

## **A geomorphological map of the Dutch shoreface and adjacent part of the continental shelf**

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Received 27 April 1988; accepted in revised form 9 May 1989

**Key words:** geomorphological map, continental shelf, Dutch shoreface, ridges, bars, ebb tidal deltas, sandwaves

### **Abstract**

The last decades there has been a steady encroachment of human activities into the Dutch marine environment. Knowledge about the seafloor lithology and geomorphology is imperative for further development of the Continental Shelf but also for a proper management of the shoreface, beaches and dunes, that act as a sea defence for the densely populated, low lying areas of Holland. To ensure that the coastal strip retains this function in the future, an understanding of its morphodynamics and its governing processes is of primary importance, especially in view of the projected rise in sea level. Within this framework, a geomorphological map, scale 1:250.000, has been prepared of the Dutch coastal region and adjacent part of the continental shelf which shows the distribution and characteristics of major morphological elements below the LW-line such as the shoreface, ebbdelta's with related shoals and channels, tidal ridges and sandwaves. In this paper the units identified on the map are described and their origin and behaviour is discussed.

### **Introduction**

The Dutch coastline and nearshore zone is comprised of three major geomorphological units. From south to north, these are: a former island and delta complex (Zeeland), a long strip of coastal dunes (Holland) and an arc of barrier islands separated by tidal inlets that enclose a tidal basin (the Wadden Sea) (Fig. 1a).

The coast and adjacent continental shelf is comprised of predominantly sandy Quaternary deposits that have been reworked during the Flandrian transgression.

Much of the hinterland behind the coast, in par-

ticular in Holland, lies below sea level. It is here that the major economic centres have developed with their characteristic high population densities. Today, some ten million people reside and work in this area. In the light of this, the most important function of the dunes, beaches and shoreface is as a defence against the sea. To ensure that the coastal strip retains this defence function in the future an understanding of its morphodynamics and its governing processes is of primary importance. The projected rise in sea level emphasizes this need.

High population pressure and the desire for further economic development places an increasing demand on the coastal zone and continental shelf

for recreation, possible land reclamation and exploitation of mineral resources. As a result a comprehensive coastal and submarine infrastructure has been developed. This incorporates: harbour access channels, pipelines and cables. In addition a zonation scheme has been implemented for allocating shipping lanes, oil concessions, mining rights and dump sites. Knowledge about the sea floor lithology and geomorphology is imperative for management of both the coastal defences and further development of the continental shelf. Superficial sediments have been mapped (Schüttenhelm 1980; Van Montfrans et al., 1988, see Fig. 1c).

Until recently, information on sea floor morphology could only be obtained from nautical charts and their detailed precursors: the sounding fair sheets. The scales used for many of these charts, typically 1:150.000 or 1:375.000, means that only large submarine features could be distinguished and then only in outline, i.e. the given isobaths (see Fig. 1b). Similarly, because nautical charts are designed for shipping purposes less depth information is plotted for the deeper areas in between shoals. As such the sea floor topography in the areas is not represented. To compensate for these shortcomings the North Sea Directorate and Survey Department of the Rijkswaterstaat (Ministry of Transport and Public Works of the Netherlands) produced a geomorphological map that encompasses the shoreface of the Dutch coast and adjacent part of the continental shelf.

In addition to the information contained in bathymetric charts, this morphological map gives bedform information without much loss of depth information. The work was carried out within the framework of the research project *Kustgenese* (Coastal Genesis) which is aimed at gaining knowledge about the large scale morphology, morphodynamics and governing processes of the Dutch coastal zone.

The map consists of four sheets (Fig. 1a) which are added to this paper as an Appendix and are inserted in the back of this issue. Individual sheets correspond to the major geomorphological units of the Dutch coastal zone.

The maps are constructed in the stereographic projection. The deviation between this projection

and the UTM projection used for the geological maps, scale 1:250.000 (Cameron et al., 1984) is, for the area considered, of little consequence i.e. approximately less than 85 metres. The geomorphological interpretation is based on 1:10.000 and 1:25.000 fair sheets that were compiled by the Rijkswaterstaat and the Hydrographic Service of the Department of Defense respectively between 1976 and 1984 and sounding profiles. A selection of the profiles is presented in Fig. 2. Fair sheets of the British Admiralty were used for the westernmost sheet. All sounding data are reduced to N.A.P (Normaal Amsterdams Peil), which is about mean sea level. More information about the cartographic aspects of this map can be found in Van Alphen & Damoiseaux (1988).

In this article the map and its legend are described. In addition the dynamics and genesis of the principal morphological elements are examined.

### Description of the legend

For the purposes of description a purely practical distinction is made between macro and meso scale geomorphology. This division implies the recognition of the scale in time and space at which different processes are manifest. The nomenclature used is merely descriptive and where possible the association between nomenclature and causal process has been avoided. As such no distinction is made between features of natural and anthropogenic origin. Two schematic cross sections are given in Fig. 3.

#### *Macro-scale bedform units*

Macro-scale bedform units have a horizontal dimension ranging from several kilometres to tens of kilometres and heights of several metres to tens of metres respectively.

In the legend these bedforms are indicated by capital letters. On the map they are denoted by individual colours and their outline is printed in black.

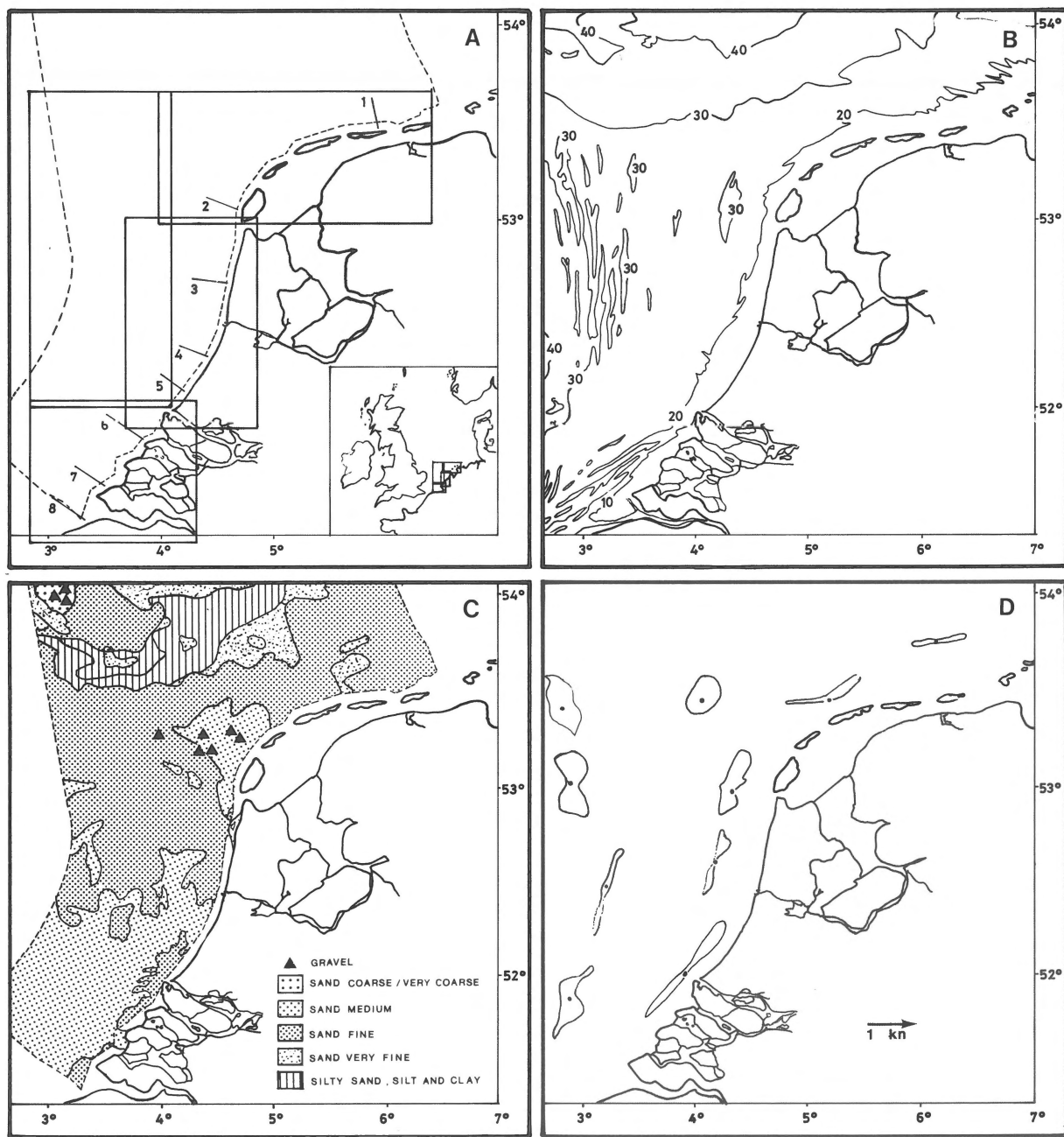


Fig. 1. Situation of the sheets of the geomorphological map and profiles of Fig. 2 (A); bathymetry of the area considered (depth in metres below LLWS) (B); superficial sediments, according to Van Montfrans et al., 1988 (C); tidal current envelopes at average tidal conditions (D).

**A: Seabottom.**

This is the relatively flat part of the continental shelf where the slope is generally less than 1:1000.

Thus defined it is found primarily seaward of the 20 metre isobath.

**B/C: Coastal slope (shoreface).**

The coastal slope is the transition zone between the

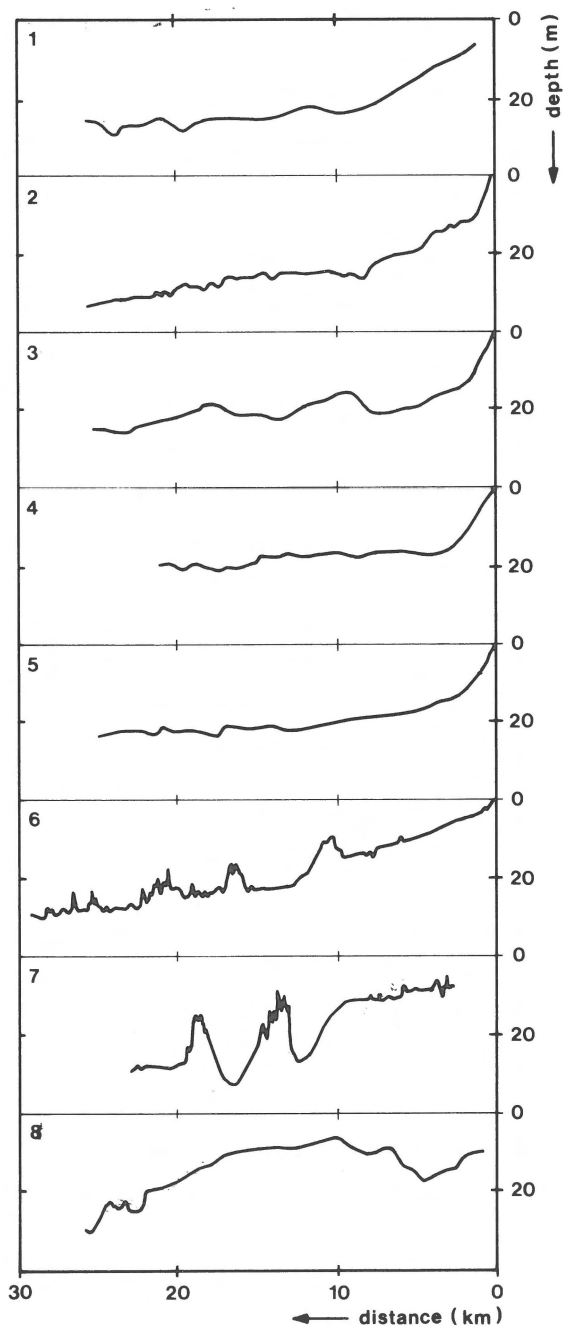


Fig. 2. Selection of profiles of the Dutch shoreface and adjacent part of the continental shelf. For location: see Fig. 1a

relatively flat shelf and the coastline. The transition between the shelf and gently sloping shoreface is defined where the gradient increases to more than 1:1000. Bedform C has a gradient larger than 1:100.

At tidal inlets the coastal slope is interrupted by an ebb tidal delta.

Bedforms A, B and C are the major geomorphological units upon which the following bedform-units are superimposed.

D/E: *Bank and ridge*.

The term bank or ridge is used here to describe linear structures several tens of kilometres long and several kilometres wide. The maximum height, measured between the deepest point in the trough and the crest of the bank, amounts from several metres (D) to several tens of metres (E). The position of the deepest parts in the troughs between ridges or banks is indicated by a grey line.

Many banks and ridges are covered with sandwaves. On the map no distinction is made between banks and ridges, although in general ridges have steeper crests than banks.

F: *Terrace*.

A terrace is defined as an almost flat area attached to the shoreface and with a minimum surface area of one square kilometre. On the maps the average depth of the terrace below N.A.P. is given in metres. On the seaward side it stands proud of the adjoining slope by more than several metres. Terraces occur on the middle sheet: in the north the so-called Pettemer Polder, and in the south, near the mouth of the New Waterway, the Loswal Noord. The latter is the dumpsite of dredged material from the navigation channel and harbours in this area.

G,H,J, (K,L,M): *Ebb delta*.

An ebb tidal delta is a more or less fan shaped accumulation of sediment, found seaward of a tidal inlet. The higher, more seaward delta lobe shoals are relatively flat with gradients less than 1:1000 (G). The delta lobes are dissected by flood and ebb dominated tidal channels, that give the deltas their complex patterns of shoals. The seaward parts of the delta lobe have gradients that typically lie between 1:1000 and 1:100 although larger gradients may also occur, H and J respectively. These units can be considered as an extension of the coastal slope.

Due to the closing of several estuaries in Zeeland, completed in 1986, ebb delta deposits of the

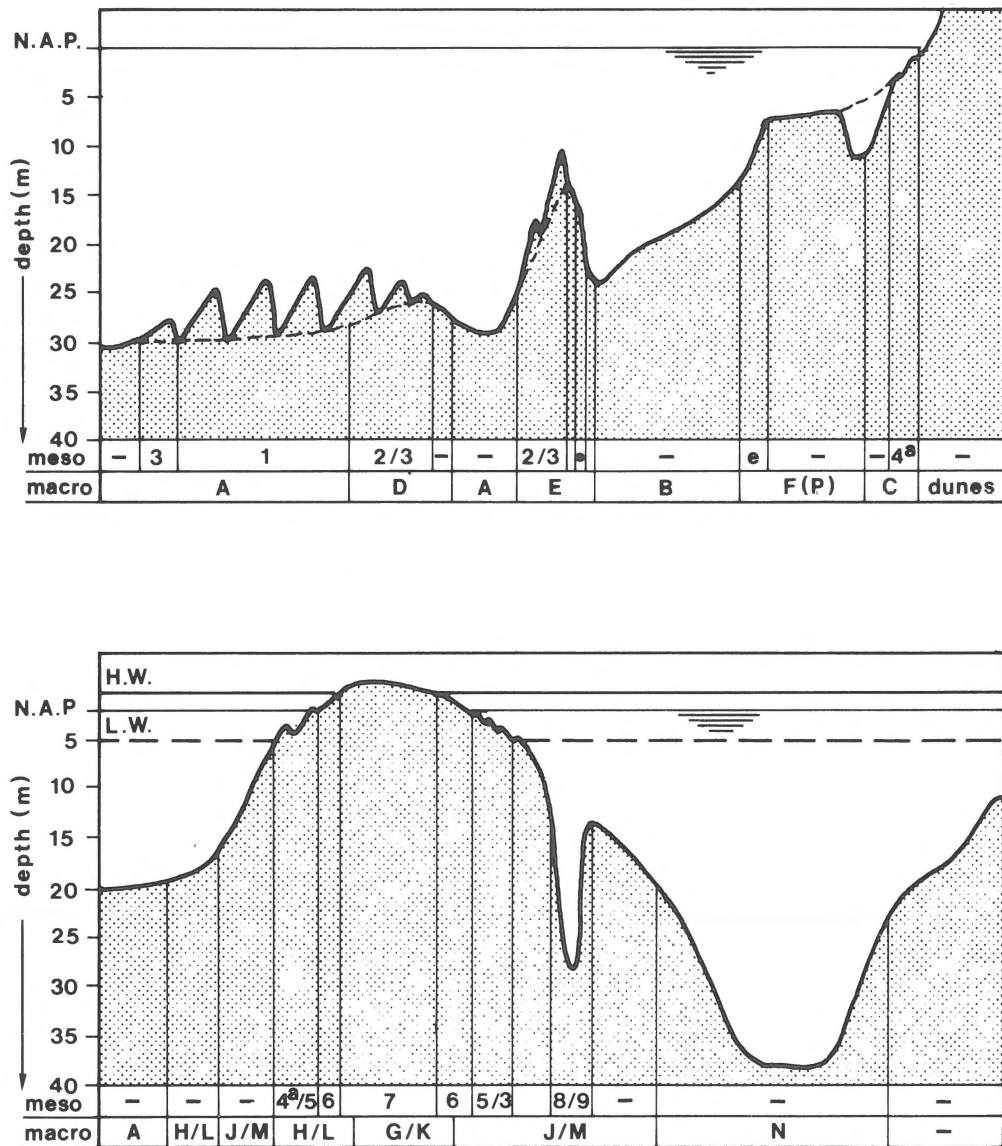


Fig. 3. Schematic cross sections to explain the legend of the geomorphological map. The upper figure refers to centre section of the Dutch coastline (Holland) with a closed shoreface of about 100 kilometres long; the lower figure refers to locations where the shoreface is interrupted by tidal inlets, tidal channels and ebb tidal deltas. The letters and figures are explained in the text.

Haringvliet, Grevelingen and Oosterschelde estuaries are now being reworked to new coastal features. They do however still show their former shape (units K, L, M).

N: *Tidal channel.*

Here a tidal channel is defined as an elongated through where ebb and flood discharges are almost equal. In most cases they are situated in the nar-

rowest part of the tidal inlet, the tidal gorge, but they also occur just outside the inlet. Tidal channels are several kilometres long, 1 to 2 kilometres wide and several tens of metres deep. The channel profiles in both the ebb and flood direction are almost identical and this is one aspect that differentiates them from ebb and flood channels.

While the bottom of tidal channels is often cov-

ered my migrating sandwaves, these patches are too small to be shown as separate units on the map.

*P: Plateau*

A plateau is an elevated plane separated from the shore by deep water or a channel. The average depth of the plateau below N.A.P. is given in metres.

On the maps the boundary between the above mentioned morphological units is indicated with a heavy black line. Where this boundary is uncertain or covered by meso-scale bedform units, the boundary line is dashed.

*Meso-scale bedform units*

Meso-scale bedform units have dimensions that are an order of magnitude smaller than those of the macro scale units. In the case of linear features they are less than 10 metres high. On the maps they are coded in figures (some with lower case letters) and printed in red. The macro scale morphology upon which they are superimposed can be deduced from the colour of the macro scale units and the combination capital letter-figure.

*1,2,3: Sandwaves.*

Sandwaves are wave-like bedforms with wavelengths greater than 60 metres and a trough to crest height of at least 2 metres. On the geomorphological map sandwaves are differentiated on the basis of their height. Sandwaves are most abundant on the relatively flat continental shelf south of 53° N. Their crestlines may extend for several kilometres. In general, the orientation is perpendicular to the dominant surface current i.e. almost parallel to the Dutch coast. As such crest-lines are aligned almost perpendicular to the shore. Sandwaves also occur on ridges, banks, in tidal channels and on delta shoals. In these cases sandwave height seldom exceeds 4 metres.

*4: Bars.*

*4a: Longshore bars.*

Longshore bars, or genetically speaking, breaker bars, are small elongate ridges of sand that occur on the upper part of the coastal slope. While their

length may exceed several kilometres they are generally about 100 metres wide and 1 to 2 metres high. Longshore bars are most abundant along the central part of the coastline, i.e. between Scheveningen (beachpost 105) and Groote Keeten (beachpost 10). North and south of this area longshore bars are absent or there is only one longshore bar present. In the central part of this area, there may be as many as three successive bars present. Longshore bars also occur along the coasts of the Wadden Islands and along the margins of the ebb delta shoals between the Wadden Islands.

*4b: Isolated bars.*

Isolated bars impart a subtle linear relief on the continental slope. They may be several kilometres long and are mostly 3 to 6 metres high. They approach the coastline at an angle of 10 to 30 degrees.

Isolated ridges are found off Zeebrugge, Petten and Texel. A man-made isolated ridge extends seaward from the Loswal Noord dumpsite near Hoek van Holland.

*4c: Reef bow bars.*

Reef bow bars are sandwave-like undulations that occur above the 10 meter isobath on the eastern side of some ebb deltas between the Wadden Islands. They radiate from the delta rim and gradually fade out in an easterly direction.

Reef bow bars have lengths of about one kilometre and wavelengths of about 500 metres. They are approximately 2 metres high.

*5,6,7: Shoals.*

Shoals are the most elevated parts of the ebb deltas.

Three units can be distinguished:

7: supratidal, situated above high water level;

6: intertidal, situated between high and low water level;

5: subtidal, situated below low water level but above the 5 metres isobath.

The ebb delta shoals of the Vliestroom and Marsdiep are covered by fields of sandwaves.

*8(9): Ebb or flood channel.*

Both flood and ebb tidal channels occur on ebb deltas. They are smaller than the previously described tidal channels and are characterized by a predominant flood or ebb tidal flow. In both cases

the cross sectional profiles and depths diminish in the direction of flow. In general, flood channels are slightly smaller than ebb channels.

On the geomorphological map the dominant discharge direction of these channels is indicated by an arrow.

In Zeeland former flood and ebb tidal channels are silting up. They are indicated by separate units (9).

### *Various*

In addition to the morphological units mentioned above, other morphological information is presented on the maps.

#### – Navigation channels.

The most important navigation channels are those leading to the ports of Zeebrugge (Belgium), Rotterdam and Amsterdam. These are maintained by dredging. In the case of Rotterdam and Amsterdam the larger part of the actual channel floor consists of leveled sandwaves. The depth maintained below N.A.P. is given in metres.

#### – Escarpment.

Slopes with gradients steeper than 1:100 are indicated separately on the map and are exclusively applicable to the major morphological units. On the shoreface an escarpment may indicate a lithologic inhomogeneity. In case of a bank, ridge or bar, however, it may indicate that the bedform concerned migrates i.e. in the direction of the escarpment.

#### – Depth.

Actual depth information is incorporated by giving the depths of highest and lowest points by crosses and dots respectively. Additional depth information is given in the form of the 10, 20, 30 and 40 metres isobaths.

### *Sea-defence*

The coastal sea defences like dunes, dikes and groynes are also shown on the map. In many cases there is a causal relationship between local morphology, marine processes and coastline behaviour

which has called for protecting the coast by artificial structures like dikes, groynes etc.

The most important sea dikes are the 'Hondsbosche Zeewering' (between beachpost 20 and 26) and the 'Westkappelse Zeedijk' on the western end of Walcheren.

Groynes have been placed along the shores of: Zeeuwsch Vlaanderen, Walcheren and Schouwen-Duiveland, between Hoek van Holland and Scheveningen (beachpost 100–117) ('Delflandse Hoofden'), in front of the 'Hondsbosche Zeewering', from Groote Keeten to Den Helder and along the coasts of Texel (beachpost 13–16) and Vlieland (beachpost 41–54).

## **Discussion**

### *Shoreface*

The basic elements of the sea bed geomorphology are the relatively flat seabottom or shelf and the sloping shoreface or coastal slope. Generally, the transition between seabottom and shoreface occurs at the 20 metres isobath.

Looking at the coastline as a whole, it is apparent that the distance from the shore to where the shoreface joins the shelf decreases from approximately 10 kilometres in the north and south to 2.5 kilometres in the central reaches. Consequently the average shoreface slope is steepest in the central area where gradients of about 1:200 occur, whereas gradients are 1:700 to the north and south. As wave energy is dissipated by bottom friction, it can be expected that in areas with a narrow shoreface wave energy is dissipated over a shorter width of the coastal slope. The abundance of longshore bars and the extensive dune development along the central part of the coast as compared to other stretches of the coast probably is genetically related to this steep energy dissipation gradient (Wiersma & Van Alphen, 1988). Strangely enough, it is here in the central region of the coast, that the coastline is stable or accreting while elsewhere coastal erosion prevails (Kohsiek, 1988a). The largest regression of the coastline (200–1100 m) occurred on Texel

whereas on Vlieland, Terschelling and Ameland and the promontories of the islands in the Delta area (Voorne, Goeree, Schouwen) a regression of about 100–400 m has been measured during the last century.

According to Kohsiek (1988a), locally the behaviour of the coastline during the last 20 years has largely been determined by large coastal engineering projects such as the extension of the harbour moles to IJmuiden and the closure of the Rhine and Meuse estuaries in the south.

In the case of the Wadden Islands the behaviour of the coastline seems to be strongly influenced by the regular attachment of slow easterly migrating shoals, originating from the adjacent ebb delta. As a result the coastline erodes or progrades in a cycle with a period of 20 to 50 years. (Kohsiek, 1988a).

The behaviour of the upper shoreface is often dominated by the *seaward* migration of longshore bars. Annual surveys show that especially between beachpost 60 and 100 this longshore bar behaviour is quite regular. The cycle of bar development along the water line, seaward migration and fading away beyond the 10 metres isobath comprises 4 to 5 years. The migration velocity is about 60 metres per year (Bakker & De Vroeg, 1988). The surveys also showed that the isolated ridges off Texel and Petten are mobile features. Possibly they form a link in the diabathic exchange of sand between shelf, shoreface and beach.

### *Delta's*

Along the northern and southern stretches of the coastline the shoreface is interrupted by ebb deltas with their associated channels. In the south the inlets have been so large and so close together that ebb deltas have fused.

From about 1930 the ebb deltas of the Haringvliet and Grevelingen estuaries have eroded because of decreasing tidal prism in the landward parts of the estuaries (Van den Berg, 1987).

When these estuaries were closed in the seventies, the strong tidal currents discharging into the North Sea were all but stopped. Consequently, today wave action dominates sediment transport

and sand from the former delta rim has been pushed landward. Much of this material is now being incorporated into longshore shoals, while at the same time the shoreface is becoming less steep (Kohsiek, 1988b). The most pronounced shoal development has taken place on the northwestern side of the former ebb delta. It is here that wave and current induced sand streams meet (Van den Berg, 1987).

Measurements show that the Oosterschelde estuary has eroded during the last century, causing its ebb delta complex to enlarge (Van den Berg, 1986). Today, the ebb delta of this estuary protrudes beyond the degenerating ebb deltas of the former Haringvliet and Grevelingen estuaries. The presence of a sandwave field seaward of the Oosterschelde delta may be related to this outbuilding process because longshore currents are constricted between the growing delta and nearby Steenbank. This constriction of the tidal currents may also explain a relative steepening of the central part of this delta lobe.

A plateau and stable shoal (Domburger Rassen) occur in the area between the ebb deltas of the Oosterschelde and the Westerschelde estuaries. The presence of this shoal and plateau may be related to the occurrence of an erosion resistant subsurface. Clayey layers are exposed along the nearby beach. It is thought that the Raan plateau, which lies further to the south, owes its existence to the presence of erosion resistant layers as well (Laban, 1979). Here these layers are found at about one metre below the plateau surface.

A comparison of historical surveys from this area has revealed that the Raan plateau is rather stable, that the active channels are confined to the landward boundaries of the delta and that since 1800 the Wielingen became deeper and wider while the Deurloo filled in (Van den Berg, 1987).

In view of this it is thought that the main outflow from the Westerschelde estuary has shifted southward and that outbuilding of the southern part of the delta is now taking place (Van den Berg, 1987). At present the Wielingen acts as the main approach channel to the ports of Vlissingen and Antwerpen. Like most other tidal channels the Wielingen bends to the south when viewed from the land. Van Veen

(1936) argued that this general tendency is caused by the tidal phase lag between ebb currents at sea and those discharging from the estuaries. In this phase of the tidal cycle the water slope at sea is directed southward. Consequently water levels across the mouth of the estuary are lower along the southern bank. As such the strongest ebb currents develop along the southern margin. At the same time southerly moving ebb currents have already developed. These cause the water discharging from the estuary to be deflected southwards.

More or less the same processes operate on the ebb tidal deltas of the Wadden Sea. Recently the morphodynamics of Texel Inlet have been studied (Sha, 1989). Cyclic morphological changes occur with a periodicity of about 70 years. The cycle comprises the development of an ebb dominated channel and a shoal, landward migration of the shoal, burying of a flood marginal channel and finally attachment to the shore, while at the same time the ebb channel rotates clockwise.

### *Shelf*

The southern and central part of the relatively flat seafloor is covered by an extensive field of sandwaves which becomes patchy in a western (deep water) direction. Within this field sandwave height may be up to 12 metres in the central part while at the boundaries they gradually fade out to low undulations with heights of about 1 metre. Terwindt (1971) reports a seasonal breakdown of sandwave height in winter and build-up in summer of about 2 metres. This he attributes to wave activity. Sandwave lengths may vary from 60 to 600 metres. Near the crest they can have slopes of about 1:10. Sandwaves are superimposed by smaller megaripples. From the trough to the crest of the sandwave megaripples increase in height from about 0.5 metre to about 1.5 metres (Terwindt, 1971).

In the area covered by the map from south to north the sandwaves become increasingly asymmetric with steeper slopes facing north (see also Terwindt, 1971). Mc Cave (1971) was of the opinion that this observed asymmetry was a clear indication that the sandwaves migrated in a northerly

direction. He estimated their speed of advance as being about 15 metres per year. Terwindt (1971), using controlled detailed surveys over a period of three years, was unable to detect any migration greater than 85 metres, the navigational error in the surveys.

With respect to sandwave origin two opinions are expressed in research literature.

Nio (1976) related sandwave origin to higher current velocities that may have been present during the Flandrian transgression. By implication therefore sandwaves are a relic, moribund morphology.

Mc Cave (1971) and Stride (1982) on the other had relate the origin of sandwaves to present day conditions, viz. depth averaged current velocities during spring tide greater than 0,6 metres per second; low to moderate wave activity (depth larger than 18 metres) and an elongated, asymmetrical tidal ellipse. Mc Cave (1971) attributes the gradual decrease in sandwave height towards the north to both the decreasing asymmetry of the tidal ellipse and the decreasing grainsize of the material.

Another, smaller sized, sandwave field occurs off Texel and Vlieland. In this sandwave field, the sandwave pattern is not so regular as in the south where crestlines can in some cases be followed for several kilometres.

According to Mc Cave (1971) this sandwave field owes its existence to the asymmetry of the tidal ellipse. Another explanation for the presence of this sandwave field is that relatively strong currents occur there. This is indicated too by the presence of coarse sands in this area (see Fig. 1c). North of the sandwave field in the south and the isolated field off Texel the seafloor becomes a rather featureless plain. Superficial sediments also fine towards the north (see Fig. 1c) while current velocities also decrease (see Fig. 1d).

The eastern part of the northern sheet shows that banks are aligned parallel to the tidal currents and that they gradually become larger in easterly direction. This seems to correlate with the current pattern and increasing current velocities in that direction (Stolk et al., 1987, p. 50).

Large complexes of ridges are found in the southern part of the area, just off the ebb deltas and

off the central part of the coast between Noordwijk and Egmond.

The first complex is known as the Zeeland ridges. Laban & Schüttenhelm (1981) concluded that these ridges are built on top of or are leaning against a core consisting of older deposits. These initial ridges appear to be elongate in shape. Although the ridges seem to be rather stable the superposition of sandwaves suggests that active sand transport occurs; it is thought that a clockwise eddy-like water circulation and sand transport pattern, generated by the alternating tidal currents, determines sandbank formation and maintenance of the present forms (Houbolt, 1968; Pattiaratchi & Collins, 1987).

The ridges found off the central part of the coast resemble the shoreface-connected ridges described by Swift et al. (1978). Generally they are aligned at angles of between 20° and 35° with the coast, opening towards the south. Like the ridges described by Swift et al. (1978) they consist of cohesionless Holocene sandy material (Wiersma & Van Alphen, 1988). Although this ridge topography is recorded on maps from about 1700, it has not yet been possible to establish whether these ridges have migrated. To date the origin of these ridges and their function in the sand transport system is discussed (Wiersma & Van Alphen, 1988). Recently their development has been linked to a dynamic response of the present seabed to an asymmetric current regime (Huthnance, 1982) and to currents in combination with waves (De Vriend, 1988). Boczar-Karakiewicz et al., (1987) related the origin of similar ridges to infragravity waves, i.e. waves with a period between 30 to 300 seconds.

Northwest and west of the shoreface-connected ridges, another complex of elongated, parallel, north-south trending depressions and ridges occurs. Their lengths vary from 50 to 100 kilometres. Knowledge about their origin, composition or behaviour is limited. The depression situated north-south along 4.0° E is supposed to be a Saalian buried glacial valley (see Cameron et al., 1984). The Bruine Bank has been studied relatively well. It has a remarkably steep cross profile, with a highest elevation of about 19 metres below N.A.P., while in the accompanying troughs the largest depth is

about 45 metres. The surface of this ridge is covered by sandwaves, pointing with their steepest slope northward on the western slope of the bank and in opposite direction on the eastern slope. Thus sand seems to move around the ridge (Houbolt, 1968). The Bruine Bank itself appeared to consist of fine sands and clayey layers of Flandrian age, possibly deposited as a former beach barrier (Oele, 1971). Houbolt (1968) and Laban (1988, personal communication) assume the ridge to be an erosional remnant, also of Flandrian age. Maintenance of the present forms may be due to the same mechanisms as mentioned at the Zeeland ridges, viz. a clockwise water and sand circulation.

The question of linear sandbank formation and maintenance is treated in a recent overview paper by Pattiaratchi & Collins (1987).

### Acknowledgements

We would like to thank H. van Wees and H. Koppejan for their technical support in producing the final map and dr. J.H. van den Berg for useful comments. Particular thanks are due to dr. J. Wiersma who launched the concept of producing a geomorphological map of the seabed and who stimulated the production of the map and its publication during all stages of the work.

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