

**MORPHODYNAMIC DEVELOPMENT AND PRESERVATION OF
PHYSICAL SEDIMENTARY STRUCTURES IN TWO PROGRADING
RECENT RIDGE AND RUNNEL BEACHES ALONG
THE DUTCH COAST¹⁾**

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ABSTRACT

Berg, J.H. van den (1977). Morphodynamic development and preservation of physical sedimentary structures in two prograding recent ridge and runnel beaches along the Dutch coast. *Geol. Mijnbouw*, 56, p. 185-202.

The two studied beaches both form part of the coastal barrier system which extends along the eastern margin of the southern North Sea. One of them (at Schouwen) is bordered by the coalescing ebb deltas of two major tidal inlets; the other one (at Zandvoort) lies beyond the influence of inlets.

The ridge and runnel beach environment is divided into areas lying relatively sheltered from wave action behind ridge or berm crests and seaward dipping surfaces exposed to the influence of swash and backwash during the tidal cycle. Both of the areas are characterized by a set of sedimentary bedforms and structures, which produce distinctive associations in preserved sediments. Comparison of data on sampled structures from buried sediment layers with information from repeated measurement of beach variation, permitted reconstruction of the location of these associations as preserved during the last few years in sections perpendicular to the coastline.

Major differences in the morphodynamics of the two beaches as well as in the location of associated sedimentary structures preserved in these sections, are related to the degree to which the beaches are sheltered from storm waves and to rates of progradation.

INTRODUCTION

Scope of study

Modern sediment studies provide insight into sedimentary structures of superficial deposits on a variety of shorelines. They give, however, little information about the preservation potential of these structures in relation to morphodynamics and processes of progradation. This diminishes their value for the interpretation of ancient shoreline deposits. A major objective of this study is to investigate this relationship at two prograding ridge and runnel beaches along the Dutch coast, at Zandvoort in the province of North Holland and Schouwen, in the province of Zeeland (fig. 1). This was achieved by combining knowledge of the uppermost beach

layers, available from previous literature, with a long series of measurements of short-term beach variation in the study areas.

Results of this comparative study are supplemented by data on preserved structures in deeper beach layers, obtained by a shallow drilling program carried out on the beach at Schouwen in May and October, 1975.

General setting of the study areas

Both beaches investigated are situated on the shore of the coastal barrier system of the eastern margin of the southern North Sea extending from Belgium to Denmark (fig. 1). The wave climate of this part of the North Sea is characterized by the absence of oceanic swell and – owing to its position within the temperate climatic belt – by a frequent occurrence of storm waves. Usually storm waves are generated by westerly storms flanking low-pressure centres passing from west to east across the northern part of the North Sea.

Local variations in wave climate along this shoreline arise from differences in nearshore sea bottom morphology. At places where nearshore shoals are high and broad storm waves are largely dissipated before reaching the shore. Such is

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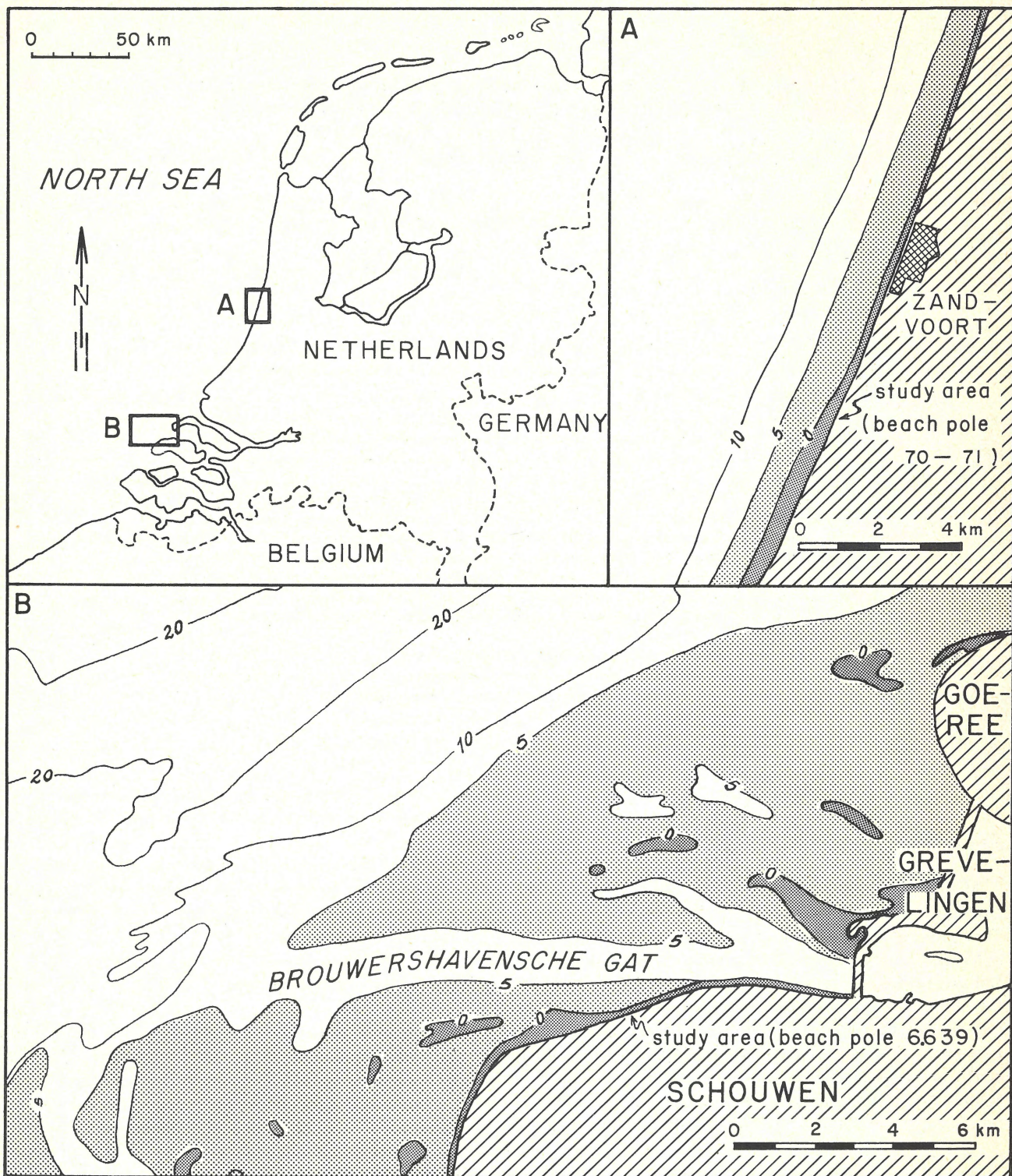


Fig. 1
Location of study areas. Depths in meters below Mean Low Spring Tide.

the case in the beach area studied at Schouwen, beach pole 6.639³⁾ which is protected against severe storm wave attack by a series of extensive shoals partly emergent at low tide. These shoals belong to the coalescing tidal "delta" systems of the Oosterschelde and Grevelingen⁴⁾ estuaries bordering the Schouwen land mass to the south and the north respectively. The nearshore⁵⁾ at Zandvoort beach, pole 70-71³⁾, on the other hand, lies on a long stretch of coast uninterrupted by tidal inlets and beyond the reach of tidal delta systems.

Along the Dutch coast the nearshore zone of such areas is characterized by a system of straight, parallel, longshore bars. Along the Zandvoort coastline three of these bars are mostly present, the innermost bar being the highest. Since the crests of these bars are narrow and do not reach above the low water mark, they are not able to dissipate incoming storm waves as effectively as in the Schouwen beach example. Both of the beaches have a semi-diurnal tide. The coast at Zandvoort has a tidal range of 1.6 m whereas at Schouwen the range is 2.4 m. Maximum spring ranges are about 2.2 and 3.2 m respectively. So both beaches are labelled "mesotidal" in the classification of shorelines by Davies (1964).

Median grain sizes range from 210 to 260 microns in the Schouwen area (analyses by the author) and from 190 to 250 microns on the beach near Zandvoort (Doege, 1954).

PREVIOUS WORK ON SHORELINE ENVIRONMENTAL MODELS

It is generally agreed upon that, in studying sedimentary structures of recent environments, clues for environmental comparison with ancient sediments can be found in both the vertical and the lateral sequence of structures. With this in mind several authors have constructed hypothetical vertical sequences of different types of prograding coastal and nearshore areas as models for paleo-environmental interpretation. The sequences are based upon detailed description of sedimentary structures, their relation to bedforms, physical processes and their areal distribution at the moment the investigations were carried out.

Environmental models of various types of shorelines, based upon those data, have been constructed or suggested by Clifton *et al.* (1971), Davidson-Arnott & Greenwood (1974), Davis *et al.* (1972), Dörjes *et al.* (1970), Evans (1958, 1965), Hayes *et al.* (1969),

³⁾ These numbered beach-poles belong to a fixed system of measuring poles extending all along the Dutch coast and established by the Rijkswaterstaat (the Government Board for Ways, Waterways and Harbours).

⁴⁾ The Grevelingen was closed by a dam in 1971.

⁵⁾ After Clifton *et al.* (1971) the nearshore is defined as the area lying between the location of the transformation to solitary waves and the shoreline.

Howard & Reineck (1972) and Reineck & Singh (1973).

The present author is not completely convinced that these studies on modern environment have such a great diagnostic value in interpreting ancient sediments as has often been suggested. All the models which are now available are based upon data from more or less accidental circumstances prevailing during the period when the investigations were being carried out. Usually no serious attention is paid to possible deviations from the "normal" hydrodynamic and morphological situation found and described during field study. In particular, information from periods of storm waves is generally scarce, if not absent. This is partly due to the fact that on most shorelines storm waves are not commonly encountered. Furthermore, weather and wave conditions during storms are not pleasant to work in and do not permit day to day observation of nearshore bedforms and structures.

However, most nearshore and coastal environments open to storm waves undergo important cycles of erosion and deposition, accompanied by temporary morphological transformations at the passage of onshore storms. Bedforms, sedimentary structures and distinct structural associations formed during these cycles will generally deviate from the "normal" situation during quiet weather and waves. This can be clearly demonstrated from the type of shore studied by Clifton *et al.* (1971): during their field survey, which was carried out in summer, under conditions of "normal" weather and waves, they were able to divide the nearshore micro-morphology and related depositional structures into five zones or "facies" occurring in bands parallel to the shoreline. Each of these "facies" had a distinctive set of internal structures. Migration of facies in response to change in waves or tide produced "assemblages" of structures where facies-zones overlapped.

The environment studied by Clifton *et al.* is part of an ocean-facing pocket beach with a topography and wave climate which can be found along many stretches of the Pacific coast of the U.S.A. Major morphological changes of these beaches throughout the year are well documented. So it has been observed many times that occasionally storm waves arriving at these relatively steep swell-built beaches may cause quick and spectacular beach erosion. The sand eroded from the beach is carried seaward, where it generally accumulates in a temporary more or less pronounced longshore bar (e.g. Shepard, 1950; Ingle, 1966; Silvester, 1974). This bar continues to grow until its crest is high enough to steepen and break the majority of incoming storm waves (Silvester, 1974). Thus, during storms these normally non-barred nearshores (including the non-barred nearshore area described by Clifton *et al.* (1971) may be transformed temporarily into barred ones. The bar material returns to the beach during subsequent quiet weather conditions by the action of the normal swell waves. During this recovery of sand to the beach shoaling swell waves will generally break on the bar pouring water into the trough between beach and bar. This will promote the formation of

important rip currents on low points of the bar which are fed by longshore "feeder" currents in the through. On bar crests an important net shoreward transport of water will be found.

In the non-barred nearshore investigated in summer 1969 at the Oregon coast such circulation cells were only very weakly developed (Clifton *et al.*, 1971). Furthermore, as long as part of the wave spectrum breaks on the bar, the "energy level" of the waves ultimately reaching the beach is small compared to what it would be in non-barred situations.

So the hydrodynamics and morphology of the summer non-barred nearshore differ in many aspects not only from storm beach conditions, but also from the topographically more complicated beach during the recovery period. Consequently the hydrodynamically controlled sedimentary bed-forms and structures will differ too.

During onshore gales, those parts of the nearshore which are exposed to the severest wave action may be eroded below the level of the "normal" or swell built profile. Sedimentary structures formed on top of these erosional surfaces during the storm and in the following recovery period remain undisturbed by further wave action, at least until the next storm, because the swell built profile never reaches these depths. According to Wunderlich (1971) beaches along the Gulf of Gaeta, Italy, are denuded during storms to such an extent that in prograding sequences only structures of the storm beach are likely to be preserved.

Thus, investigations which are only based on structural features encountered during summer conditions don't have much value for comparison with ancient shoreline sediments. The investigations should seek to describe and analyse sedimentary structures from all the typical combinations of hydrodynamics and morphology of the environment.

These considerations lead to another serious criticism in applying the subdivision of modern coastal environments based on wave energy to ancient shore-sequences, which seems to become common practice in this field of sedimentology. This subdivision was first suggested by Price (1955) and Tanner (1958). Price used offshore gradients of 1,5 and 2,5 feet per mile to separate low, moderate and high energy conditions. Tanner used yearly averages of breaker heights of 10 and 50 cm for the same divisions. In a study on the shoreline stability of the Florida coast Tanner (1960) showed that a downshore gradient in wave energy level was responsible for a change in the longshore transport of sand. So wave energy was considered to be an important factor in shaping the coast and the energy level was adopted as a main factor in his morphogenic classification of coasts. Another classification of shorelines of world-wide scale was proposed by Davies (1964) and is based on wave energy and two other hydrographic characteristics, tide and predominant wave form, which are also important morphogenic factors.

These three classifications can all be applied to studies in which the shape and shaping of coastlines is discussed. A review of articles in which the concept of wave energy has

been applied in this way, has been given by Tanner (1973).

Recently these classifications have also been adopted in defining modern coastal sedimentary environments which are used as models for environmental interpretation of ancient sediments. Clifton *et al.* (1971), Howard & Reineck (1972) and Davidson-Arnott & Greenwood (1974) qualified their nearshore study areas, according to average yearly wave height, as high, low and low to moderate energy environments respectively. We believe that these additions are not relevant here since — as it has already been made clear — preserved structures of shoreline environments generally do not represent "normal" wave conditions or levels of average wave energy.

One criterion which would be of more relevance in distinguishing between shoreline sediments in this field of sedimentology is certainly topography. On a local scale offshore bars, shoals or cliffs may shelter the beach to some degree from the influence of storm waves and so a decrease of the share of storm-generated layers in preserved sediments will occur. On a larger scale topography influences the tides and also some characteristics of the wave climate which are important to beach dynamics and the preserved sequences. In most marginal seas oceanic swell is excluded or is otherwise minimal. Intermittent storm wave action here results in a more or less permanent offshore bar system, because the local swell is not able to sweep the sand eroded by storm waves and stored in the offshore bars, to the beach. So, compared to oceanic coasts, beach profiles on marginal seas may never lose this "storm" character (Silvester, 1974). On the other hand, maximum fetch lengths in marginal or enclosed seas limit the maximum size of storm waves and may be an important factor in reducing the influence of storm-generated layers in preserved sediments.

Differences in preserved sequences of the beaches discussed in this paper can not be related to these large-scale topographical factors, since both beaches investigated are located on the same stretch of shoreline of the "marginal" southern North Sea.

DYNAMICS AND SUBDIVISION OF RIDGE AND RUNNEL BEACHES

Both beaches investigated are characterised by the presence of ridges and runnels lying parallel or at a slight angle to the coast (fig. 2).

Ridges and runnels are formed by wave action. According to King & Williams (1949) ridges are initially formed as "swash bars" within the swash zone by onshore sediment transport landward of the plunge point of the waves breaking on the beach. Prerequisites for their formation are a large tidal range, a fairly restricted fetch and a large volume of available sediment (King & Williams, 1949; King, 1959).

Consequently most ridge and runnel beaches are found



A

B

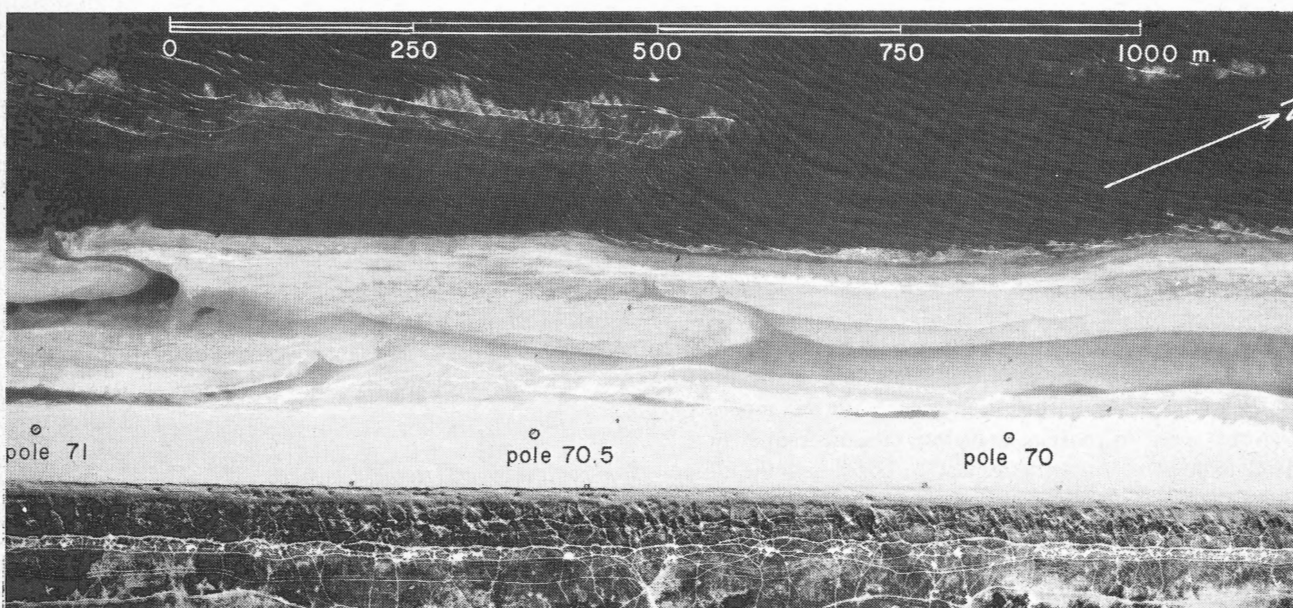


Fig. 2
Areal photographs of the studied beaches; A: the Schouwen beach at 23-4-1974; B: the beach near Zandvoort at 7-4-1974.

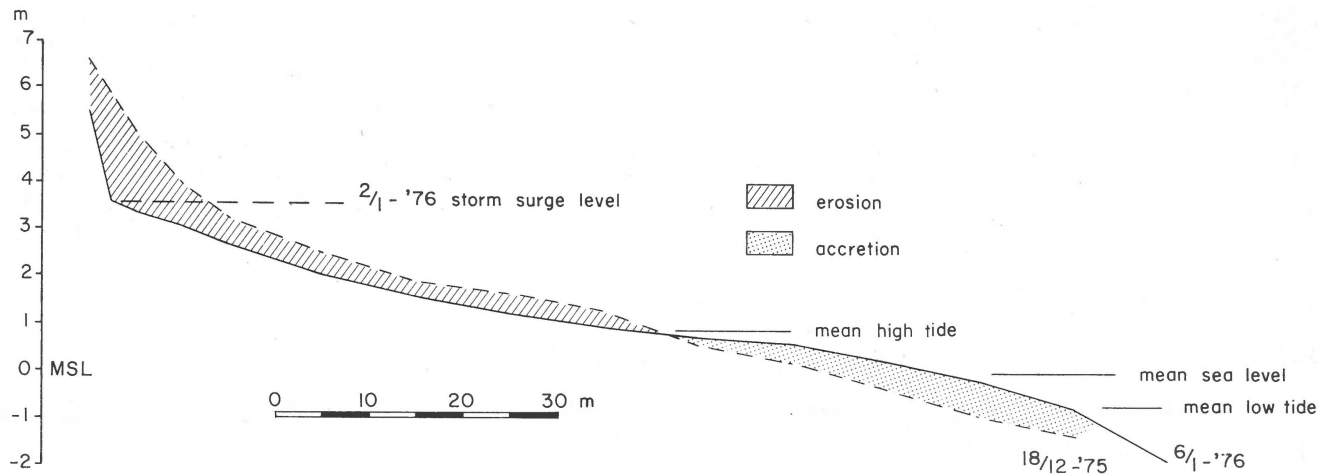


Fig. 3
Beach profile before and after the January 2, 1976 storm at pole 71, Zandvoort.

along the coast of marginal seas like the North Sea. Present knowledge of the morphodynamics of these beaches at various coastlines having different wave and tidal regimes, gives rise to a distinction between two types of ridge and runnel beaches:

- beaches having a semipermanent ridge and runnel topography; periods when ridges occur alternate with periods when no ridges are present;
- beaches on which ridges and runnels are permanent features.

The beach investigated at Zandvoort belongs to the first group, the Schouwen beach can be classified within the second category.

Semipermanent ridge and runnel beaches

In general, beaches with semipermanent ridge and runnel topographies like the beach at Zandvoort lie open to destructive wave attack during storms. During onshore gales the relief of ridges, runnels and berms is flattened and if conditions are favourable, considerable erosion of the beach may take place, especially of the backshore area.⁶⁾

On ridge and runnel beaches of New Hampshire and Northern Massachusetts Hayes & Boothroyd (1969) were able to distinguish five factors controlling erosive effectiveness of storms on unsheltered beaches: size and intensity of storm, speed of movement of low pressure centre, tidal phase, path of storm with respect to beach and the time interval between successive storms. The same factors can be applied to the beach at Zandvoort. Sand eroded from the beach is deposited near the low water line and the resulting

storm profile is flat to concave with a low gradient (fig. 3).

On stationary or prograding shorelines most of the sand eroded during storms is returned by means of landward migrating ridges, which are formed within a few days to some weeks after the storm. From observations of beach profiles in the New England coast, eastern U.S.A., Hayes & Boothroyd (1969) revealed three stages of beach morphology in relation to storm occurrence:

- early post-storm (up to 3 or 4 days after the storm) – The profile is flat to concave upward and the beach surface is generally smooth and uniformly medium-grained. Severest storms leave erosional scarps in the backshore or the dunes;
- early accretional, or constructional (usually 2 days to 6 weeks after the storm) – Small berms, beach cusps and ridge and runnel systems are rapidly formed;
- late accretional or maturity (6 weeks or more after storm) – Landward migrating ridges weld into the backbeach to form broad, convex upward berms.

The application of this three-stage model to the Zandvoort beach is evident through the studies of Douglas (1954). In addition to this a large number of observations on the variation of beach morphology carried out during the last 10 years (which will be discussed later) also confirms this view.

Permanent ridge and runnel beaches

In contrast to the first group these beaches are sheltered from wave attack to such a degree, that during onshore gales ridges will not be completely flattened. Also, the beach is not seriously eroded and processes of recovery after storms are of minor importance to beach morphodynamics. The Schouwen beach belongs to this category.

⁶⁾ According to the terminology of Emery (1960) the mean high water line is here considered to be the boundary between backshore (supratidal zone) and foreshore (intertidal zone).

At the beach of Blackpool (Lancashire, England) which is one of the earliest studied examples of this type, ridges lie parallel to the coastline. They do not move systematically towards the shore, but maintain their position for long periods (King & Williams, 1949). Ridges are most persistent at positions where the tide level stands for a relatively long time during the tidal cycle. This is due to the fact that on these levels the process of 'swash bar' or ridge formation is most effective.

Ridges tend to lie at right angles to the waves forming them. Where waves approach dominantly from a direction oblique to the shoreline, ridges have a tendency to adjust themselves to that dominant direction and generally lie at an angle to the coastline (Greswell, 1937). This holds true for the orientation of ridges on the investigated beach of Schouwen (fig. 2) as well as for the beaches of South Lincolnshire, England, which have been subjected to a number of detailed morphological studies by King & Barnes (e.g. Barnes & King, 1955; King & Barnes, 1964). It was noted by these investigators that as a consequence of the oblique approach of the waves and the resulting dominant direction of longshore movement of sand, ridges generally move down the shore and, in doing so, appear to move inland on any one profile perpendicular to the shoreline. Similarly in the Schouwen study area the shoreline is directed towards the ENE and constructive waves can only approach from a westerly direction, with the result that ridges diverge from the coast to the east and also move in that direction along-shore.

Structural associations of modern ridge and runnel beaches

Sedimentary structures, their relation to bedforms and their superficial distribution on ridge and runnel beaches are described and interpreted by many authors, e.g. Douglas (1954), Davis *et al.* (1972), Hayes *et al.* (1969), Hoyt (1962), Reineck (1963), van Straaten (1953; 1959), Wunderlich (1972). From these studies it can be deduced that, generally speaking two hydrodynamically and morphologically controlled associations of sedimentary structures can be distinguished in this environment (fig. 4):

Association I: formed on seaward facing beach slopes generally subject to repeated swash and backwash processes.

Association II: deposited in runnels and parts of the upper beach sheltered from surf and swash action by ridges or by a berm.

All beaches surveyed by the above mentioned authors are subject to cycles of high erosional and depositional processes which are related to the passage of onshore storms and definitely belong to the group of semi-permanent ridge and

⁷⁾ The surf zone is here defined as the area between the seaward edge of the swash zone and the innermost breaker line.

⁸⁾ For stratification and cross-stratification in this paper the terminology of McKee & Weir (1953) is adopted.

runnel beaches. Up to now no detailed studies of primary structures of beaches with permanent ridge and runnel systems have been done. However, this study demonstrates that the same division of structural associations is applicable to the permanent ridge and runnel beach at Schouwen.

In order to clarify the major points of difference, the main sedimentary features of these associations will now be discussed briefly. For more detailed description and explanation of the structures and their directional properties the reader is referred to the quoted studies.

Association I — The predominant type of structure in this association is even, parallel lamination, dipping slightly seaward and occurring in wedge-formed sets (e.g. Thompson, 1937; McKee, 1957). The even character of the laminae is due to the effect of surf⁷⁾, swash and backwash. During periods of low waves, surf and swash are restricted to relatively narrow zones migrating up and down the beach with the tides, and "swash" lamination is produced on the sea facing slopes of berms and ridges during high and low tide respectively. During storms, most of the beach is covered by a boiling surf and swash zone and even lamination seems to be the only structure to form on the flat storm profile (e.g. Hayes *et al.*, 1969; Davis *et al.*, 1972; Wunderlich, 1972; Reineck & Singh, 1973).

During quiet weather and periods of high water, megaripples can occur near the low water mark at some of the previously studied ridge and runnel examples (Hayes *et al.*, 1969; Reineck, 1963; van Straaten, 1953) and sometimes even on the flat tops of ridges on the lower part of the beach (Reineck, 1963; Wunderlich, 1972; Parker, 1975).

According to Parker (1975) megaripples on the crests of ridges only develop when the angle between the breakers and the ridges is large and currents on the ridges therefore have a strong longshore component. This causes these megaripples and their corresponding cross-lamination to be oriented obliquely to the coast (Parker 1975; Reineck 1963).

Until now no consistent pattern in the orientation of cross-strata in sets produced by megaripples near the low water mark has been described.

The occurrence of megaripples of association I is restricted to the foreshore zone. On the other hand, structures produced by wind action are formed almost exclusively in the backshore area. For this reason this association will be subdivided in a lower (ass. Ia) and an upper unit (ass. Ib). The main characteristics of the two units are illustrated in fig. 4.

Association II — In runnels and part of the backshore area which is protected by a berm or ridge, wave-ripple cross-lamination formed during high-tide is commonly preserved. Small-scale current ripples and sometimes megaripples are formed by currents flowing down the runnels towards the sea. Migration of these bedforms produces trough-formed

ridge and runnel beach environment

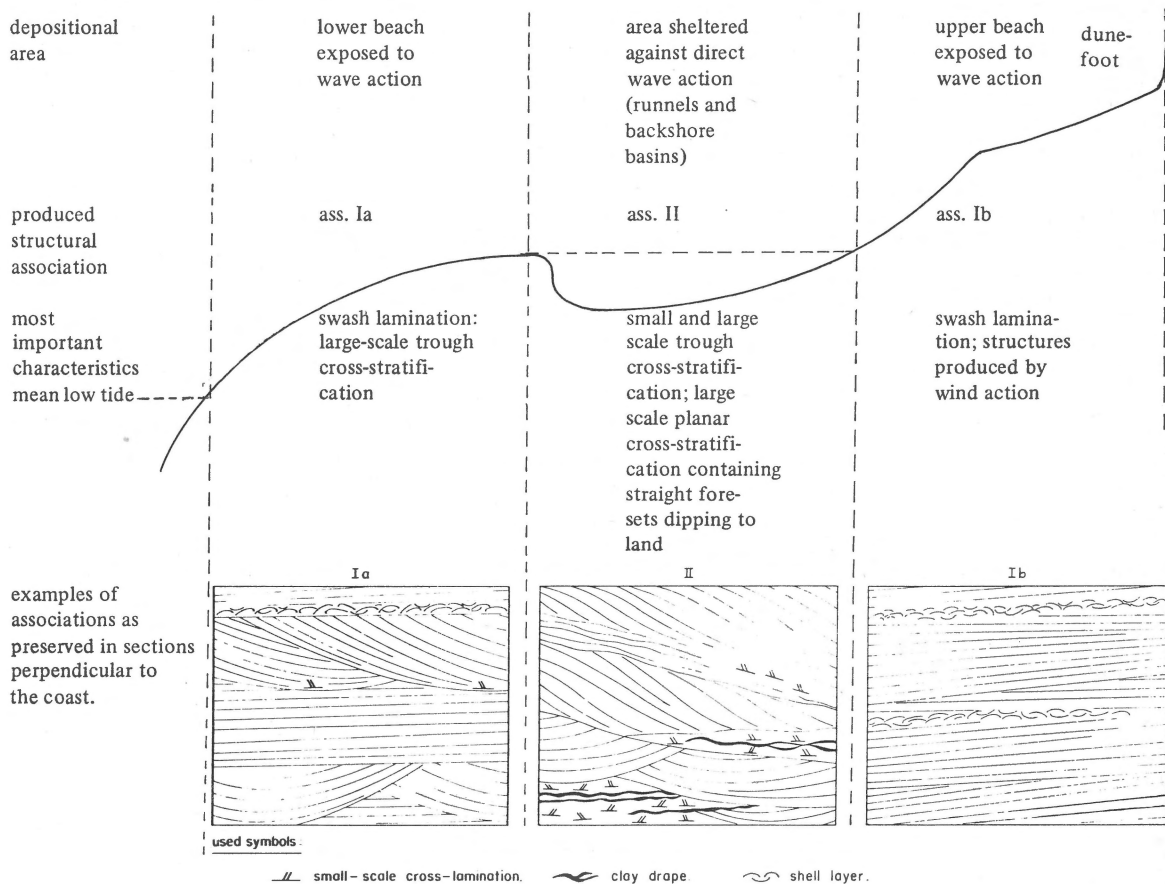


Fig. 4
The subdivision of depositional areas and produced structural associations in the ridge and runnel beach environment.

sets composed of small-scale or large-scale cross-stratification containing concave to tangential cross-strata⁸). Foresets are predominantly oriented in directions parallel to the beach (van Straaten, 1959; Hayes *et al.*, 1969; Davis *et al.*, 1972; Reineck, 1963).

In coastal waters which contain important quantities of clay in suspension, deposition of mud in clay drapes or even in continuous clay layers in runnel sediments may be important (Parker, 1975; Wunderlich, 1972). Clay layers of up to 10 cm in thickness are found in Sapelo Island beaches (Wunderlich, 1972).

Landward oriented lee slopes of ridges are characterized by sets of large-scale planar cross-stratification which are produced during landward migration of the ridge and runnel systems. Sets are generally wedge-shaped (Reineck & Singh, 1973; Psuty, 1966; Panin, 1967; Thompson, 1937).

Foresets are predominantly straight and show a low-angle as well as a high-angle dip to a maximum of 30 degrees in a shoreward direction (Hoyt, 1962; Davis *et al.*, 1972).

During landward migration of a ridge and runnel system ripple cross-laminated beds of the runnel are buried by land-

ward migrating cross-stratification of the ridge. This produces typical vertical sequences in deposits representing this association. The example of this association given in fig. 4 shows such a sequence.

Aeolian influences — On the higher parts of the beach the hydrodynamically controlled structural associations are complemented by some wind generated structures. Wind ripples, dunes and adhesion ripples are often produced but commonly removed quickly by deflation or waves. More frequently preserved are deflation surfaces sometimes showing a concentration of shells as a lag deposit (Doe gla s, 1954).

PRESERVATION OF SEDIMENTARY STRUCTURES IN THE INVESTIGATED BEACHES

Criteria for subdivision into the structural associations proposed here, are related to simple morphological characteristics of a two-dimensional beach profile. On landward

dipping slopes and areas sheltered from swash action by a ridge or berm, association II is formed while elsewhere association Ia or Ib is produced. So on every beach it can easily be deduced from the morphological profile where different associations may form (fig. 4). This means that by comparing successive measurements of profiles valuable information may be gathered about how the different structural associations will be distributed in preserved sediments. Of course, the analysis of beach profiles only permits one to determine a crude outline of the general characteristics of preserved structures. More detailed descriptions of the latter can only be expected from the analysis of cores and of trenches dug into the beach.

In the following paragraphs the known sedimentary structures are integrated into the picture of the dynamics of the studied beaches in so far as it can be reconstructed from measurements of beach variation.

Sedimentary structures in the deeper layers of the beach, where they will remain undisturbed in the course of progradation, are sampled by using a tube coring technique which was developed for this purpose (van den Berg, this volume).

A sampling programme was only carried out at the study area of Schouwen. It was decided that equivalent samples at Zandvoort beach should not be collected. In the first place because disturbances by human activities are too extensive here and in the second place most of the important sedimentary structures which occur at the surface at Zandvoort have already been described by Doeglas (1954). Furthermore the Zandvoort beach belongs to the group of

semi-permanent ridge and runnel beaches of which individual structures and their relation to morphology have already been described by a number of authors and hardly need further investigation (see previous paragraph).

So the lack of information of primary structures from cores will not prevent a discussion on preserved sediments of the Zandvoort beach.

The beach near Zandvoort: results of the measurements

Measurements of beach variation started more than one hundred years ago, when a fixed range system was established all along the coast by the Rijkswaterstaat. Since then the horizontal distance of the low water line, the high water line and the dune foot were measured yearly from fixed poles lying along the coast at distances of 1 km or less.

These observations show that from 1860 until 1960 the dune foot of the beach near Zandvoort moved more than 50 metres seawards (Edelman, 1967). In 1968 three beach profiles near Zandvoort were chosen by the Rijkswaterstaat for more detailed measurements of beach variation within short time intervals (beach pole 70, 70.5 and 71 (see also fig. 2)). The distance between two neighbouring poles is 0.5 km. Variation in beach height is measured at iron pipes placed at 10 meter intervals from the dunes to the low water line.

The analysis of structural associations preserved in the beach at Zandvoort is based upon a record of 111 such beach surveys covering a period of 8 years, from January 2, 1968 till January 6, 1976. During this period the dune foot re-

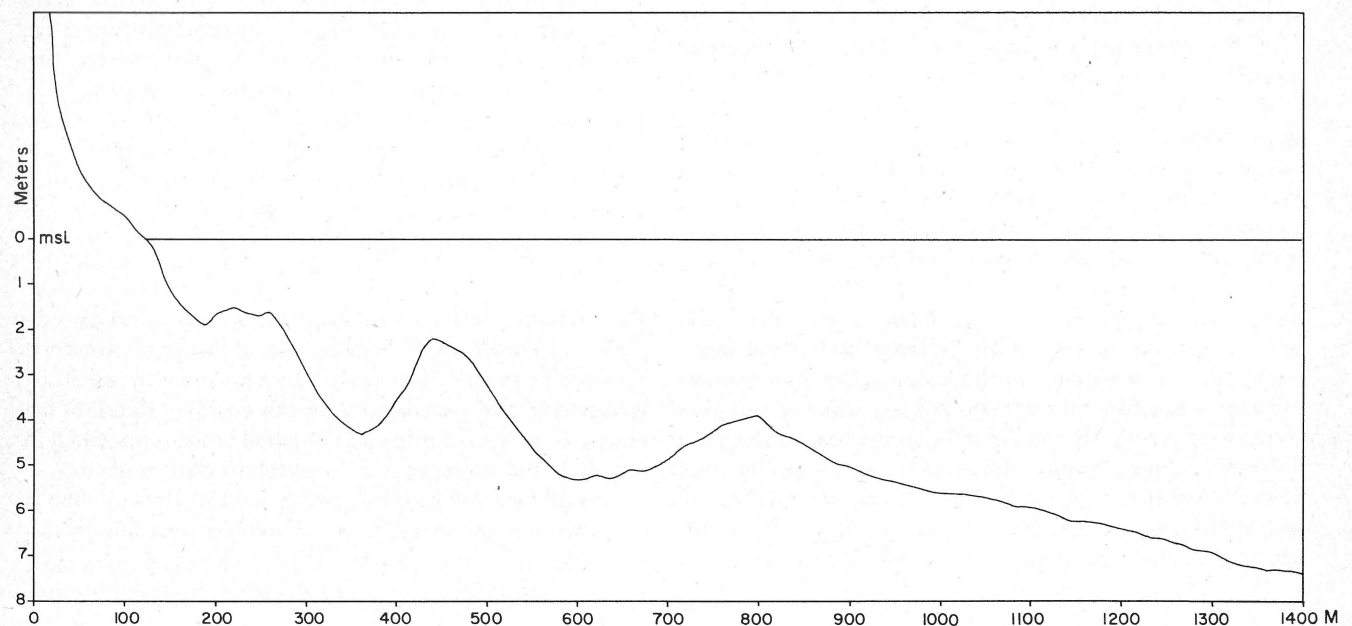


Fig. 5
The beach to offshore bottom profile at beach pole 71, near Zandvoort (January 1974).

mained in practically the same position and the beach did not show any continuous gain or loss of sand.

So the recorded variation in beach height is not related to long term coastal processes but is only to be explained as a short term variability due to changing wave and weather conditions.

As stated before the beach at Zandvoort belongs to the group of semi-permanent ridge and runnel beaches. During these 8 years of observation numerous storm-related cycles of erosion and deposition occurred.

The successive surveys indicate that storms have to be rather severe and of long duration to produce the characteristic post-storm profile on this beach. This is due to the well developed system of longshore bars off the coast where part of the energy of the incoming storm waves is dissipated (fig. 5). Morphological changes which can be explained by cycles of erosion and deposition are therefore often confined to so called accretional stages (see above).

At beach pole 70, typical flat post-storm profiles have only been measured 8 times during the total of 111 beach surveys (7.2%). Late accretional profiles characterized by the absence of runnels and by a relatively steep seaward dipping foreshore, make up 21.7% of the record. Of the beach surveys at pole 70 71.2% consisted of early accretional profiles showing one or two ridges (1.2 ridges on average).

Preservation of structural associations — In fig. 6A the observed lowest points of the beach sections analysed were plotted and linked to form a basal profile. The last surveyed record (January 6, 1976) is indicated by the upper lines of the sections. Above the basal profile the beach has been reworked since January 1968. So the figure shows deposits laid down and preserved between January 1968 and January 1976 in sections perpendicular to the coast. In these sections areas are indicated which, according to the data, are reached by low-lying runnels or unsheltered sea facing slopes alone, or by both runnels and seaward dipping beach slopes. It is obvious that at those levels which are only reached by runnel floors, the sediments deposited will consist of association II, whereas in areas deeply denuded under conditions of unsheltered sea facing slopes association I will be preserved.

We must be aware that the lowest position of runnels or unsheltered sea facing slopes, as recorded from the beach surveys, will not be completely identical to the real maximum depth of reworking. Such maximum depth of reworking may very well have occurred on a day when no measurements were made. Also megaripples on the beach may give a distorted picture; in this case erosion can be greater than 15 cm below the average beach level. These two factors will in reality cause a somewhat lower level of reworking which can not be deduced from fig. 6A. There are, however, no

reasons to suppose that this would fundamentally change the picture.

Beach erosion during storms and during accretional stages — On January 2, 1976 an exceptionally severe storm affected the Dutch coastal area. Storm surge levels at some places approximated to the values of the February 2, 1953 storm surge, which caused extensive flooding of coastal areas in the country, especially in Zeeland. The January 2, 1976 storm surge level reached N.A.P. + 3.6 m⁹⁾ at Zandvoort beach, or 2.7 m above the mean high water level. The resulting post-storm profiles, which were measured on January 6 and which formed the end of the measurement series, show an important denudation of the beach near the dunes to levels that had not been reached earlier during the 8 years of observations.

As can be seen in fig. 6A all of the observed profiles lying between the last recorded situation and the level of N.A.P. + 1.6 m are unsheltered sea facing slopes. Like the last recorded situation most of these are part of post-storm profiles, above N.A.P. + 1.2 m even the basal profile is made up of only post-storm profiles.

In contrast with the erosive effectiveness of major storms on the backshore even under exceptionally severe wave attack the lower beach does not undergo important denudation. On the contrary, as illustrated in fig. 3, storms can result in considerable accretion of the lower beach. These facts are in accordance with the findings of Edelman (1968), who stated that denudation of Dutch beaches during serious wave attack is most severe in the backshore area.

In addition it is important to note here, that measurement of relatively low positions in the foreshore of the Zandvoort study area was always connected with some fair weather accretional situation. In most locations on the foreshore low positions are only reached by deep scouring runnels. Near the low water line extremely low positions are sometimes reached by unsheltered seaward dipping slopes of late accretional stage, when large quantities of sand were removed from the foreshore and transported towards the backshore to form high, broad berms.

The deduced progradational sequence of structural associations — A compilation of the vertical sequence of structural associations in the three analysed sections which would be preserved if slow progradation of this coast continued in the same way as it has for the past hundred years, is presented in fig. 6B. In this sequence four zones can be distinguished:

- A. a basal zone composed of ass. Ia and ass. II. This zone is transitional between the beach and the upper shoreface.
- B. a zone from about N.A.P. -0.6 m to N.A.P. +0.6 m made up of ass. II and representing deposits of foreshore runnels.
- C. a zone consisting of ass. Ib and ass. II deposited in the upper part of the foreshore and the lower part of the backshore.

⁹⁾ Beach heights are reduced to Amsterdam Ordnance Datum (N.A.P.) which is about equal to Mean Sea Level; N.A.P. + 3.6 m means 3.6 m above the N.A.P. level.

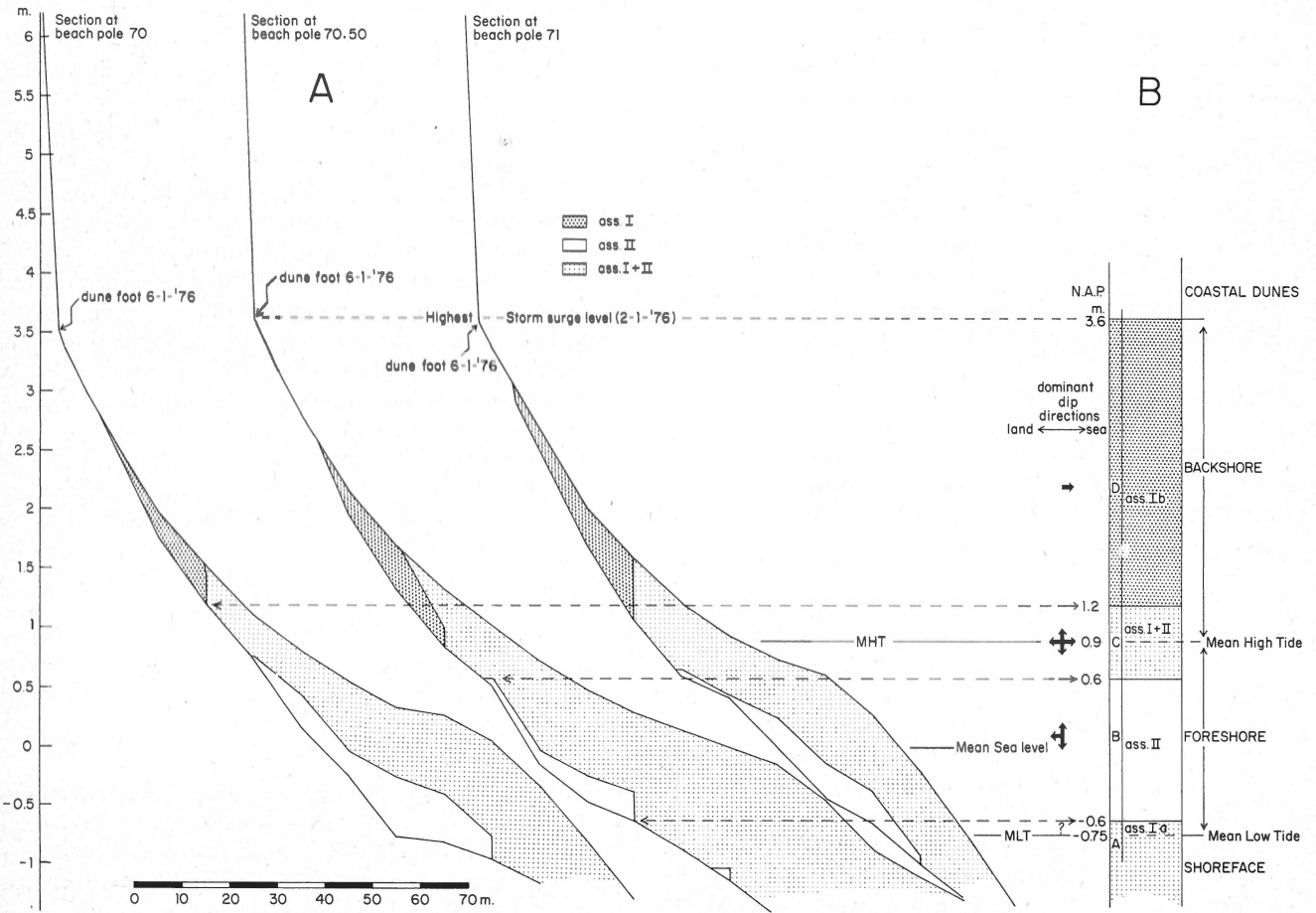


Fig. 6
 A: structural associations in 3 beach sections near Zandvoort preserved according to measurement analysis from 2-1-1968 till 6-1-1976.
 B: structural associations preserved in a vertical sequence, which will be produced by continuing progradation, as compiled from the beach sections.

D. an upper supratidal zone more than 1.2 m thick and made up of ass. Ib.

The preserved deposits of the lower beach, the zones A and B, represent fair weather conditions or, in terms of wave energy, low to moderate wave energy levels. On the other hand the preserved sediments of the backshore or deposits of zone D predominantly represent storm or high wave energy conditions. In the upper foreshore zone C forms a transition between fair weather deposits of the lower foreshore and the predominantly storm generated layers of the backshore.

The beach at Schouwen: results of the measurements

Regular measurements of beach- and nearshore variations around Schouwen started in the course of the 19th century. Measurements were carried out by the Rijkswaterstaat and the available data have been interpreted and discussed by de Smit & van Malle (1971). According to these investigators natural processes of accretion and erosion along the Schouwen shoreline are determined mainly by the position of adjacent offshore banks and tidal channels of the Grevelingen and Oosterschelde ebb "tidal delta" systems (fig. 1). The

extensive shoals, which sometimes emerge during low tide, provide shelter against destructive storm wave attack and promote beach accretion; whereas active tidal channels, when situated close to the shoreline, have an erosive influence on the beach. The pattern of shoals and channels is changing constantly in the course of time and, in relation to this, a change of the location and rate of progradation or erosion along the coast occurs.

The available material upon which the analysis of long term coastal behaviour was based, dates back to 1880 and consists mainly of an uninterrupted record of yearly observations on the distance of dunefoot, mean high water level and mean low water level relative to the beach poles.

Accretion and morphological change — With respect to our study area these measurements show, that a long period (from 1880 till 1930) during which the beach remained in static equilibrium, was followed by a period of rapid accretion. From 1930 till 1955 the line of MLW and of MHW shifted 150 m and 100 m seawards respectively. From 1955 till 1962 however the beach showed a retreat of the MLW line of 60 m, the MHW line retreated 55 m.

A measuring programme consisting of very frequent and detailed observations of beach height was started by the Rijkswaterstaat in 1962. As at Zandvoort, the beach height is measured at iron stakes placed at 10 m intervals in a line perpendicular to the coastline. From July 3, 1962 till June 6, 1972 measurements were carried out weekly, thereafter fortnightly.

During this period the beach experienced considerable accretion. From 1962 till 1967 the sand of the profile between N.A.P. +3.5 and -0.75 m increased altogether by 30.1 cubic metres per metre width of beach. From 1968 till 1975 accretion was much faster, averaging 40.4 cubic metres per year. Fig. 7 shows that the rapid accretion during these recent years coincides with an overall decrease of beach

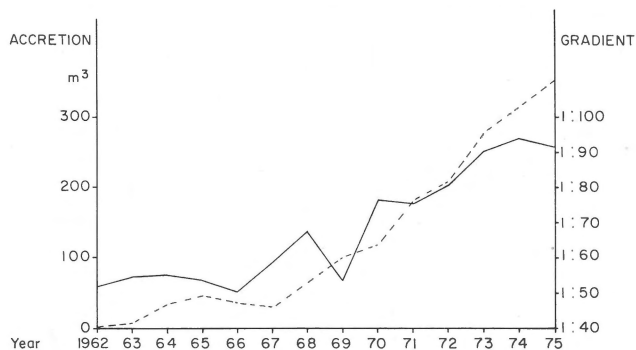


Fig. 7

Accretion of beach profile and change in overall beach gradient in the study area on Schouwen.

----- cumulative accretion between N.A.P. +3.5 and -0.75 m in cubic meter per meter width of beach, according to average year profiles.

—— overall gradients of average year profiles (according to linear multiple regression analysis).

Data obtained from Rijkswaterstaat; data reduction by the author.

gradients. This is caused by a differentiation of the rate of accretion in the lower and upper part of the beach; fast accretion of the lower beach is followed by a much smaller accumulation in the upper part of the beach. The transfer of the surplus sand from the foreshore towards the backshore is apparently considerably delayed. This is also apparent in the difference in seaward shifting of the low water line (120 m) and the M.H.W. line (90 m). The formation of new foredunes occurred even later; the position of the dune foot was found only 15 m further seaward in 1975 than in 1968.

The retarded accretion on the backshore and dunes caused a considerable increase in beach width, — or decrease in overall beach gradient — which in turn resulted in an increase in the number of ridges within the beach profile. This increase can be seen from their average occurrences: 1.2 ridges during 1962-1967 and 3.1 ridges in 1972-1975.

During the first period of slow progradation ridges were practically restricted to the foreshore zone. Landward movement to the backshore generally ended in a welding of the ridges on a relatively steep seaward slope. Because of this relatively high beach gradient the innermost ridges could — in this early period — also be eliminated during onshore storms. After 1967, when a gradual overall decrease of the beach gradient occurred, ridges were able to migrate further landwards and to a higher position on the backshore before welding occurred.

Differentiation of structural associations in preserved deposits — Compared to the beach observations at Zandvoort morphological change between successive measurements at Schouwen was very slight. This was due to the fact that consecutive beach surveys were more closely spaced in time, and because morphological change at the Schouwen beach was considerably slower and without major disturbances in sedimentation owing to its wave-sheltered position; at the Schouwen beach the average landward migration of ridges is less than 3 m per week, whereas at Zandvoort displacements of more than 20 m per week are common. Furthermore regular measurements were carried out within shorter intervals. For these reasons changes of the beach profile within these intervals were very slight. These circumstances enabled the correlation of data of consecutive measurements to be made in great detail.

Fig. 8 shows the section of preserved beach deposits from the beginning of detailed measurements in July 1962 till October 14, 1975 (upper line in this figure). Differentiation of the deposits of this section is based on the same subdivision of depositional beach areas as used in the Zandvoort study area.

Deposits composed of association II and Ib — As is shown in fig. 8 most of the preserved sediments consist of association II, which is connected with the dominating influence of the continuous presence of ridges and runnels on this beach. After 1967, when the average gradient of the beach has been decreasing due to rapid upgrowth of the lower beach, ridges

were able to move to higher positions on the backshore. This caused a step by step landward migration of the structural association II sequence over the seaward facing slope of the structural association Ib sequence from a level of N.A.P. +0.2 to +1.1 m in the period of slow progradation up to more than N.A.P. +2 m after 1972 (fig. 8 between location B and A).

Fig. 8 gives further details of the geometry of the sedimentary units of individual runnel and overlying ridge complexes which were preserved during the course of progradation. The eroding troughs form the lower boundaries of these complexes. Fig. 8 (right part) also shows that, instead of a decrease in depth as one would expect from their migration towards the backshore, the individual runnels often show a temporary deepening in a landward direction. This is caused by insufficient compensation by lateral accretion of land-

ward migrating ridges, when sand is removed by longshore currents within the runnel. This is very often the case in the lower part of the beach. Genetically, ridges can be described as "swash bars", since their formation and migration is mainly governed by wave swash processes (King & Williams, 1949). So ridges within the lower beach are especially dynamically active during low water levels.

During high tide, when the water level is more than 1 metre above the ridge crests, waves commonly do not break anymore on these ridges and landward sand transfer over the ridges towards the forelying runnels is unimportant and eventually may not compensate the removal of sand in the runnels by longshore currents. In the course of landward migration, however, the elevation of the ridge crests gradually increases and finally becomes so high that wave activity on the ridges only consists of surf and swash processes. In

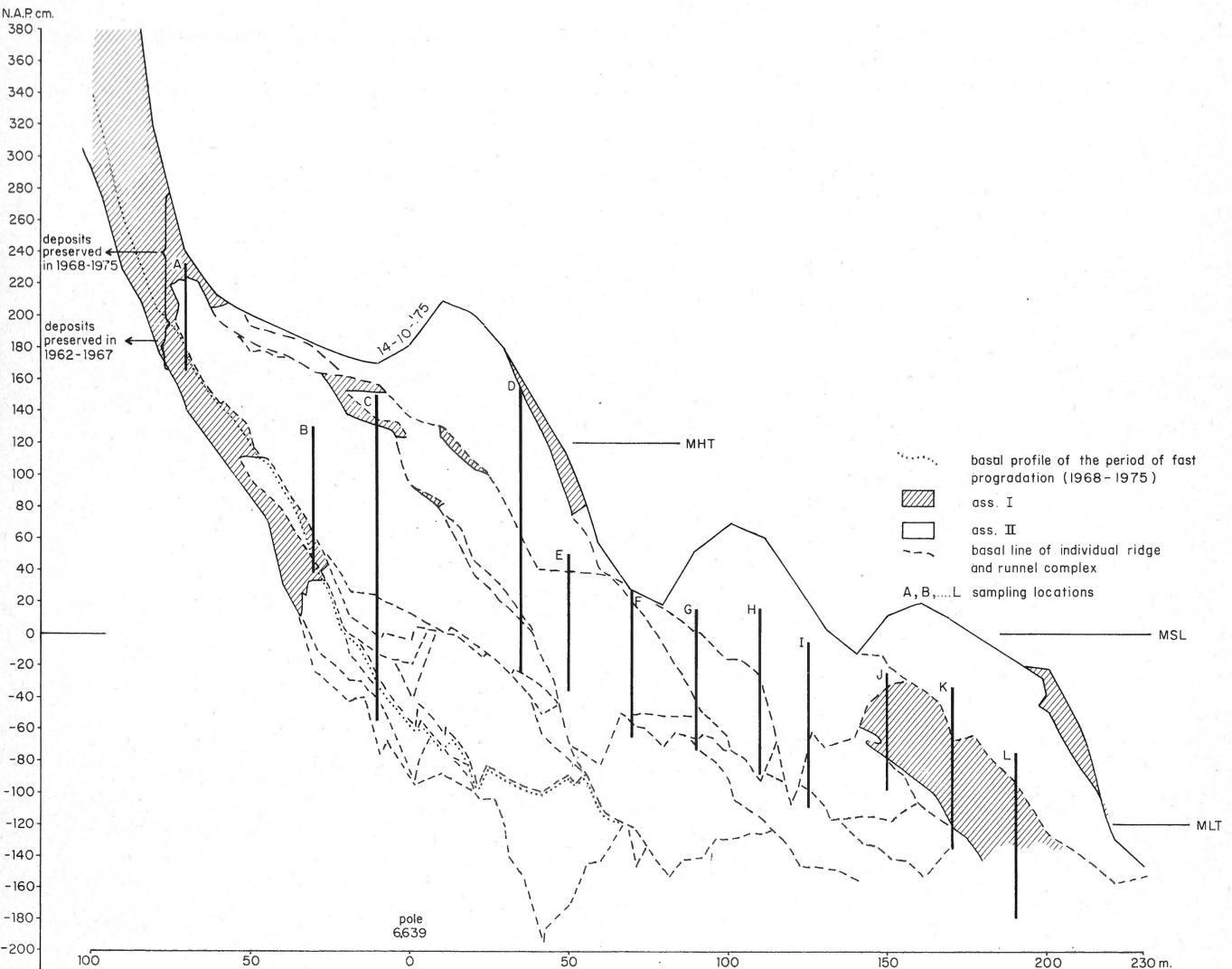


Fig. 8 Beach deposits preserved from 3-7-1962 till 14-10-1975 in a section transverse to the shoreline according to measurements of beach variation at measuring pole 6.639, Schouwen.

this situation landward sand transfer over the ridge during submergence is always important and consequently processes of runnel erosion and ridge accretion are better balanced; runnels will then decrease in depth while they migrate landwards as they follow the average beach gradient.

This characteristic of runnel development is clearly demonstrated in fig. 8: In the lower part of the section lower boundaries of preserved ridge and runnel complexes change irregularly, whereas in the upper part the lower boundaries show a continuous rise in elevation in the landward direction. The transition point where the runnels become less erosive occurs at different elevations for each individual runnel. This is understandable, because it does not depend on the depth of the runnel but is related to the height of the ridge. It is obvious from fig. 8 that runnel bases lying above mean sea level within this section dip uniformly seaward. Obviously for these runnel elevations the ridge crests have surpassed that critical height above which runnels always decrease in depth in the course of landward migration. According to the measurements this critical height is found at about 0.7 m below mean high tide (N.A.P. +0.5 m).

Deposits composed of association Ia — Despite the decreased eroding capacity of runnels in the upper part of the beach and the fast progradation during the last few years it can be observed that landward migration of runnels is always accompanied by some slight erosion which is generally sufficient to remove the mostly thin sheets of ridge stoss side accumulations (ass. Ia, see fig. 8). The only important deposit composed of ass. Ia which can be expected to be preserved in the long run is found between 140 and 200 m seaward from measuring pole 6639. However, this deposit does not really belong to the ridge and runnel system. The origin of it is connected with a channel, belonging to the offshore tidal delta system which was found very close to the shoreline in spring 1973 and which caused temporary but considerable erosion of the lower beach. Later on sediments composed of association I were deposited on the landward margin of this channel.

The beach at Schouwen: results of the sampling program

Information about sedimentary structures visible in lac-

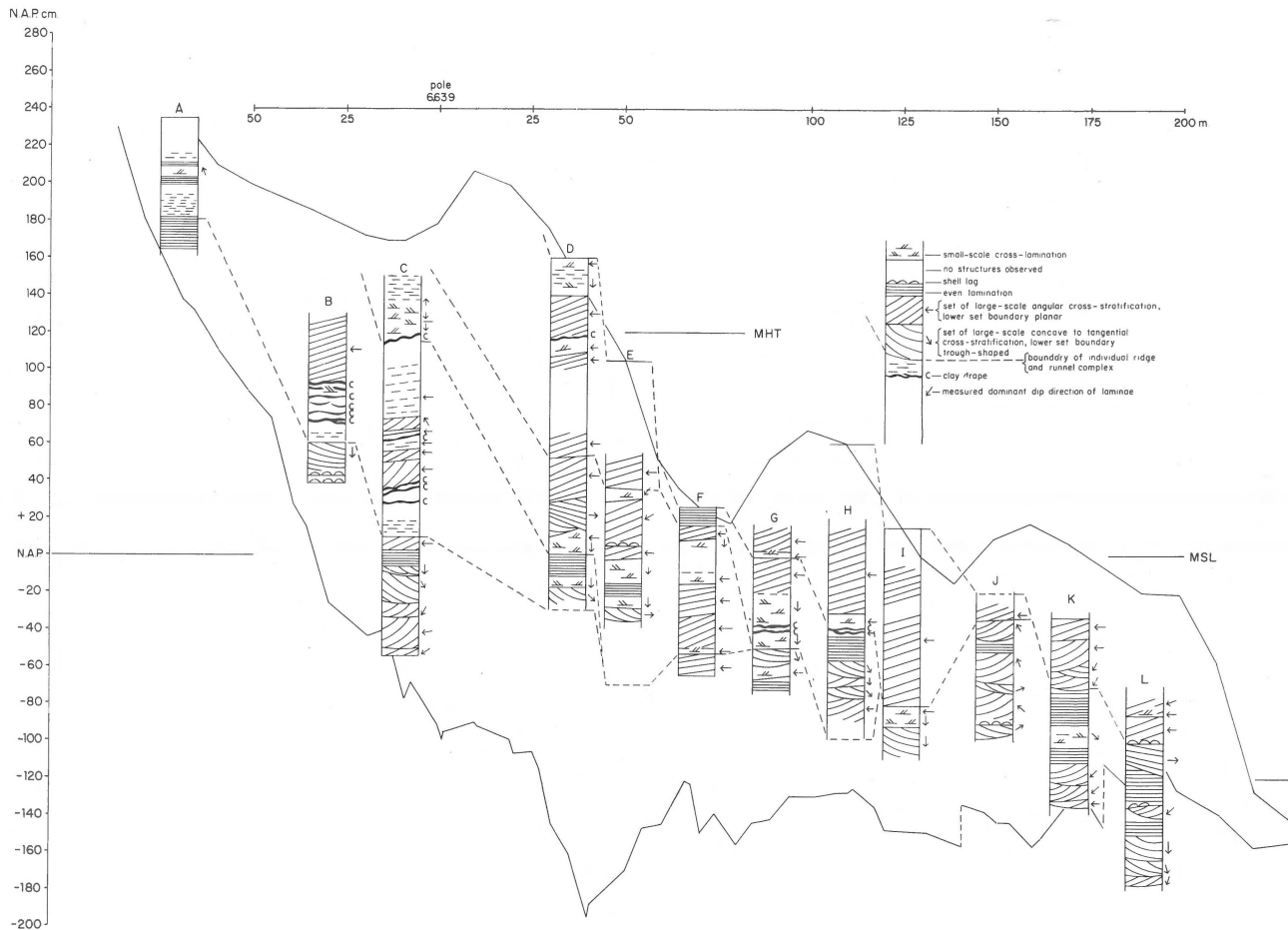


Fig. 9
Physical structures at 12 sampling stations on the beach profile at measuring pole 6.639, Schouwen, as revealed from lacquer peels, and their lateral relationship as interpreted from structural sequences and measurements of beach variation.

quer peels made from walls of trenches dug into the beach and compiled from groups of borings taken in trenches at 12 sampling stations along the measured beach profile is summarized in fig. 9 (for the sampling methods used see *van den Berg*, elsewhere in this volume).

Deposits composed of association II: ridge and runnel systems — In the description of association II it was mentioned that a characteristic vertical sequence of sedimentary structures originates when runnel sediments are buried by a landward migrating ridge. According to *Hayes et al.* (1969) this vertical sequence can be subdivided into three units (from below upwards): a basal or runnel unit with small-scale and large-scale trough cross-stratification predominantly dipping in directions parallel to the shoreline. These runnel deposits are overlain by a middle unit in which the most important component is large-scale cross-stratification containing straight to convex foresetting representing the lateral accretion of the ridge. Finally this complex is covered by an upper unit consisting of even lamination and other structures which are formed on top and on the seaward face (stoss side) of the ridge.

When we compare the visible structures on lacquer peels with our information about preserved ridge and runnel systems deduced from measurements (as presented in fig. 8) it is possible, in a number of cases, to recognize boundaries between sequences of individual ridge and runnel systems on the lacquer peels and to correlate them across to profiles of neighbouring sampling stations (see fig. 9). In doing so it appeared that the sequences of structures representing ridge and runnel systems in the samples are in general incomplete: practically none of the sets of land-oriented cross-stratification of the ridge slip faces is overlain by horizontal to gently seaward inclined even lamination of the ridge crest and ridge stoss side. This is in accordance with the conclusions of the previous paragraph. Ridge crest sediments largely belong to association Ia, which is almost invariably removed between ridge and runnel sequences.

Since down runnel currents tend to erode and transport rather than contribute to deposition, it is understandable that the basal or runnel units are usually badly represented and are sometimes even absent (for instance in fig. 9 upper sequence at location D, above N.A.P. +0.5 m; sequence at F between N.A.P. -0.5 and +0.2 m).

The presence of the middle unit of the ridge and runnel sequence in the sediments largely depends on the preservation of the individual ridge and runnel complexes. If only a thin layer is preserved most of the ridge accretion unit will be removed and only the basal unit will remain; such is the case in the lower part of the sampled deposits at C (below N.A.P. -0.1 m), which according to fig. 8 is formed by a number of relatively thin remnants of ridge and runnel complexes. Owing to the fast beach accretion of the last few years the preserved thickness of younger ridge and runnel systems is generally larger than before and with it the share of ridge lateral accretion units in the sediment has also increased.

In some of the lateral accretion units several phases of active lateral accretion can be recognized which are separated by erosional unconformities (location C from N.A.P. +0.3 till +1.2 m and F from N.A.P. -0.5 till +0.2 m). On the trace of the erosional plane a few small-scale cross-stratified sets are often intercalated, sometimes draped with thin clay laminations. Sets of large-scale high-angle cross-stratification are produced during periods of rapid lateral accretion of the ridges.

Erosional unconformities are produced during periods of temporary flattening of the steep slip faces of the ridges. The transition to more gently inclined surfaces may be achieved by a number of different processes. As pointed out by *Wunderlich* (1972) small changes in the foreset angle of the ridges and slight traces of erosional unconformities may be attributed to tidal fluctuations.

Most erosional unconformities observed in lacquer peels, however, are much too large to be attributed to such small changes in the angle of ridge foresetting. They point to a greater change in slope, which must be connected with changing conditions of incoming waves and/or wind.

It was observed several times by the author that the landward front (slip face) of the ridges was flattened after westerly storms. Measurements indicated that this flattening was accompanied by serious erosion of the upper part of the slip face. Modifications to a more gently inclined surface are also occurring when strong winds are blowing from a northeasterly direction. Longshore currents set up by these winds force water into the runnel entrances, which for reasons discussed earlier always open to the east (see also fig. 2). This reduces the down-runnel return flow and so indirectly counteracts the landward movement by the waves of water and sand over the ridges. Under those conditions lateral accretion of the ridges is delayed or even halted and the steep and unstable slip faces are flattened by waves overtopping the ridges.

As soon as favourable conditions for ridge migration return, slip face accretion is reactivated and a new set of steeply inclined large-scale cross-stratification builds out over the flattened ridge lee side. In front of the steep slip face wave and/or current ripple lamination together with a few mud drapes, may be formed on the gently inclined surface. These deposits of runnel origin become intercalated between tabular or wedge-formed, large-scale, cross-stratified sets after burial by the landward migrating steep slip face.

When, in the course of landward migration of a ridge and adjacent runnel system, the ridge crest becomes so high that it is only overtopped during high tide by the swash of the larger waves, the morphology of the system changes. The runnel is reduced to a shallow depression, since down-runnel currents have become weak and remove only small quantities of sand. The ridge is transformed gradually into a berm with its characteristic steeper seaward face and more gently inclined landward slope and with only local and temporary development of a small and steep slip face. The shallow depression is filled up by large-scale low-angle, land-oriented,

cross-lamination, covering and merging in landward direction into small-scale cross-lamination of current and wave ripple origin (Wunderlich, 1972). The ridge and runnel system sampled at location B (above N.A.P. +0.6 m) and the one occurring between N.A.P. 0 and +0.5 m at station D have merged into this "backshore depression fill" sequence at stations A and C respectively.

In those upper reaches of the ridge and runnel complex measured dips of low-angle cross-laminated units are about $0-4^\circ$ towards land, whereas in foreshore deposits dips of ridge-foresetting are between 10 and 20° and occasionally up to 30° .

Deposits composed of association I – After 1967 ridge and runnel systems were able to migrate to higher positions on the backshore than before. This resulted in a burial of the sediments formerly laid down on "unsheltered" sea facing slopes (association I) by sediments of ridge and runnel systems (largely association II) and between 20 and 70 m landward of measuring pole 6.639 (fig. 8).

Measurements of the beach profile suggest that the lower part of the beach sample of station A represents deposits of formerly unsheltered seaward-inclined beach slopes. Ridge and runnel systems arrived at this part of the beach in 1971 and burial by ridge and runnel sequences started in spring 1972. The conclusions drawn from the measurements are confirmed by the record of physical structures, for below N.A.P. 1.8 m at sampling station A, deposits consist of evenly laminated sand, indicating deposition by swash processes on unsheltered sea facing slopes (fig. 9).

Information on preserved structures of the higher backshore is rather scarce, for much of the original bedding has been disturbed by human activities. If not disturbed in this way, the laminations are generally faint and irregular. This seems to be a characteristic feature of the deposits of the higher beach in this location. Part of it can be attributed to wind action: erosional structures such as scour and tool marks resulting from deflation are often produced, giving rise to faint and irregular flat surfaces in the deposits (evidence for wind generated depositional structures could not be found). On the other hand, faint lamination is likely to be produced by disturbance of the stratification owing to the escape of air from dried surficial sand layers during sudden flooding of the area.

From measurements we know that association Ib inter-fingers in a landward and upward direction with foredune aeolian sands in a fairly wide zone between N.A.P. 3.3 and 4.0 m.

The measurements indicate that another deposit composed of association I exists between 140 and 200 m seaward of measuring pole 6.639 (fig. 8). The association of structures revealed from samples taken from this layer at the stations J (below N.A.P. -0.3 m, K (below N.A.P. -0.7 m) and L (below N.A.P. -1.0 m) does correspond very well indeed with the description of structural association Ia since it is composed of evenly laminated sands (swash lamination) and

sets of large-scale trough cross-stratification which do not show any preferred directional orientation.

Directional properties of sampled cross-laminations – From readings of cross-lamination azimuths as indicated in fig. 9, a rose diagram was composed which clearly shows a bimodal pattern (fig. 10). The land-oriented cross-lamination of the ridge accretion units forms a maximum with 45.2% of the number of readings. A secondary maximum is formed by the predominantly eastward orientation of the small-scale cross-stratified beds and large-scale, cross-stratified sets of the runnel (basal) units of the ridge and runnel sequences. Instead of showing the characteristic bimodality in two opposite directions parallel to the main strike of the coastline (as mentioned in the previous paragraph) cross-lamination azimuths of the runnel sediments are predominantly oriented in only one of these directions. This is due to the fact that ridges on this beach always diverge eastward from the coast (or in other words that runnels always open eastward to the sea), which determines the downrunnel return currents responsible for most of the runnel cross-lamination to be directed towards the ENE.

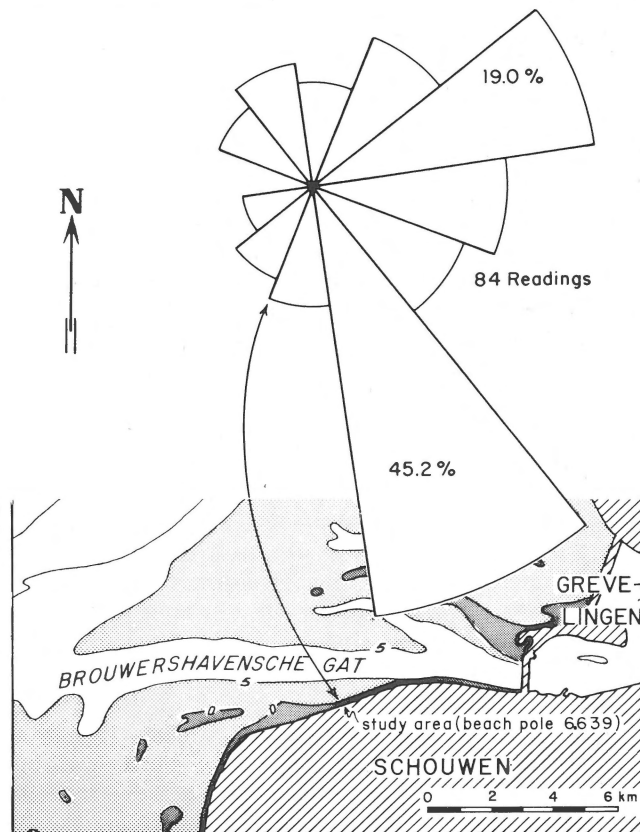


Fig. 10
Rose diagram of crossbed azimuths as measured in lacquer peels from samples of the Schouwen study area.
Areas of segments are proportional to the number of readings.
Depth in m below Mean Low Spring Tide.

Comparison of the constructed sedimentary sequences of the two beaches investigated

The beach area studied at Schouwen has recently shown a change into a remarkably higher rate of progradation. As described above this was accompanied by a change in the location of zones composed of distinct structural associations preserved in the vertical sequence (fig. 8) and by a change in the preservation of individual ridge and runnel systems: increase in thickness of "ridge and runnel sequences" and an increasing share of the middle or ridge accretion units within it (fig. 8 and 9).

On the other hand, the vertical zonation of the structural associations in deposits representing the period of slow progradation of the Schouwen study area, from 1962 till 1967 (fig. 8), and the sequence constructed from the — also slowly prograding — beach near Zandvoort (fig. 6B) do not show great differences. Apparently the local difference in storm wave shelter and the related difference in morphodynamics between the two studied beaches are too slight to produce appreciable differences in preserved vertical sequences, at least when only the position of zones of different structural associations is considered; Some little differences may exist in the quantitative ratios of various internal structures in the same association, as preserved at the beaches studied at Zandvoort and at Schouwen. However, it is obvious that the effect on preserved sediments of the changing rate of progradation on the Schouwen beach overshadowed the effect of the local difference in storm wave protection and beach dynamics between the two beach areas.

CONCLUSIONS

In comparing sequences of sedimentary structures in modern and ancient shoreline environments, the current use of the division into low, moderate and high energy environments according to the yearly average of wave breaker height is meaningless since sedimentary structures preserved in these environments will generally not represent average wave conditions.

Until now practically no data have been available on the longterm preservation of sedimentary structures in shoreline sediments. For this reason it is not yet possible to evaluate individual factors influencing preserved sequences and it is unfortunately far to early to propose a good and refined alternative to the existing wave energy classification.

It is clear however that differences between the morphodynamics and the preserved sequences of the two described beaches are mainly due to local differences in the degree of shelter from storm waves and the rate of progradation.

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