraulic and sediment transport modelling: — *Grasmeijer et al., 2019*

1220339-000-ZKS-0068

Field campaigns study areas

	2017							2018											
	June	July	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Cores		vibro/box														box			
Multibeam				Ameland		Terschelling									Ameland	Noordw	Terschel		
					Noordwijk														
Frames						Ameland		Terschelling 1		Tersch. 2	Noordwijk								

The timing of the field campaigns was as follows:

Ameland Inlet	cores	4 July **2017** vibro- and box cores; 5 September **2018** box cores
	multibeam sonar	5-7 September **2017**; 7-8 August **2018**
	frame measurements DVA	8 November - 12 December **2017**
Terschelling	cores	4-5 July **2017** vibro- and box cores; 4 September **2018** box cores
	multibeam sonar	28 November -2 December **2017**; 9-12 October **2018**
	frame measurements DVT1	11 January - 6 February **2018**
	frame measurements DVT2	12 - 26 March **2018**
Noordwijk	cores	3 July **2017** vibro- and box cores; 6 September **2018** box cores
	multibeam sonar	21-26 September, 19-24 October, 13-23 November **2017**; 13-28 September **2018**
	frame measurements DVN	4 April - 15 May **2018**

Vibro cores 2017

Collected cores Kustgenese 2.0 'Diepe Onderwateroever'					
series		*Ameland*	*Terschelling*	*Noordwijk*	*Totaal*
Vibro cores 2017	planned	13	8	10	31
	collected	9	6	8	23

- Vibro cores can be used to study sediment sequences. The corer pushes a 5 or 6 m long steel tube with a pvc liner into the sea bed to collect the sediments underneath. After reaching the maximum penetration, the tube is retracted and the corer is hoisted on board, after which the liner containing the sediment can be pulled out.
- In 2017, a series of 23 vibro cores has been collected along 8 transects normal to the coastline (see section 2). Offshore Ameland Inlet, one transect was sampled in line with the main ebb channel. Eight planned stations were not sampled due to too shallow water depths considering the draft of the survey vessel and the height of the vibro corer.
- The collected vibro cores were up to 5.40 m long, with a minimum length of 2.45 m and an average of 4.24 m. After retrieval, the cores were cut in 1m-sections and stored. Upon arrival in port, the cores were transported to the core facility of Geologische Dienst Nederland (GDN) in Utrecht, where the sections were cut lengthwise, photographed and described.

Core description and interpretation

- Standard core description includes specification of the variation with depth in sediment composition, grainsize distribution and sorting. Additionally, lithological boundaries, sedimentary structures and shell content are described. The core descriptions are subsequently stored in the DINO data base of GDN.

- For this project, the sedimentological environment where the deposits were formed have been deduced using the core descriptions and photographs. Moreover, the thickness of the active-layer, the deposit formed by recent sea-bed processes, was determined for each core.
- See Oost et al. (2019a) for detailed descriptions of the vibro cores.

Multibeam sonar surveys 2017, 2018

In order to get more detailed information on the morphology of the shoreface, the study areas were surveyed using multibeam echosounders in late summer to fall 2017 and in the same season in 2018. Meteorological conditions preceding and during the surveys differed (see table), which had consequences for the observed morphologies.

Multibeam surveys study areas

Study area	*2017 survey*	*2018 survey*
Ameland Inlet	5-7 September	7-8 August
conditions preceding survey	quiet months	quiet month, some events before
conditions during survey	2m waves	quiet
Terschelling	28-30 November, 12 December	9-12 October
conditions preceding survey	2 stormy months	Incomplete data, small-scale storm preceding
conditions during survey	End November quiet, later increasing wave heights	quiet
Noordwijk	End September, end October, end November	13-28 September
conditions preceding survey	Storm 2 weeks before survey	September comparatively quiet, small storm in June
conditions during survey	Survey interrupted by severe storms	Started quiet, increasing waves halfway

See Oost et al. (2019b) for details on the multibeam surveys.

Shoreface sediments

- Seabed sediment samples have been collected using box corers. Box corers sample a ‘block’ of sediment from the sea bed, leaving the internal structures and layering intact. Moreover, benthic animals remain in-situ which enables observation of the relationship between animal and sediment.

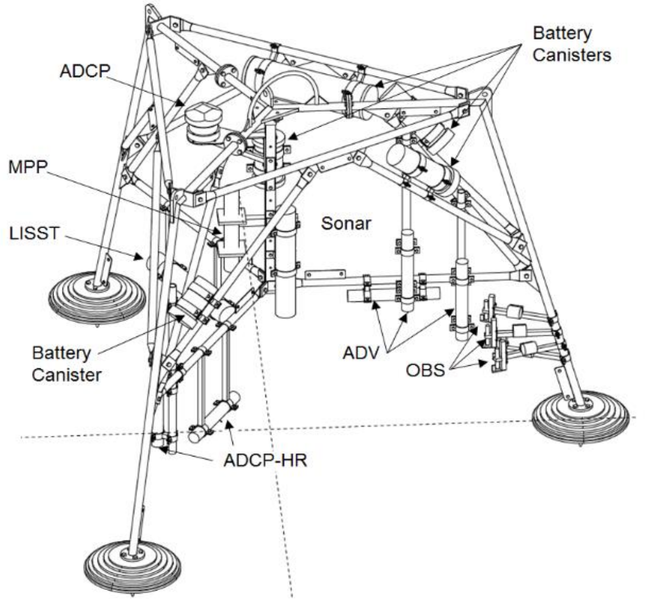
- Watch box corers in action in the videos:
  - https://www.youtube.com/watch?v=hc2_cAG31-k
  - https://www.youtube.com/watch?v=1T-HOryeOI4

Sea-bed sediment grain sizes

- The grain-size distributions of the surface sediments in the box cores have been determined using Malvern laser diffraction.
- The d50 value, which is the median value of the grain sizes smaller than 2 mm, gives an indication of the grain-size distribution.
- Additionally, the percentage mud (defined here as grain sizes smaller than 63 micron) is given.
- Coarse sand (large d50 value) is an indication of a high energy level during sediment transport. The mud percentage gives additional information on the energy level. Deposition of mud usually indicates quiet conditions.

1220339-000-ZKS-0068

Frame measurements



Ameland Inlet

DVA 8 Nov - 12 Dec 2017; -10 m, -16 m, -20 m

Terschelling

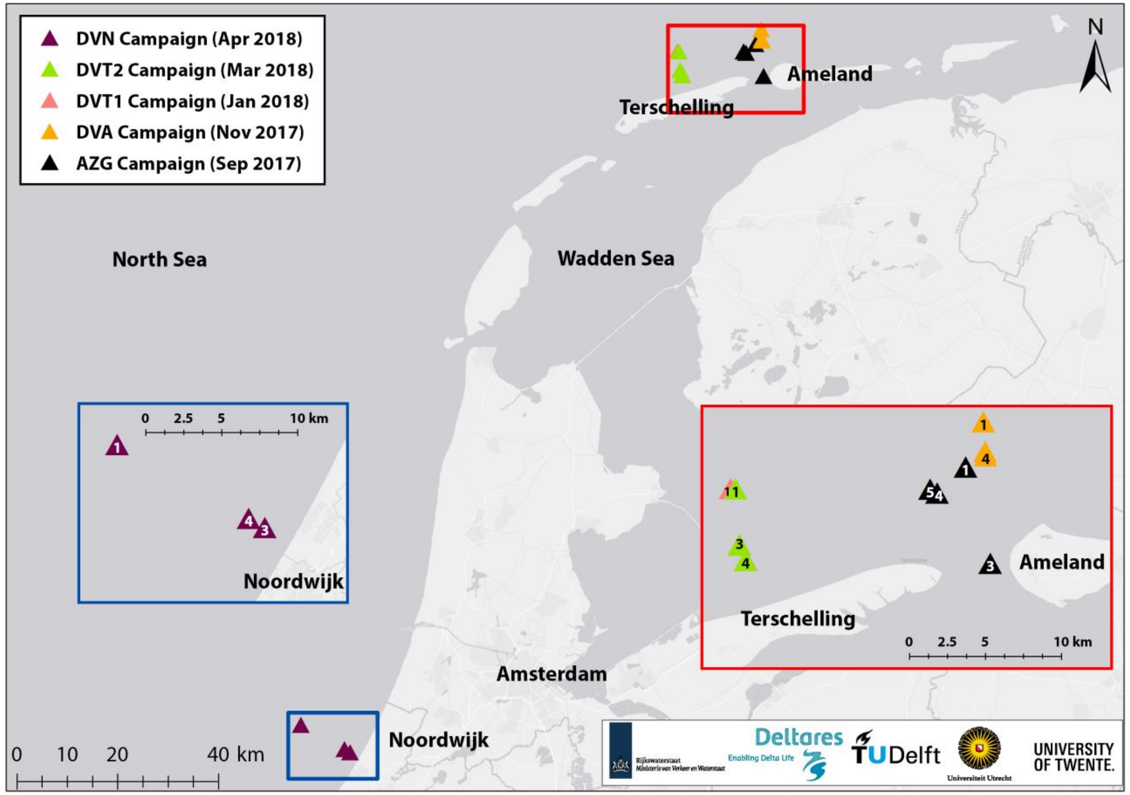
DVT1 11 Jan - 6 Feb 2018; -10 m, -14 m, -20 m

DVT2 12 - 26 March 2018; -10 m, -14 m, -20 m

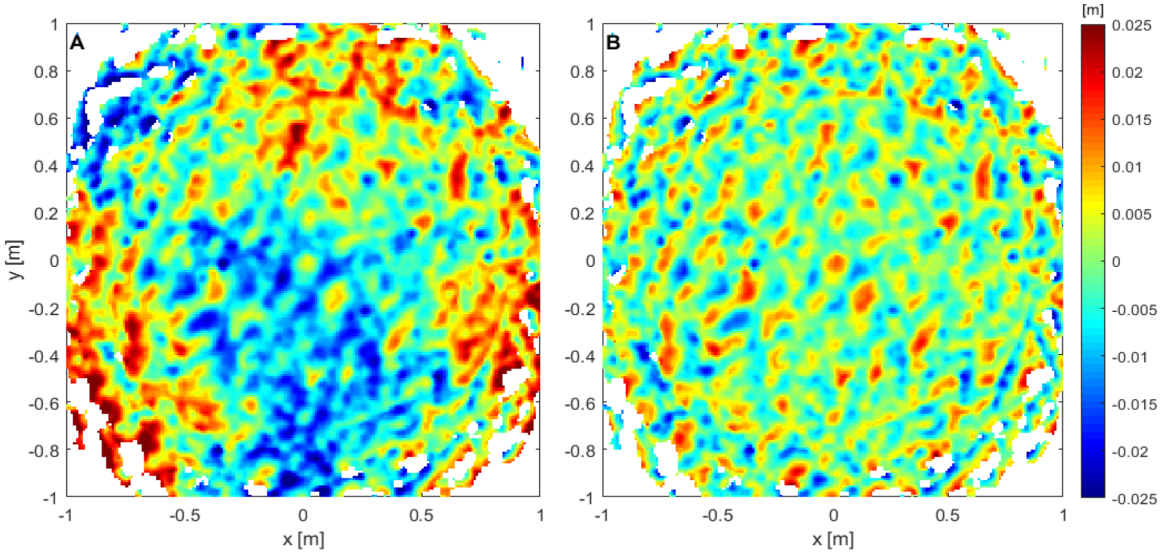
Noordwijk

DVN 4 April - 15 May 2018; -12 m, -16 m, -20 m

See Van der Werf et al. (2019) and Schrijvershof et al. (2019) for details



SONAR ripple data



Original (left) and detrended (right) SONAR measured bed levels at DVA F1 (20 m water depth)

The ripples were in most cases 3D, rather than 2D.

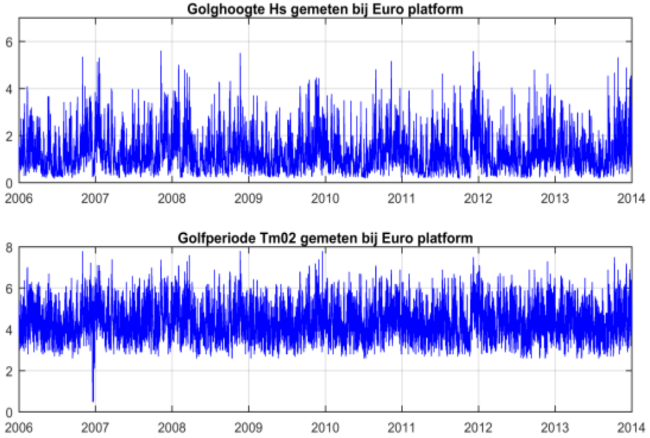
See Schrijvershof et al. (2019) for details.

Site	Grain size (μm)	Mean depth (m)
DVA1	226	20.3
DVA3	197	16.3
DVA4	197	11.2
AZG1	225	6.8
AZG3	216	16.2
AZG4	186	9.0
AZG5	186	6.5
DVT1-1	237	19.2
DVT2-1	237	19.0
DVT2-4	197	11.6
DVN1	332	20.3

Modelling Dutch lower shoreface sand transport

Hydrodynamics from 3D Delft3D-FM model North Sea

Wave transformation matrix using near-bed observation station



The widely-used Van Rijn (2007) formula is a generally valid formula for sand transport under waves and currents, based on a large set of lab and field data.

1DV Van Rijn transport model → Net sand transport along Dutch Shoreface

The waves and currents were validated using KG2 and earlier data. We did not find data available to compare to computed net sand transport at the Dutch Lower Shoreface.

Pros	Cons
complete coverage Dutch lower shoreface	relatively low resolution (900 m)
3D currents, incl. density effects	no wave-current-interaction
2013-2017 real-time forcing	only valid for depths larger ~16 m

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