Mid- en Late-Holocene Coastal Evolution in the Beach-Barrier Area of The Western Netherlands

L. van der Valk

STELLINGEN

Behorende bij het Proefschrift "Mid- and Late-Holocene Coastal Evolution in the Beach-Barrier Area of The Western Netherlands" van L. van der Valk, te verdedigen op 3 november 1992 te Amsterdam.

1. Als het criterium van de fluviatiele herkomst van het sediment als kenmerk voor delta's moet gelden, dan is de Rijndelta gedurende het Holoceen slechts tijdelijk een delta geweest.
Kruit, C.-, 1963: Is the Rhine delta a Delta ? Verh. KNGMG Geol. Serie 21-2, 259-266.
De Groot, Th.A.M.- & De Gans, W.-, (in press): Facies variations and sea-level rise response in the lower Rhine area during the last 15.000 years (The Netherlands). Meded. Rijks Geologische Dienst.

2. De trend in de ontwikkeling van de schone Hollandse kust sinds het begin van de progradatie is die van een graduele versteiling van het kustprofiel, gekoppeld aan het stelselmatig in aantal afnemen van zeegaten in het kustvak Hoek van Holland-Bergen en een toename van de eolische 'lek' vanuit de zeereep.

3. De kustafzettingen in West Nederland beneden de zgn. dagelijkse golfbasis zijn primair storm-geinduceerd.
Dit proefschrift.

4. Het is aannemelijk dat in het Subboreaal het energetisch golfklimaat in de kustzone van de zuidelijke Noordzee aanzienlijk lager is geweest dan thans. De toenmalige lage zeespiegelstand, in combinatie met de morfologie van de Noordzeebodem ter plaatse zijn in dit opzicht bepalend geweest.
De Gee, A.- & Ridderinkhof, H.- , 1991: Hydrografie en geomorfologie. - in: De ecologie van het Friese Front. NIOZ-Rapport 1991-2, Texel, 15-20;
dit proefschift.

5. De fase van progradatie in de ontwikkeling van westkust van Nederland staat niet op zichzelf, maar vormt een noodzakelijke fase in de lange-termijn kustontwikkeling.
Beets, D.J. et al., 1992: Holocene evolution of the coast of Holland. Marine Geology 103, 423-443 (= Hoofdstuk IV van dit proefschrift).

6. De vorming van de Jonge Duinen langs de Hollandse kust is niet catastrofaal verlopen.

7. De (huidige) terugwijking van de Hollandse kust ten noorden van Egmond en ten zuiden van Scheveningen is niet aan neotektoniek te wijten.
contra: Wiersma, J.-, 1991: De ontwikkeling van de Hollandse kust; een kwestie van schaal. Grondboor en Hamer 45, 129-134.

8. Het altijd te beperkte oplossend vermogen van de beschikbare dateringsmethoden vormt een uitdaging voor de geologische creativiteit.

9. Ten onrechte wordt tot nu toe bij de palynologische analyse van klastische sequenties veel te weinig aandacht geschonken aan de taphonomie van pollenkorrels en palynomorfen.

10. De verregaande algemene ontwatering (op landbouwtechnische gronden doorgevoerd) van de hogere gronden van Nederland, heeft niet alleen een geweldig verdrogend effect gehad op deze gronden, maar ook op het voorstellingsvermogen van werkers aan de jongere geologie van dit gedeelte van Nederland.

11. Bioturbatie verlaagt de draagkracht van klastische sedimenten in hoge mate.

12. Het tracé van de Hoge Snelheid Trein in West Nederland dient ondergronds te worden aangelegd.

13. Aan het subsidiebeleid van de overheid voor organisaties, die zich bezighouden met natuurbehoud, dient niet getornd te worden. Elke andere besteding van dat geld staat garant voor kwaliteitsverlies van natuurgebieden.

14. Uit oogpunt van concurrentievervalsing dienen vervullers van de zgn. vervangende dienstplicht niet in hun eigen of aanverwante vakgebieden werkzaam te zijn.

15. Het tegen (geringe) vergoeding uitreiken van een OV-jaarkaart aan studenten is niet bevorderlijk voor de lichamelijke conditie van die bevolkingsgroep.

16. De maatschappelijke acceptatie van het versterkte broeikaseffect ijlt voor bij de wetenschappelijke. Dit blijkt o.a. uit televisie-reclames waarin een voor het product wervende werking moet uitgaan van het feit dat het niet bijdraagt aan het afsmelten van de ijskappen.

MID- AND LATE-HOLOCENE COASTAL EVOLUTION IN THE BEACH-BARRIER AREA OF THE WESTERN NETHERLANDS

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Photo: North Sea coast at the Wassenaarse Slag, Province of Zuid-Holland, with multiple bars visible, at low tide.
Rijkswaterstaat, North Sea Directorate, courtesy N. Vink.

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MID- AND LATE-HOLOCENE COASTAL EVOLUTION IN THE BEACH-BARRIER AREA OF THE WESTERN NETHERLANDS

ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad van doctor aan
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door

LAMBERTUS VAN DER VALK

geboren te Scheveningen

Febodruk, Enschede
1992

Promotoren	:	prof.dr. W. Roeleveld
		prof.dr. W.H. Zagwijn
Copromotor	:	dr. D.J.Beets
Referent	·	drs. Th.B. Roep

aan mijn ouders
aan Jeannette, Floris en Maarten

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SAMENVATTING

Het in dit proefschrift besproken gebied beslaat de kust van West-Nederland tussen Hoek van Holland en Alkmaar en het aangrenzende ondiepe deel van de Noordzee. Het doel van het onderzoek was het verwerven van een gedetailleerd inzicht in de opbouw en de ontwikkelingsgeschiedenis van de westkust van Holland en met name in de kustuitbouw gedurende het Subboreaal en een deel van het Subatlanticum. Hiertoe hebben de Vrije Universiteit (Amsterdam) en de Rijks Geologische Dienst (Haarlem) gezamelijk een boorprogramma uitgevoerd, zowel in de kustzone als in de Noordzee, en zijn ontsluitingen in het kustgebied bestudeerd.

De uitwerking van deze gegevens is in tweeën opgesplitst. In het eerste deel wordt verslag gelegd van de waarnemingen aan de recente sedimenten, terwijl in het tweede deel de Holocene kustafzettingen behandeld worden zoals deze zijn aangetroffen in de ontsluitingen en de boringen (Hoofdstuk I).

Het eerste deel (Hoofdstuk II) bevat de uitwerking van waarnemingen aan recente strand- en onderwateroeversedimenten tot een maximale diepte van ongeveer 10 m beneden gemiddeld zeeniveau. Met behulp van de verdeling van schelpen en strandmetingen (JARKUS bestand) zijn ideeën geformuleerd over de graad van omwerking van het bovenste deel van de kustzone. Deze blijkt hoog te zijn, waarbij de afwezigheid van levende mollusken in de zgn. brekerbanken opviel. Daarnaast wordt met behulp van de fossiele, golfgedomineerde kustafzettingen een schatting gegeven van de verhouding tussen de verstoring die het gevolg is van natuurlijke oorzaken (met name stormen) en verstoring die door de bodemvisserij veroorzaakt wordt. Toenemende bodemvisserij zou schadelijk kunnen zijn voor het bodemleven in de ondiepe Noordzee (Hoofdstuk III).

Het tweede deel omvat een drietal uitgewerkte onderwerpen met betrekking tot de West-Nederlandse Holocene kustafzettingen. In Hoofdstuk IV wordt een overzicht gegeven van de kustontwikkeling van de gehele West-Nederlandse kust gedurende de laatste 6000 jaar. Hierbij wordt gebruik gemaakt van de geintegreerde gegevens van de Hoofdstukken V en VI, en vele andere, deels ongepubliceerde gegevens van de Rijks Geologische Dienst. De ontwikkeling van de West-Nederlandse kust in de genoemde periode is gerelateerd aan de snelheid van de relatieve zeespiegelrijzing en de morfologie van het oppervlak van de Pleistocene afzettingen. De overgang van een zgn. open kust (getij-gedomineerd) naar een gesloten strandwal-kust (golf-gedomineerd) is de belangrijkste geologische gebeurtenis tot aan de Middeleeuwen. In het Atlanticum wordt het door de golven aangevoerde zand gebruikt om het getijdengebied tussen de twee kapen (één ten westen van Rotterdam: de uitstroming van de Rijn/Maas lopen en één ten noorden van Den Helder: de stuwwalrest van Texel) te vullen met zand. Nadat in het begin van het Subboreaal de snelheid van de zeespiegelrijzing was afgenomen, het getijdengebied was opgevuld en de geulen dicht gingen, werd het nog steed aangevoerde zand en dat van de eb-getijden delta's van de verdwenen geulen voor uitbouw van de strandwalgordel gebruikt. Een eenvoudige zandbalans wordt gegeven.

Hoofdstuk V beschrijft de ontwikkeling van het gedeelte van de strandwalkust tussen Monster en Scheveningen, dat onmiddelijk ten noorden van het uitstroomgebied van de Rijn en de Maas lag gedurende het Atlanticum. Als gevolg van de bijzondere situatie die zich daar voordeed aan het eind van het

Atlanticum, vond hier een eerste snelle uitbouw van de strandwallenkust plaats. De kust werd waarschijnlijk uitgebouwd met de Boreale/Vroeg Atlantische Rijn/Maas delta zanden en de sedimenten van de eb-getijden delta van het zeegat, waarvan de hoofdgeulen richting Zoetermeer liepen.

In Hoofdstuk VI wordt een beschrijving gegeven van de ontwikkeling van een deel van het strandwallengebied een aantal kilometers ten zuiden van Haarlem, wat tot nu toe in de diepte nauwelijks onderzocht was. Door middel van sonderingen en boringen is een E-W dwarsdoorsnede door het gebied gemaakt. Deze dwarsdoorsnede ligt ongeveer halverwege het estuarium van de rivier de Oude Rijn, die bij Leiden, en later bij Katwijk uitstroomde en het estuarium van het Oer-IJ, dat eerst vlak ten noorden van Haarlem en later ten noorden van Beverwijk uitstroomde. Van de sedimenten in deze dwarsdoorsnede zijn enkele lithologische parameters onderzocht: onder meer korrelgrootte, kleigehalte en eveneens sedimentaire structuren. Tevens zijn paleontologische data onderzocht (diatomeen, foraminiferen, mollusken en pollen). De onderlinge relaties worden besproken. De indeling in de tijd van de sterk zandige kustafzettingen is tot stand gebracht door middel van oudere en meer dan 30 nieuwe C14 dateringen. De laatste zijn uitgevoerd op geselecteerd schelpmateriaal. De pollenanalyse heeft gegevens opgeleverd met betrekking tot de herkomst van het verspoelde fossiele stuifmeel en tevens het fijnkorrelige klastische materiaal. Voor het stuifmeel konden drie brongebieden aangewezen worden. Hiernaast wordt een paleogeografische reconstructie gegeven van het zgn. zeegat van Haarlem, dat in de periode van de ontwikkeling van de strandwallen in dit gebied een belangrijke rol heeft gespeeld. De uitbouw van de strandwallenkust in de periode 5600 BP tot ongeveer 2000 BP heeft plaatsgevonden ondanks een zeespiegelrijzing van 3 tot 4 meter. De West-Nederlandse kust volgt hiermee niet de zgn. Bruun-regel, die (in zijn algemeenheid) voorschrijft dat een kust die zeespiegelrijzing ondervindt, terugschrijdt. Het afwijken van deze regel is vermoedelijk het gevolg van de ruime zandvoorraad, dat blijkbaar voorhanden was in de ondiepe Noordzee, vlak voor de kust. De kustontwikkeling is tevens gerelateerd aan de ontwikkeling van de zeegaten ter weerszijden van de dwarsdoorsnede door de kust.

Een Hoofdstuk VII (Conclusies) besluit dit proefschrift. Enkele van de belangrijkste volgen hier. De ontwikkeling van de West-Nederlandse als geheel staat in het teken van de snelheid van de zeespiegelrijzing per tijdseenheid, invloed van de morfologie van het oppervlak van de Pleistocene afzettingen en de beschikbaarheid van zand. Afhankelijk van de combinatie van een of meer van deze factoren vindt kustterugschrijding danwel kustuitbouw plaats. In het algemeen is de kusthelling steiler geworden in de bestudeerde periode. Voor de interpretatie van de oude sedimenten is de bestudering van recente sedimenten van belang gebleken.

SUMMARY

The area discussed in this thesis covers the coast of the western Netherlands between Hoek van Holland and Alkmaar, and the adjoining shallow part of the North Sea. The objective of the investigation was to acquire a detailed understanding of the structure and the geological development of the coast of the western Netherlands, especially of the coastal progradation during the Subboreal and part of the Subatlantic. For that purpose, the Free University of Amsterdam and the Geological Survey of The Netherlands at Haarlem have jointly undertaken a coring programme in the coastal zone as well as in the North Sea. Also artificial exposures in the coastal region were studied.

The discussion and evaluation of these data are subdivided into two parts (Chapter I). In the first part the observations of the recent sediments are reported, while the second part covers the Holocene coastal sediments as they were found in the cores and artificial exposures.

The first part of the present thesis (Chapter II) contains the elaboration of the observations of recent beach- and shallow marine sediments up to a maximum depth of about 10 meters below mean sea level. Using the distribution of shells and beach-measurements (JARKUS data) ideas are formulated on the degree of reworking of the upper part of the coastal zone. The degree of reworking appears to be high. The absence of living molluscs in the so-called breaker-bars is striking. In addition, making use of the fossil, wave-dominated coastal barrier sequence as found, some ideas are presented concerning the relation between the sea-bottom disturbance as a result of natural causes (i.e. storms) and the disturbance caused by bottom-fishing. Increased bottom-fishing could be detrimental to the benthic fauna living in this shallow part of the southern North Sea (Chapter III).

The second part of this thesis covers three subjects with regard to the Holocene coastal sediments of the western Netherlands.In Chapter IV, a review is given of the development of the coast of the western Netherlands during the last 6,000 years. Use is made of the integrated data of Chapters V and VI, and many other, partly unpublished data of the Geological Survey of The Netherlands. The development of the coast of the western Netherlands in the period mentioned is related to the rate of the relative sea-level rise and the morphology of the surface of the Pleistocene sediments. The transition of a so-called open coast (tide-dominated) to a closed beach-barrier coast (wave-dominated) is the most important geological event up to the Middle Ages. During the Atlantic, the sand, supplied by the waves is used to fill-in the tidal area between the two headlands: one headland west of Rotterdam, the outflow of the Rhine-Meuse River branches, and one North of Den Helder, the remains of the push moraine of Texel. After the rate of the sea-level rise had dimished in the beginning of the Subboreal, and the tidal channels were filled in with the sand that was still being supplied, this sand and that of the ebb-tidal delta's of the vanished gullies, was used for the progradation of the coastline. A simple sand budget is given.

In Chapter V the development of the part of the beach-barrier coast between Naaldwijk and The Hague, located immediately north of the area of the outflow of the Rivers Rhine and Meuse during the Atlantic is studied. As a result of the local situation at the end of the Atlantic, the beach-barrier coast started prograding. The coast probably prograded using the reworked Rhine-Maas delta sands of the Boreal/Early Atlantic and the reworked sediments of the ebb-tidal delta which

main channels ran in the direction of Zoetermeer.

In Chapter VI a description is given of the development of a part of the beach-barrier area a few kilometers south of Haarlem of which the deeper structure is not well-known . Using cone penetration tests and cores, an East-West cross-section was made through the study area. This cross-section is located about halfway the estuary of the Old Rhine River, which flowed into the North Sea at Leiden and later at Katwijk, and the estuary of the Oer-IJ, which first had its outlet just north of Haarlem and later north of Beverwijk. Some lithological parameters of the sediments in this cross-section were examined, among which grain-size, clay content and also sedimentary structures. Palaeontological data were also examined (diatoms, foraminifera, molluscs and pollen). The mutual relationships are discussed. The time classification of the very sandy coastal sediments was accomplished using older, and over 30 new, radiocarbon datings. The latter were executed on selected shell-material. The pollen analysis resulted in data with regard to the origin of the transported pollen and also of the fine grained clastic material. Three regions of origin could be determined for the pollen. In addition, a palaeo-geographic reconstruction is given of the so-called sea-arm of Haarlem, which has played an important role in the development of the beach barriers in the region. The progradation of the beach barrier coast in the period of 5,600 BP to about 2,000 BP took place in spite of a sea-level rise of 3 to 4 m. The coast of the Western Netherlands thus does not follow the so-called Bruun-rule, which generally precribes that a coast experiencing sea-level rise, should recede. The fact that this rule is not followed, is probably due to the ample supply of sand, apparently available in the shallow North Sea, close to the coast. The development of the coast is related to the development of the tidal channels/estuaria on both sides of the cross-section normal to the coast.

Some of the most important conclusions contained in the final Chapter VII of the thesis follow here. Coastal development in the Western Netherlands is governed by the rate of sea-level rise, the morphology of the Pleistocene surface and sand availability. Dependent on the combination of various factors coastal retreat or coastal progradation will take place. Generally speaking, the coastal profile steepened during progradation in the period studied. For the interpretation of ancient sediments, the study of recent sediments was important.

CHAPTER I

INTRODUCTION

CHAPTER I

INTRODUCTION

This study is concerned with the evolution of the coast of Holland. Its principal aim is to investigate the causes and dynamics of barrier formation and rapid coastal progradation which took place in the western Netherlands during the Subboreal and Early Subatlantic. Eventually a sedimentological model of barrier formation should emerge from a reconstruction of the geological history of the mid-Holland coast (the area between Alkmaar and Hoek van Holland) in that period and from an analysis of the environmental parameters involved in barrier formation.

The present study is a joint venture of the Department of Quaternary Geology of the Vrije Universiteit Amsterdam (VU) and the Geological Survey of the Netherlands (RGD), carried out by the author as a PhD-study under the supervision of Dr D.J. Beets, Dr W. de Gans and Prof. Dr W.H. Zagwijn (RGD) and Prof. Dr W. Roeleveld and Drs. Th. B. Roep (VU). The start of the study more or less coincided with the initiation by the Public Works Department (Rijkswaterstaat) of a national "Coastal Genesis" project. This project, which aims at a better understanding of the mechanisms determining the present and future development of the Dutch coast, was initiated in 1985 by Rijkswaterstaat. Hitherto, actuo-geological research of the coast of the western Netherlands received little attention, probably because of with the poor accessibility of the upper 15 m of the shoreface related to the high level of wave energy. In the past few years, however, "Coastal Genesis" a project conducted by governmental bodies, universities, research institutes and individual researchers, has resulted in a substantial amount of new data. The present study has both contributed to as well as benefitted from recent developments in this area.

The PhD-thesis consists of three parts.

1. The recent environment.
Actuo-geological data were gathered to a certain extent in order to permit a more detailed interpretation of the fossil depositional record. Although this work was not very extensive a number of data and observations concerning the recent sedimentary environment of the coast of Holland are presented (Chapters I and II).

2. The ancient environment.
Since Van Straaten's classic study of the coastal barriers of the western Netherlands (1965), additional work on the barrier sediments has mostly focussed on what could be studied by means of auger boreholes and/or in shallow construction pits, i.e. up to a depth of 5 m below surface. Insight into the formation of the coastal barrier strand plain on the one hand and into the geological architecture on the other was not readily available. During recent years Roep, Beets, De Jong and Westerhoff (for references see the individual chapters) have supplied many new data on and insight into the development of coastal barriers

and coastal plains, based mostly on shallow data. For continued research, the availablity of deeper data was considered essential and hence, RGD and VU decided to core two transects through the coastal barrier system perpendicular to the coast. The northern transect is situated south of the city of Haarlem (referred to as the Haarlem cross-section throughout the text) and the southern between the Oude Rijn (a former course of the River Rhine) and the city of The Hague (the Wassenaar cross-section). These two transects were extensively radiocarbon-dated and are the backbone of the present study. Detailed core analysis was performed especially on the Haarlem cross-section, as this area was generally less well-known than the area of the Wassenaar cross-section. The results of the study of the Haarlem cross-section are discussed below. The Wassenaar cross-section was discussed earlier in an unpublished report by Van Someren (1989). As a by-product of the project, more data on the Sea Level Rise which took place during barrier progradation could be gathered.

Next to the analysis of these cores, a large number of smaller and larger temporary exposures were studied. They are referred to only scarcely. An exception was made for the large temporary exposure near The Hague, South-Holland. It is discussed in Chapter V. Furthermore, the knowledge gained from the study of the barrier cores in a transect south of Haarlem (Chapter VI) and the analysis of an early barrier sequence in South-Holland near The Hague (Chapter V) was used in the large-scale reconstruction of the evolution of the coast of Holland during the second half of the Holocene (Chapter IV).

3. Conclusions.

Combining these two approaches led to a better understanding of the coastal development in the western Netherlands.

After a brief survey on the distribution of molluscan shells and sediments on the recent coast, it was summarized that in the zone occupied by the breaker bars almost no infaunal animal life would be possible because of the frequent reworking by storm waves. The empty molluscan shells are redistributed repeatedly until they reach a certain equilibrium position according to the position of (present) Mean Sea Level. This feature can be used for the interpretation of fossil coastal sections. The present mean fair weather wave base varies from -3 to -6/-7 m (Chapter II)

Coastal development case histories are presented in Chapters V and VI. A remark can be made as to the start of the coastal progradation. Generally, this progradation started more early in the south than in the north of the barrier area. Depending on the interpretation of the radiocarbon data (which were performed especially for this project on shell material), age differences between the start of the southerly progradation and the northerly could amount to almost one thousand radiocarbon years.

It is likely that this age difference is associated with available sand sources. During the Atlantic, the marine-influenced area in South-Holland is smaller than in North-Holland because the outflow position of the River Rhine is situated in the former area. The Rhine presumably brought sand into the coastal area during the Boreal and Early Atlantic. This sand was to be used later as a source for progradation (Chapter IV). Chapter V presents a case history of the early coastal progradation in the south. It can be seen to differ from the mid-Holland case history, which is studied in Chapter VI. Here, progradation started several hundreds of years later than in the south. Progradation in the mid-Holland area is documented until at least 2,000 BP. During progradation the coastal profile (0 to -18m NAP; NAP = Dutch Ordnance Datum, about equal to Mean Sea Level) steepened. Below daily wave base, the sedimentation is governed by storm-wave activity.

In this way comparatively unknown parts of the coast of the western Netherlands were explored. Data from the recent coast were used for the analysis of ancient sediments and visa versa. Despite this, there is still much work to be done. The quantification of sand masses incorporated in the formation of the coastal deposits is desirable. The obtained volumes should be combined with the time frame according to which the coastal deposits were formed as to construct the coastal sand budget. Mapping the shallow coastal zone (less than 20 m water depth) would improve further understanding of the coastal system. Also, the contribution to the coastal mechanism of tidal currents as opposed to currents due to waves deserves attention from geologists and engineers.

In this thesis, all references are given in their original form. In some cases reference is made to Van der Valk (in prep); it is this thesis which is meant.
This thesis is a contribution to the IUGS-UNESCO sponsored IGCP-project 274 "Coastal evolution in the Quaternary", as well as to the Dutch "Coastal Genesis" project.

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1. THE RECENT ENVIRONMENT

CHAPTER II

MOLLUSCAN SHELL DISTRIBUTION AND SEDIMENTS OF THE FOSSIL AND MODERN UPPER SHOREFACE OF THE COAST OF HOLLAND (HOLOCENE, W. NETHERLANDS)

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CHAPTER II

MOLLUSCAN SHELL DISTRIBUTION AND SEDIMENTS OF THE FOSSIL AND MODERN UPPER SHOREFACE OF THE COAST OF HOLLAND (HOLOCENE, W. NETHERLANDS).

ABSTRACT

The lithology, sedimentary structures and (sub)fossil molluscan content of Subatlantic (Holocene) barrier deposits in the western Netherlands and the modern Dutch shoreface are compared. The taphonomy and depth distribution of common Recent North Sea fauna is shown to be distinctive in the interpretation of fossil sections. ^{14}C methodology is discussed in an appendix.

Key words - Coastal barrier, shoreface, molluscs, taphonomy, sedimentology, Holocene (Subatlantic), ^{14}C analysis, The Netherlands.

INTRODUCTION

In comparison with data available on Recent benthic molluscs in the shallow North Sea (Eisma, 1966; De Bruyne, 1990), information on the distribution of (sub)fossil molluscs in this area is extremely scarse. (Sub)fossil molluscs are herein taken to be 10,000 years old or younger. In the coastal zone of the Netherlands, these molluscs can be distinguished easily from *e.g.* Eemian (the last Pleistocene interglacial stage) molluscs by their habit. Eemian molluscs are generally dull gray or white in colour and chemically leached, while Holocene molluscs generally have a much fresher appearance. Molluscs from a variety of environments that existed during the Holocene, are found in coastal deposits (Van Straaten, 1965), on the bottom of the North Sea, or washed up on the beach (Van Regteren Altena, 1937). Van Straaten (1957, 1965) used these remanié shells in an analysis of the geological history of the western Netherlands. Only few subsequent publications have been devoted to this subject (*e.g.* Van Urk, 1970).

Recently, the subject of (living) molluscan assemblages in the coastal zone of the western Netherlands has recieved more attention, because of their importance in indicating environmental changes (Van Ommering, 1988; Oosterbaan, 1988). The relationship between recent occurrences and (sub) fossil Holocene molluscs has lately been explored in a search for sand transport ways (Van der Valk & De Bruyne, 1990)

The present-day Holland coast is characterizsed by a peculiar pattern of grain size and sedimentary facies distribution. Below -18 to -16 m (all depth figures in this paper being given in m with respect to the Normaal Amsterdams Peil (NAP), which is roughly equivalent to the Mean Sea

Level (MSL)), a coarse-grained sand wave facies ('shore connected ridges') predominates, the origin of which is still a matter of debate (Jelgersma, 1979). Between -18/-16 m and -7/-6 m a generally fine sandy flat surface is present, with extensive biological life. From -7/-6 m up to and including the berm on the intertidal beach a generally barred, medium- to coarse-grained sandy facies is present. An active zone usually consists of two to three subtidal bars and one intertidal longshore bar. Only few clay layers are found. Mean tidal amplitude on this coast is about 1.8 m in transition between a mesotidal and a microtidal type of coast (*sensu* Hayes, 1979).

It is the aim of this paper to indicate how an analysis of (sub)fossil molluscs may contribute to the interpretation of fossil coastal deposits and coastal environments. It is not in the usual 'biological' way that the presence or absence of molluscan species is used. Using (sub)fossil material as if it were modern and autochtonous would lead to erroneous conclusions. The interpretation presented in this paper is related to the depositional environment, from which a given sample has been taken, and to energy conditions associated with this environment. This taphonomic approach has rarely been used in the study of modern subtidal deposits. In some publications, however, reference is made to this subject (Hertweck,1971; Cadee, 1984; Frey & Dörjes, 1988). Frey & Dörjes (1988) are the only scientists to have investigated a data set which is in part comparable to the actualistic (molluscan) subject, the Egmond transect, dealt with in this paper.

For the intertidal and supratidal part of the Holland coast several attempts have been made to construct a range chart of sedimentological features, including the depth dependence of molluscs in general and of separate species in particular (Van der Baan, 1978; Huyser, 1987; Van Schoor, 1988). For the subtidal part of the Holland coast (between about *c.* -1 m NAP and the lower boundary of the shoreface at *c.* -18 m), no systematic attempt has been made so far to investigate the vertical distribution of sedimentary structures and/or other lithological features. Investigations are hampered by the high-energetic conditions of the wave-dominated Holland coast. Only in restricted periods of the year which cannot be predicted very well, can vessels operate in the shallow zone along the shore. This is especially so for the zone above -10 m NAP.

First, this paper fills in the data gap between the supra/intertidal North Sea beach and the lower shoreface and shallow North Sea shelf. The latter was discussed by Eisma (1966). Secondly, these data are compared with the youngest beach barrier data available for the western Netherlands. The recent depth distribution of sedimentary structures and shells (living, recent or subrecent) is used to interpret ancient parts of the coastal barrier in an approach similar to that of Van Straaten (1965), but extended.

METHODS

Information on sequences, structures and shell content was collected in various ways. First of all, a series of box cores was taken off the Egmond

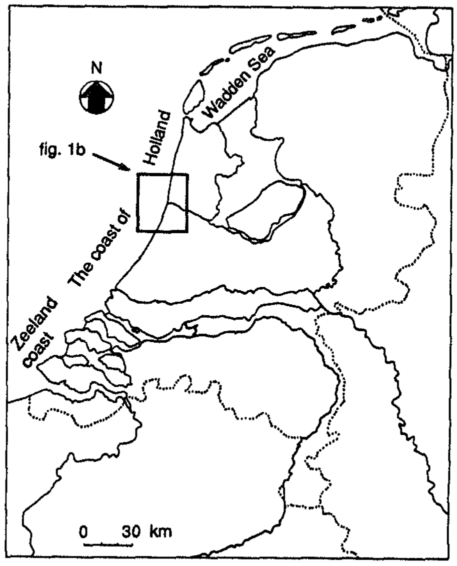

Fig. 1a. The Netherlands with the location of the study area: the middle part of the coast of Holland.

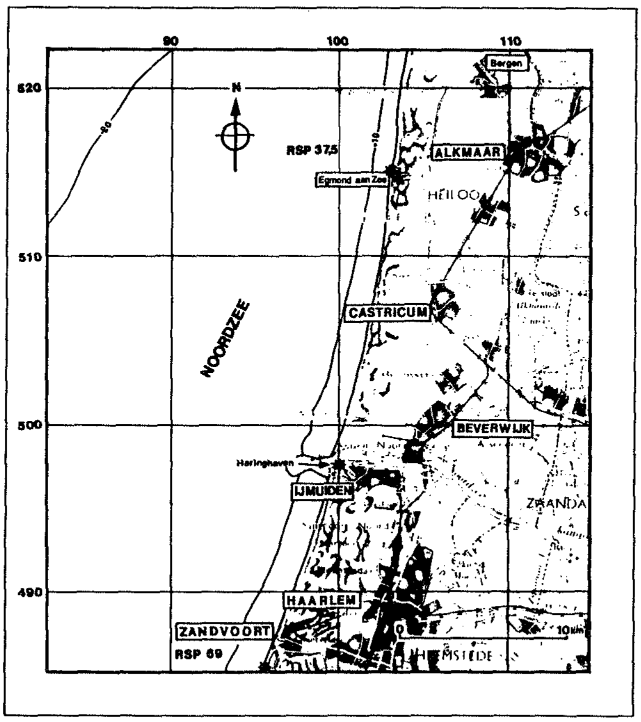

Fig. 1b. The situation of the locations in the study area, Egmond Rijks Strand Paal (RSP) 37.5, IJmuiden Haringhaven and Zandvoort RSP 69.

coast (Fig. 1) by means of a Reineck box corer. No other apparatus can be used in the shallow shoreface, because of practical limitations (Anonymous, 1983). The prime reason for selecting this transect was the fact that Roep (1984, 1986) had already done considerable work on the intertidal and supratidal part of the coastal profile. Of these box cores lacquer peels were made in order to study the sedimentary structures. The remaining part of the box cores was used to analyse lithological and biological parameters *e.g.* grain size, live organisms and molluscan shell content.

These Egmond data were then compared with two fossil beach barrier sections, one of them, a cored borehole, situated to the south of Zandvoort (Rijks Strand Paal (RSP) 69) at the high-tide level of the beach, the other situated at IJmuiden-Haringhaven, a temporary excavation, supplemented by a bailer drilling (Fig. 1). These two sections are amongst the stratigraphically youngest that are available in the Holland beach barrier area (Roep, 1984 and 1986; Van der Valk, in prep.).

Generally, the hydrodynamic regime of the modern Dutch coast and the regime of the Subboreal and Subatlantic barrier coasts are referred to as being equal in character. These parts were mapped stratigraphically by the Geological Survey as (Holocene) Older Beach and Dune Sands of the Westland Formation (Zagwijn & Van Staalduinen, 1975). The youngest of these barrier sands would correspond most closely to the recent coast.

In view of the way molluscan shells are treated in this paper, it was not necessary to identify all to the species level. Bivalve taxonomy follows Tebble (1976), while gastropod names are those listed by Janssen (1975). First, the fossil sections are given and secondly the recent survey will be reported upon. Finally, the results will be compared and the importance of the recent survey for the interpretation of fossil sections discussed.

SECTION IJMUIDEN HARINGHAVEN

General

In the autumn of 1989 an excavation at IJmuiden-Haringhaven was accessible for study (Fig. 1). Dunes covering the area had been excavated down to +3.5 m NAP during harbour construction at the start of this century. Because of its proximity to the recent coastline (500 m) and because of the geological work that had been done 1.5 km to the east of the present locality (see *e.g.* Roep, 1986), the excavation was surveyed. The information gathered from a construction pit at IJmuiden-Haringhaven was supplemented by data from a bailer drilling (by hand) down to -6.5 m NAP. In this way the separate data sets could be combined so far as to form a single consistent data set covering both exposure and borehole. Figure 2 shows the section of the excavation at about right angles to the former (and also the present-day) coastline. In Figure 3a a composite schematic section of exposure and borehole, and in Figure 3b the results of an analysis of molluscan content are shown.

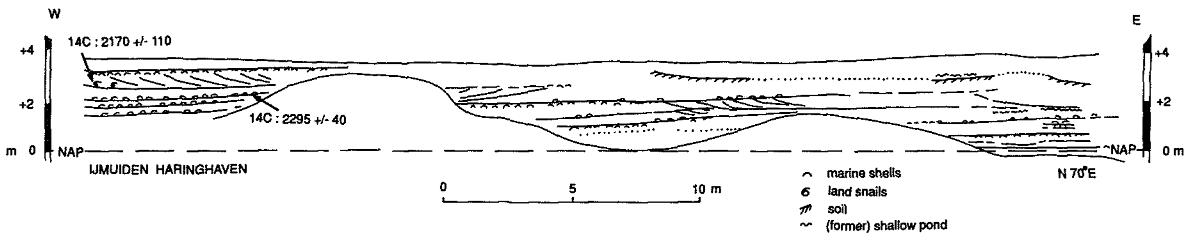

Fig. 2. The section at IJmuiden Haringhaven. The (ancient) sea is to the left. Nearly all deposits are supratidal, Intertonguing of storm planated beach and dune sands is most clearly seen in the west.For a discussion of 14C data, see Appendix.

Results

In the uppermost metre of the excavation remnants of a dune soil occur at about +3 m (Fig. 2). The soil is weakly developed with shallow decalcification and some bleaching. On top of the soil a shallow lake must have been present, as indicated by the occurrence of freshwater gastropods (*Galba truncatula* (Müller, 1774)) and on top of this again some dune sand was found (unit 1). The soil partly covers a cross-bedded unit. This unit 2 consists of seaward dipping plane-bedded sets and landward directed scoop-shaped cross-bedded sets. The zone of interfingering of these two types of sets has a thickness of about 1.2 m. The seaward dipping beds contain shell material, the landward dipping beds do so only occasionally and when they do the shell material consists mostly of the terrestrial gastropod *Cepaea nemoralis* (Linné, 1758). In the seaward dipping beds shell material is marine. The landward tips of these beds curve gently upwards and carry isolated shells (mainly large specimens of several species and some isolated coarse gravel pebbles). The strata dip seaward at 1:17 to 1:40 (mean 1:27.6; n=6). Such gradients are not unusual on the modern beach (Roep, 1986). Unit 3 occurs below +1.8 m and consists of plane beds dipping seawards at very low angles and containing some shell material. The bedding in this unit is the result of swash and backwash of waves on the former North Sea beach. Some irregular bedding was observed, usually associated with bubble sand formation. Unfor-tunately, this unit was poorly exposed. It continued further down in the borehole. At -3 m highest cm clay flasers occur. This compares favourably with the

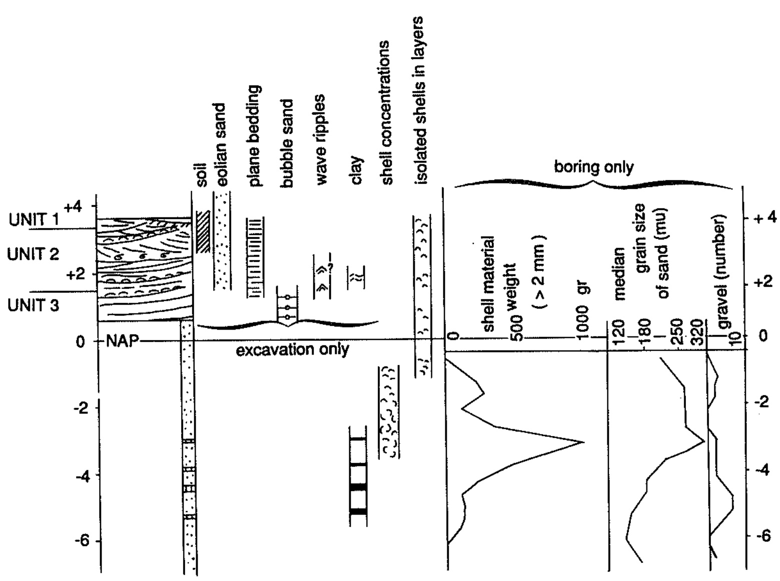

Fig. 3a. Composite schematic section in coastal barrier sands at IJmuiden-Haringhaven. Depth distribution of sedimentary features in the middle part. Inferred palaeo Mean Sea Level close to - 0.5 m NAP.

sections described by Van Straaten (1965) and by Roep (1986). The bailer drilling did obviously not yield any bedding information.

Down to -5.5 m the bivalve *Chamelea striatula* (da Costa, 1778) occurs (Fig. 3b). As in other beach barrier sections, the presence of this species indicates a rela-tively young age (Van der Valk, in prep.), which is in accordance with the age determination discussed below (see Appendix).

Figure 3b gives the percentages of valves of a number of common molluscan species plotted against depth of excavation and borehole. Three zones are dis-tinguished. Zone A is characterised by relatively few species and by high values for the bivalves *Cerastoderma* sp. and *Mactra corallina* (Linné, 1758) and low values for *Spisula* sp. Zone B is characterised by a large number of species, high values for *Spisula* sp., the gastropod *Euspira* sp.and the bivalve *Ensis* sp. and low values for *Cerastoderma* sp. and *Mactra corallina*. Zone C shows a decline of the number of species and of the curve of *Spisula* sp. A number of bivalve taxa show a curve rise: *Donax, Macoma, Tellina fabula* (Gmelin, 1791) and *T. tenuis* (da Costa, 1778). The boundary between zones A and B roughly coincides with the boundary between units 2 and 3 at +1 m NAP. The boundary between zones B and C is not clearly reflected in the units of Fig. 3a, but it could correspond to the median grain size minimum between -5.5 and -6 m.

Discussion

Unit 1 is purely aeolian with intermittent (wet) soil formation. Unit 2 and molluscan zone A are predominantly aeolian, but occasionally dunes

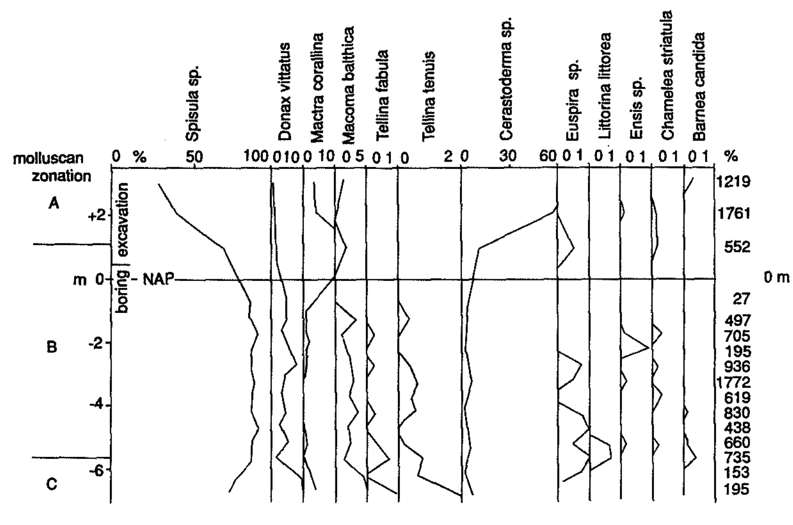

Fig. 3b. Molluscan percentage diagram (shell material > 2 mm). Numbers counted per sample are indicated.

must have been swept and eroded by storm waves at the high beach of the former coast. Nevertheless, the coastline is prograding. The largest break in the section occurs at +1.8 m where aeolian deflation stops. This level is not considered the deepest level of aeolian scour, however, because of the lack of good exposure. Unit 3 and molluscan zones B and C are marine intertidal for the upper part and marine subtidal for the lower part, probably lower than -2 m NAP: no reliable indication can be given for the depth of the lower-tide level. Taking the IJmuiden-Spuisluis section (Roep, 1986) into account, this boundary could be situated some 3 m lower than the highest shell material (here exceptionnally high at +3.7 m) and well above the highest cm clay flaser. This leaves the lower-tide level to be situated at approximately -2 m NAP. The lower boundary of erosional activity by troughs belonging to the breaker-bar system that has supposedly been present and still is present along the Dutch barrier coast, could very well be indicated by the gravel maximum, the *Euspira* sp. and *Littorina* sp. (gastropod) maxima between -5 and -6 m. The largest amounts of bivalve shell material are also present in this zone, dominated by *Spisula* sp.

It is concluded that this section shows a well-defined distribution of molluscan species related to depth in the section. This distribution can be tied to the position on the coastal profile.

CORED BORING ZANDVOORT

General

As a part of a coring programme in the beach barrier area, a borehole was drilled on the beach near RSP 69, 3 km south of Zandvoort (Fig. 1). A one-day operation allowed 11 m of cores with a diameter of 11 cm to be taken.

The beach characteristics on this part of the Dutch coast may be summarised as follows. Zandvoort beaches have already been surveyed several times (Doeglas, 1954; Van den Berg, 1977), while Short (1990) gave an overview of Dutch beaches in general. The Zandvoort beaches are characterised by one or two intertidal ridges (bar 1 according to Short, 1990) and a backshore that is usually dry and generally subject to aeolian reworking. Only during exceptional storms and storm surges the sea reaches the dune foot at about +3 m NAP. Van den Berg (1977) reported on an eight year beach monitoring survey at RSP 70. During 71.2% of this period a one or two beach ridge profile was present, while post-storm flattened beach conditions occurred during 7.2% of the time. The remainder of 21.7% was occupied by a steep, reflective profile. Short (1990) pointed out that two processes could account for this mobility pattern. First, beach erosion during severe storms and rapid recovery (Doeglas, 1954) and secondly, longshore (northward) migration of points of bar attachment.

Bar 2, the first subtidal one, is always present. According to De Vroeg (1987), this bar is usually shore attached in the area where it shows up first on the sounding profiles and is situated gradually lower seawards. When following the same morphological feature, it becomes bar 3 and finally disappears towards the offshore (Short, 1990). This is not necessarily the direction of net movement of the bars. A typical feature of this bar 2 zone is the occurrence of rip currents.

Short (1990) points out that due to a lack of data taken with sufficiently high frequency, no precise figures on bar migration could be given. It is clear from his data, however, that bar 2 migration is greatest in the mid-Dutch area of the coast. Bar 3 shows the highest mobility of all bars and, on the basis of available data, it proceeds predominantly offshore. According to Short (1990), an on-offshore movement accompanied by a net offshore movement contributes to bar crest mobility. Again, bar 3 migration appears greatest in the mid-Dutch coastal area.

Summarising, it can be stated that surf zone processes dominate sediment transport on the coastal profile down to bar 3 to a very large extent, showing increasing volume of sediment mobility towards the offshore (Short, 1990). This implies that sediment reworking will be largest in the zone of the breaker bars and that repeatedly all sediment particles including the shell material will change position until a high degree of stability is reached for every sediment particle, including the shells.

For a more long-term development (centuries) a very limited amount of data is available. A net progradation of 50 m for the dune foot has been reported for the period 1860-1960 (Edelman, 1967). These data are not apparent in the 1600-1990 development which was recorded by Ligtendag (1990): *i.e.* a coastal recession of some 120 m. It may be concluded that the resolution of the data for a longer period of several centuries is not very extensive and that (periodic ?) oscillations of the High Water (HW) line have a magnitude of 50 to 120 m, which can be well within the resolving power of the historical map analysis carried out by Ligtendag (1990).

The cored boring

At +2 m, close to the HW mark, a cored borehole was drilled. The purpose of this borehole was to find out wether recent backshore deposits could be distinguished from (presumable) older beach barrier deposits, which can be expected underneath the recent beach. Furthermore, the westernmost of these coastal barrier sands was sampled in order to compare on grain size, sedimentary structures, shell habit etc. with older barrier deposits, located further to the east. Lacquer peels were made of the cores (Fig. 4); the schematised features are summarised in Fig. 5. In Fig. 5, a recent (1965-1980) envelope of coastal sounding profiles is added. The 1980 sounding profile is indicated with a solid line.

A boundary between the recent beach sands and older barrier sands was not visible in grain size trends or in sedimentary structures and could only be established on shell habit. A change of habit of the commonest bivalve shell (*Spisula subtruncata* (da Costa, 1778)) occurs at +0.2 m NAP. Freshest shell habit of *Spisula* disappears below this boundary. This depth accords rather well with the deepest scours documented in the sounding profiles of +0.5 m NAP at the location of this beach pole, which is also the location of the borehole (Fig. 5). The shell lag between +0.5 m and 0 m NAP in the borehole may very well be related to these deepest recent scours.

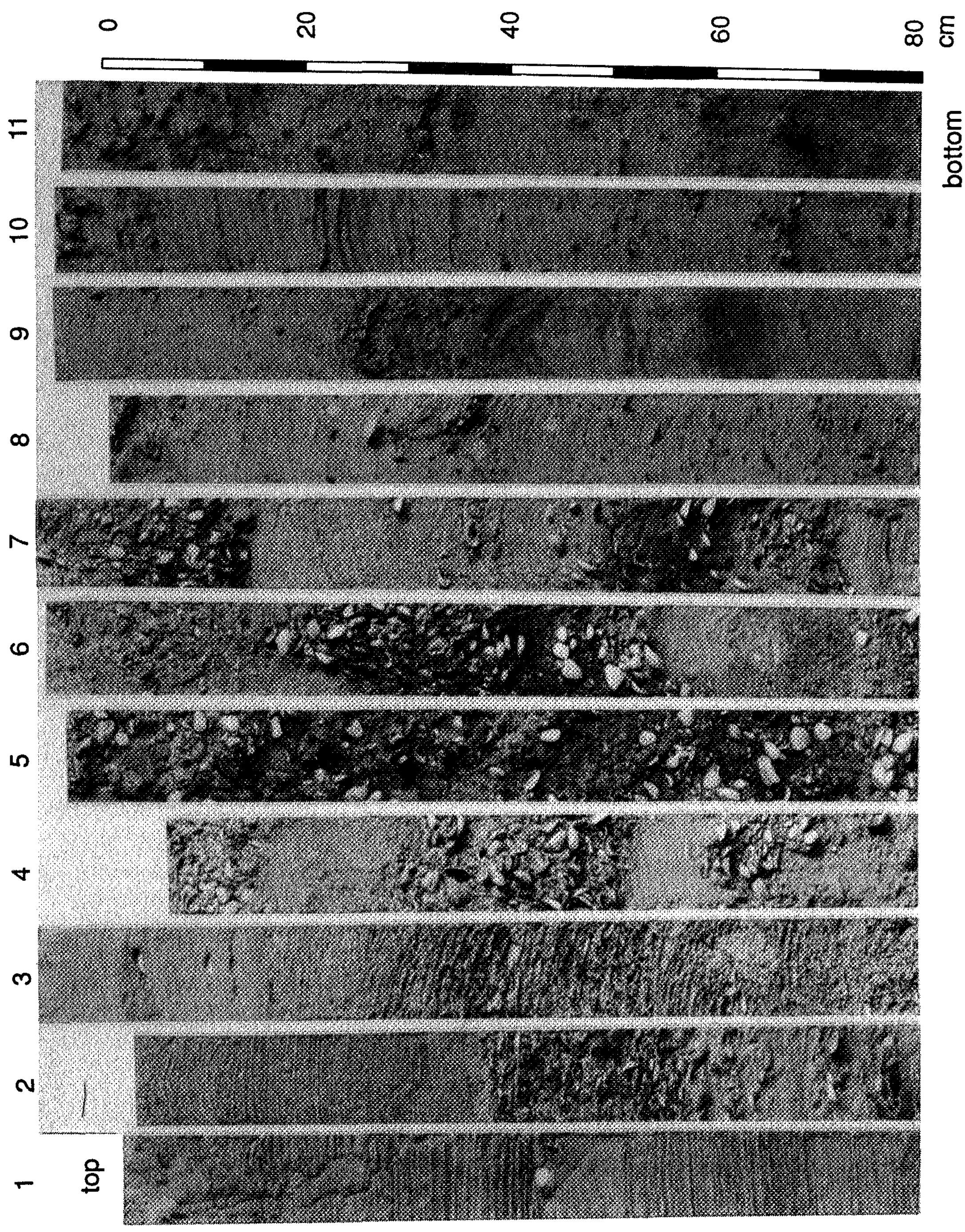

Fig. 4. Borehole Zandvoort-Rijks Strand Paal 69: lacquer peels of cores 1 to 11; one core per metre. The top of the individual cores was usually disturbed during coring. Note coarse fabric in cores 4 to 6 and thick clay layers in the lower half of core 9. Surface is at +2 m NAP. Photograph Rijks Geologische Dienst.

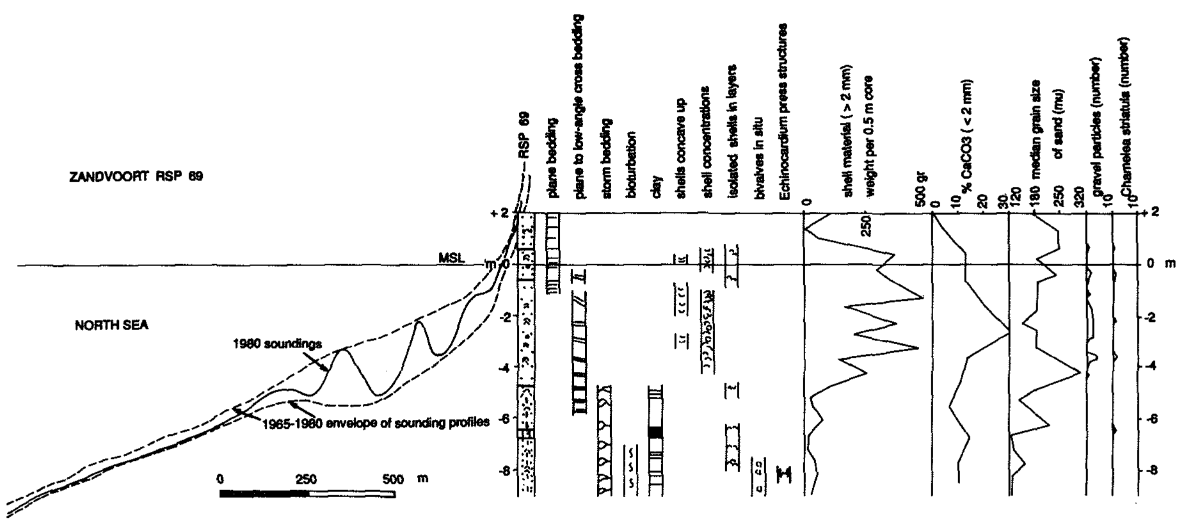

Fig. 5. Borehole Zandvoort-RSP 69, schematic section, 1965-1980 coastal longshore bar envelope and 1980 sounding profile.

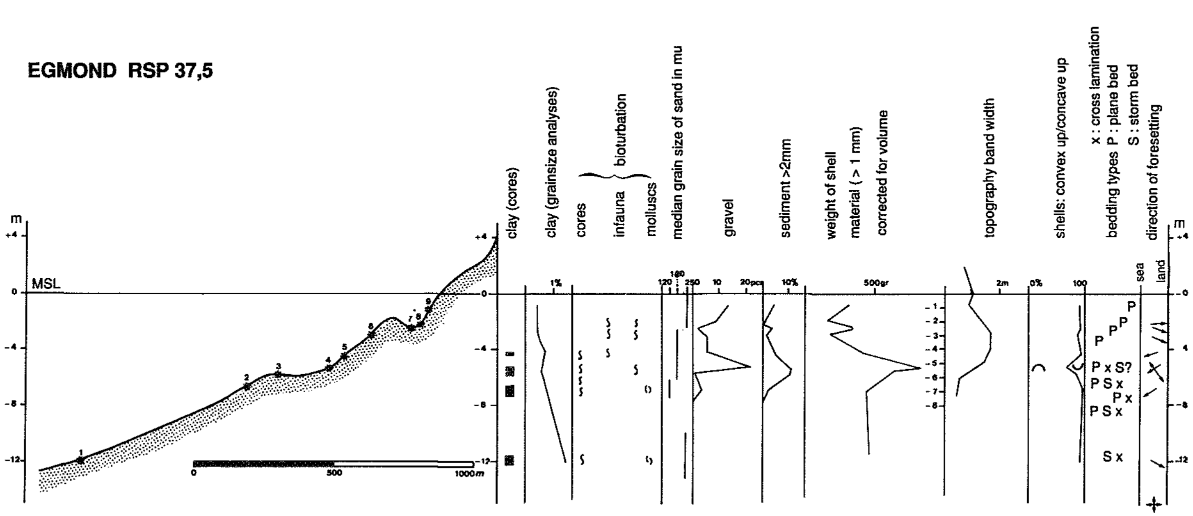

Fig. 6a. The Egmond-RSP 37.5 section: topography, lithology and sedimentary sequence.

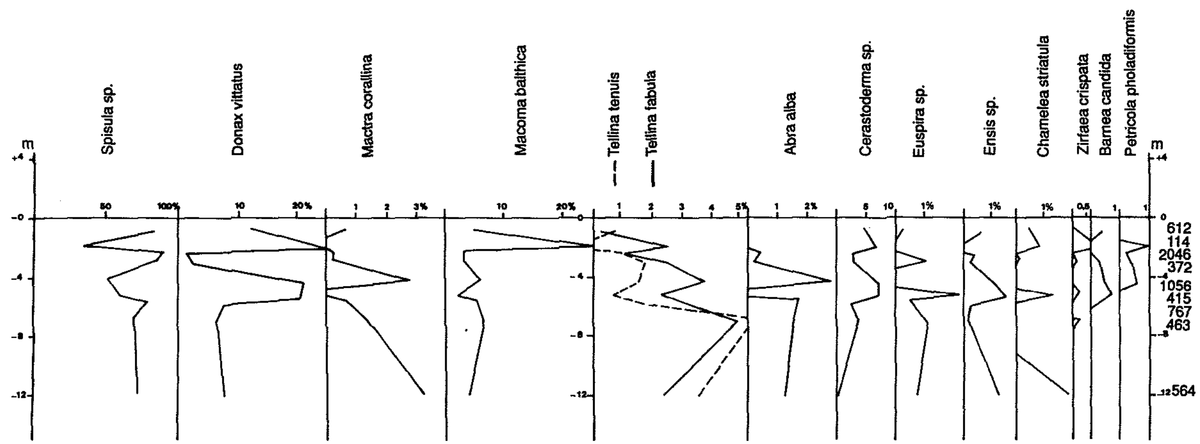

Fig. 6b. The Egmond-RSP 37.5 section: top layer molluscan relative diagram. Note horizontal scale differences between separate species. numbers counted per sample are indicated.

From the presence of bioturbation and bivalves *in situ*, together with the range of features related to sedimentary structures and the sediment itself, it is clear that a major change occurs in the depth range of -6.5 to -5 m (Fig. 5). From that zone upwards, median grain size as well as the weight of the 2 mm shell material increase. Thick clay layers occur at the boundary and bioturbation is present below -6.5 m only.

A major change in sedimentary facies, however, occurs at -6.5 m. Below this depth, (amalmagated) fining-up sequences occur, which sometimes show clay deposition at the top. These sediments are interpreted as deposits related to the wave activity associated with storms (cf. Aigner,1985).

Bioturbation in the section is most important in the interpretation of the sedimentary sequence. Bioturbation is considered to take place below mean fair weather wave-base (see the Egmond section). From - 6.5 upwards, coarse plane-bedded and occasionally low-angle cross-bedding prevail with massive shell accumulations (Fig. 4). At a depth of -1 m these are gradually replaced by generally plane to very low-angle crossed strata. Shell concentrations disappear and median grain size is not at its maximum and subject to fluctuation.

Discussion

As is apparent from the sounding profiles, the -6.5 m depth of major change in the cored borehole is not coincident. If a similarity is accepted between the recent Dutch coastal mechanism and the 2000 BP coastal mechanism (which seems reasonable; see *e.g.* Roep, 1986), it may be assumed that the -6.5 m depth is the maximum reworking depth of the 2000 BP Dutch coastal bar profile.

No ^{14}C dates are available for this locality which means that a different method of dating of the deposits below the recent beach must be used. Immediately to the east (some 400 m and 900 m) ^{14}C dates are available (Van der Valk, in press). On the basis of these ^{14}C dates and the combination of molluscan shell data of this slightly more easterly locality, it is concluded that around 2300 BP *Chamelea striatula* is present as remanié shells in the section and may be assumed to have been living on the shoreface during the Holocene for the first time. In the present borehole shells of this species were found to a depth of -6.5 m, indicating an age of 2300 BP or younger for the deposits above this level. Minimum age limits cannot be given, because no other molluscan species with later younger occurrences (*e.g. Mya arenaria* Linné, 1758 (16th century) or *Petricola pholadiformis* Lamarck, 1818 (1906)) were encountered in the samples from this borehole.

In conclusion, the Zandvoort RSP 69 core and faunal data and the implications of the recent morphodynamics lead to the following remarks, which point in the same direction.

The upper 1.5 m of the borehole is seen as the active zone of the recent beach, while the deposits below 0.5 m NAP belong to the Older Beach and Dune Sands. The age difference between the recent beach deposits and underlying coastal barrier deposits is currently estimated to be some 2000 years. The bedding type of the upper part of the barrier sands is mainly plane bed. This indicates that under the coastal regime which was active during the deposition of this sequence, the preservation potential for cross-bedding was low, which bedding type is expected to fossilise according to older (Subboreal) barrier data (Beets *et al.*, 1981). This means that mainly the plane bed strata of breaking waves at the stoss sides of bars have been preserved. These strata should dip slighly seawards. The cores were not orientated, which means that further conclusions on this point are impossible.

The difference in preserved bedding type between older and younger coastal barrier sequences can be understood when the rate of coastal progradation (Roep, 1984) is considered. Fast progradation during early barrier formation implies high preservation potential for both types of bedding, cross and plane, while in the phase of low progradation rates frequent reworking in the upper shoreface allows only the plane-bed stoss sides of the longshore bars to be preserved.

THE RECENT EGMOND TRANSECT

General

The Egmond transect is situated before RSP 37.5; samples were taken between -12 m and -1 m. At the time of coring (June 1985) there had already been several days of fair weather, with mild to moderately strong easterly winds. Prior to box-coring (by means of a Reineck box corer: Anonymous, 1983), the transect was surveyed by echosounder to determine core sites. Nine cores were recovered. From each core oriented lacquer peels were made, one parallel to the coast (N-S), the other at right angles (W-E). After removal of the peels, the rest of the cores were used for grain size analysis and collection of molluscan shells.

The shoreface at Egmond continues between -5 m and -16 m under a slope of 1:218. Below this depth, a gentler angle is present down to -20 m. At that depth, the actual North Sea bottom is reached (Niessen & Laban, 1987: encl. 2, section V-V'). The transect discussed here occupies the upper part of this section. The section's surface sediments are characterised by a slight variation in median grain sizes (180-260 µm) (Niessen & Laban, 1987). Long-term development of the coast at Egmond has been erosive, at least in historical time. Since 1664 the coastline has receded *c.* 250 m (Schoorl, 1968). This erosional tendency continues up to the present day: the beach has been raised artificially on several occasions. The negative coastal movement is generally correlated with the development of the Marsdiep channel, the main flood tidal channel of the western Wadden Sea. Since its beginning, tidal volumes (and currents) have steadily increased (Sha, 1990). The concomitant increase of sand transport capability and net inland transport towards the Wadden Sea has caused the coast south of the inlet to recede.

In Fig. 6 the box core information is summarised. Figure 6a shows lithological and structural features, while Fig. 6b provides some information on the relative abundance of 14 common North Sea molluscan species of the uppermost beds in box cores 1 to 9.

Lithology and structures

As may be seen from the columns in Fig. 6a, the lithological parameters change considerably between -5 and -6 m: sand median grain size, gravel and sediment coarser than 1 mm and 2 mm. Below this boundary curves are more regular. From this boundary upwards, many curves are highly irregular. This effect is even clearer when one looks at the presence of clay layers and the orientation of molluscan shells in the box core lacquer peels

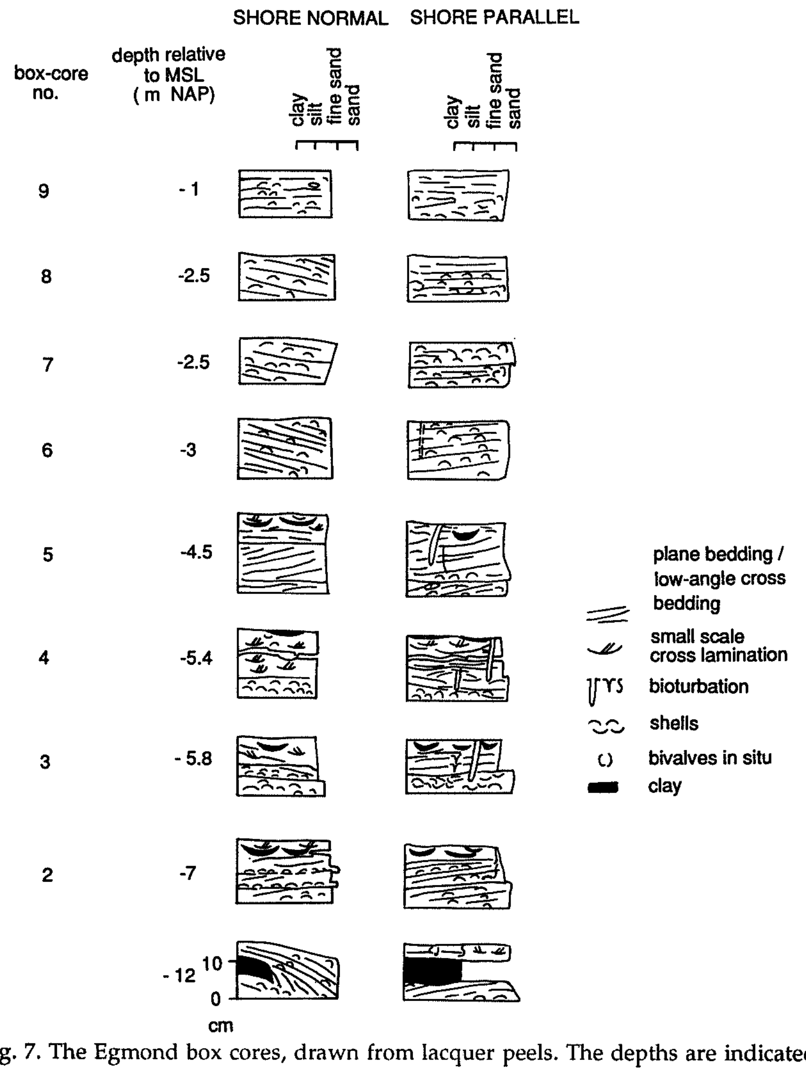

Fig. 7. The Egmond box cores, drawn from lacquer peels. The depths are indicated on the left-hand side. Peels on the left are oriented in a shore-normal direction; peels on the right in a shore-parallel direction, north being on the right-hand side.

(Fig. 7). Again the strong -5 to -6 m change is conspicuous. This marked change has no connection with the season's mean fair weather wave base, but it is demonstrated below that the change occurs at the erosional base of the longshore bar system. It becomes clear from worm burrows that the fair weather wave base was situated very high (-3 m) in comparison with data supplied by Aigner & Reineck (1983). These authors described the shoreface of the Norderney Wadden island (Germany). They found daily wave base varying between -3 and -7 m on the basis of bioturbation, during an 18 month observation period. When one compares the molluscan and worm bioturbation at Egmond, it appears that the latter occurs higher up in the coastal profile than does the former. As the sea state of the period concerned was very quiet, the -3 m depth for the uppermost burrow is realistic. It may be concluded that the -3 to -7 m variation of fair weather wave base off the barrier island of Norderney is valid for the Dutch coastal area as well.

Clay is present below -5 m, mostly as isolated flasers. At -12 m, a thick clay layer occurs (Fig. 7). The truncation of this clay layer is very probably man-induced (fishing gear)

Some remarks as to the distribution of sedimentary structures may also be made, as far as this is possible on the basis of a sole section. All structures observed in the box cores have originated very recently. As shown from the changes in subtidal topography (Fig. 10; after JARKUS measurements, kindly supplied by Rijkswaterstaat), it is very likely that all sedimentary structures have originated in a period of years, but more probably of months.

In Fig. 7 the nine box cores are shown in two sections: one section normal to the shore and another section parallel to the shore. Smallest median grain size in this coastal section is found at -5.8 to -5.4 m (box cores 3 and 4).

The dominant structure is plane bed. Below -4 m, a variety of structures occurs *i.e.* low-angle cross-bedding, cross-lamination and just underneath of bar crests, beds very similar to the storm layers described by Aigner & Reineck (1983) occur (cores 2, 4 and 5). A storm layer consists of a fining-up deposit of sand with many shells at the base with a generally fine-grained, usually bioturbated deposit at the top. As a whole, one layer is thought to be the result of waning wave conditions after a storm. For the North Sea environment the reader is refered to Aigner (1985). Cross-lamination is found only below -4.5 m.

The change of dominant bedform type at -4 m coincides with a change in sediment transport direction, as indicated by preserved sedimentary structures. As far as these observations allow generalisation, transport direction above -4 m is generally towards the beach, while below that depth direction is variable.

Molluscan shells

In Fig. 6b, molluscan shell percentages of 14 common North Sea species are presented. Of each box core every uppermost layer was analysed. The total sediment was passed through a sieve with a 1 mm mesh. Fragments were counted as far as they could be identified. Living molluscs were

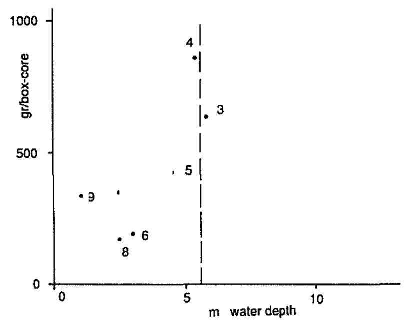

Fig. 8. Molluscan shell material weight per box core vs. water depth, corrected for volume.

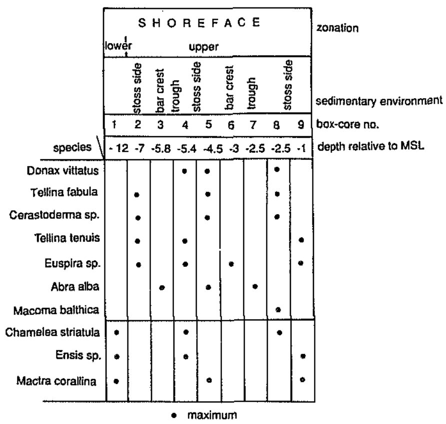

Fig. 9. Maximum occurrence of shells of ten molluscan species in the shoreface at Egmond.

counted as a single specimen and incorporated into the total. As these were extremely rare, their influence on the sum is negligible.

Comparable to the grain size distribution indicated above, a marked change is present at -6 m. This change is reflected in various ways, not only in the species composition (see below), but also in the weight of the shell material present in the box cores. In Fig. 8 this weight per unit of core volume is plotted against depth of the cores. From core 3 upwards, a highly variable amount of shell material occurs, while cores 3 to 1 are characterised by less variable amounts (compare Fig 6a).

The high amount of shell material present in core 4 is considered of prime importance. It is this core which is situated near the base of the zone in which longshore bars are continuously present on the Holland upper shoreface.

Shells of all species show highly variable scores (Fig. 6b), but below the -6 m boundary curves generally are less variable, at least for the commoner species. A very common species such as *Spisula* sp. equally shows strong fluctuations in its presence (above -6 m) as do less common species such as *Donax vittatus* (da Costa, 1778) and rare species such as *e.g. Abra alba* (Wood, 1802) and *Chamelea striatula.*

In Fig. 9 the maximum distribution of 10 molluscan species is depicted. *Spisula* sp. is not incorporated because of its overall presence, and three species of low occurrences are omitted as well. Figure 9 shows that two groups of molluscan shell occurrences may be distinguished. A group of seven species shows maximum occurrences in box cores 2 to 9 and another group of three species shows maxima in cores 1 to 9. Furthermore, it shows that box cores 2, 4/5 and 8/9 carry most maxima. This distribution is due to the sedimentary environment from which the box cores were taken. Cores 2, 4/5 and 8/9 are all taken from the 'stoss sides' of subtidal (2 and 4/5) and intertidal (8/9) longshore bars. Apparently, the molluscan species showing maxima in those positions indicate greatest stability per species. At a closer look, Fig. 9 reveals that per species individual maximum occurrences are noted. Only rarely does it show equal maxima. This indicates that every molluscan species' shell lies more or less in its most favourable, stable hydrodynamic position, even when juvenile shells are not tallied separately, as is the case here. Apparently, the -6 m boundary is a very important one, since this is the depth boundary between the two groups.

A specific vertical distribution of some molluscan shell occurrences is not unknown for the inter- and supratidal part of the Dutch coast (see Roep (1986) for a recent discussion). The basic idea is that the sedimentary environment is responsible for this distribution. However, only a limited amount of species was incorporated into this discussion (*Donax*, *Cerastoderma* sp.). It must now be considered that a larger part of the (very) common molluscan species (in their maximum values) is indicative of a certain set of sedimentary (mostly hydraulic) conditions. However, the limited character of the small data set on which the conclusions discussed below are based should be kept in mind. Additional evidence in the form of more transects of a design similar to the one discussed here are certainly needed.

DISCUSSION AND CONCLUSIONS

The determination of the set of sedimentary conditions may be as follows. From the JARKUS data (Rijkswaterstaat) a large number of coastal profiles is available for comparison. A 1960-1973 selection of summer profiles, augmented by a 1982 winter profile is shown in Fig. 10. Solid profile lines together form the envelope within which successive profiles have moved. Deepest scours together form the lower line of the envelope, which line is situated between -6 and -7 m. From this it is clear that in the breaker bar zone of the Dutch coast extensive erosional and depositional processes take place within relatively short timespans (in this case 22 years, the 1982 winter profile incorporated). The winter profile is meaningfull in

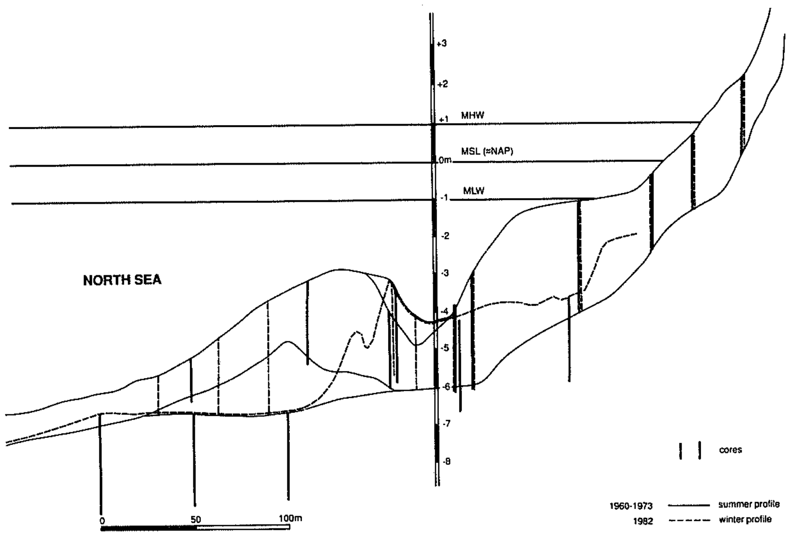

Fig. 10. Envelope of the 1960-1982 JARKUS profiles at Egmond.

this respect: it is only because of this winter profile that seaward erosion took place to such depth.

Short(1990) has recently discussed the morphology and dynamics of the Dutch coast. Bar mobility over the period 1976-1985 is found to have increased to the offshore from a mean of 60 m at the intertidal bar closest to the shore to 113 m for the next bar and 175 m at the deepest bar. These figures have been established over a nine year period(1976-1985). The active sweep zone, defined as the zone of movement of the bars, is some 800 m at Egmond (as it is for the larger part of the Dutch shoreface). Box cores 2 to 9 fall well within this zone. These figures indicate that sediment turnover within this 800 m zone is very high. Along with this sediment turnover, condensation of shell material takes place. Most molluscs are single valves of bivalves. No living molluscs were found in this zone. On the other hand, bioturbation by worms was found on several occasions. It may be concluded that some worm species (*Lanice conchilega* (Pallas, 1766) and *Nephthys hombergi* (Savigny, 1818)) are better adapted to this environment than are molluscs.

In view of the above data it is now considered acceptable that limited bioturbation is kept in the section and that molluscan shells in this zone of high turnover of the Dutch shoreface are moved and sorted in the way they are (compare Hertweck, 1971 for a Mediterranean example). The model presented here refers to the local conditions of the southern North Sea. In the fossil sections and the box core transect the same species were found. No influence of former or contemporary tidal inlets was noted, indicating that the sections and the recent transect were taken in representative Holland coast positions.

With regard to seasons, the results of Aigner and Reineck's (1983) survey off the island of Norderney may be interpreted as follows: every few months bioturbation is erased from the upper two to three metres in this zone. Erasion of bioturbation occurring lower takes place only during infrequent, severe storms.

A further conclusion is that for the depth range described in this paper the sedimentary environment that existed during the Subatlantic progradational phase of the mid-Dutch coast was the same as the present environment at the erosional coastline at Egmond. The depth distibution of sedimentary structures and the sedimentary behaviour of empty shells of a substantial amount of common North Sea bivalve species are similar. Median grain size distribution seems to be much less influenced by a common law.

The composition of empty bivalve shells in a sample is an indicator of the specific character of the set of hydronamic conditions at the sampling station on the shoreface of wave-dominated coastal deposits. It is suggested that fossil and recent sections show similar patterns in this respect in the time period covered by the data in this paper. In Fig. 11, a summary is given of the variables in the different zones. The supra- and intertidal beach is characterised by low diversity assemblages of molluscs with a marked depth-related distribution, mainly involving *Cerastoderma edule* (Linné, 1758) and *Spisula subtruncata*. The main sedimentary structure on the Holland coast beach is plane bed, dipping seawards, accompanied by bubble sand formation. The subtidal beach and barred shoreface are characterised by highly variable occurrences of a larger number of species. The mean fair weather wave base can be situated as high as -3 m in the off-storm season. The zone of high sediment turnover extends to a depth of some 6 m below MSL and is characterised by series of longshore bars. Internal structures consist mainly of plane bed and some low-angle cross-bedding. The latter has low preservation potential for the time period concerned. Clay layers and clay laminae have low preservation potential at the present-day coast. This preservation potential was much higher during the highly progradational phases of the Holland coast of the Subboreal and early Subatlantic. Large differences between summertime and wintertime coastal profiles exist. Taphocoenoses of this zone reflect depositional conditions of a highly dynamic wave-dominated environment. The amount of shell material is by far the largest and highest peaks occur near the base of this zone. Less dynamic conditions apparently existed during Subboreal barrier formation in the western Netherlands (Roep, 1986, fig. 17), judging by the preserved type of bedding in the same depth range relative to sea-level (low- and high-angle cross-bedding). Below -6 m the upper shoreface is characterised by thaphocoenoses that reflect much more closely the original faunal composition (cf. Hertweck, 1971; Frey & Dörjes,1988). Living molluscs were encountered below -6.8 m. Beds resembling storm deposits were found at Egmond below -5 m, a depth which is about equal to the older (some twenty centuries) IJmuiden and Zandvoort deposits. The same is true for the depth below which bivalve

zone	facies	limits (in m rel. to MSL)	bedding types	lithology	typical species
	supra-/ intertidal beach	+3/-1	plane beds seaward dipping	medium sand few shells, thin layers	upper: Cerastoderma sp. lower: Spisula sp.
	longshore bar/ upper shoreface	-1/-7	plane beds/ very low angle crossbeds, some storm beds	fine to medium sand, shells concentrated in layers, occasional clay layers and bioturbation	Spisula sp., highly variable numbers of: Donax vittatus, Macoma baltica, Mactra corallina, Tellina tenuis, T. fabula, Abra alba and Euspira sp.
	lower shoreface	-7/(-17)	storm beds	medium sand, clay layers and bioturbation	Spisula sp., Mactra corallina, Tellina tenuis, T. fabula, Chamelea striatula, Ensis sp.

Fig. 11. Summary of sedimentary and molluscan features for the Holland shoreface and beach.

molluscs in life position were found in the Zandvoort borehole. When one ignores the effect of sea-level rise during a period of twenty centuries, the distribution of sedimentary environments of the Subatlantic beach barrier appears to be comparable with that under the recent regime on the Holland coast.

The composition of the skletal assemblages only vaguely resembles the composition of the benthic associations present off the main Dutch Coast (Eisma, 1966). The way the taphocoenoses are tentatively interpreted herein shows they may be used in the analyses of fossil sedimentary facies, but it should be stressed that many additional structural box core data are needed before the Holland coastal regime is fully understood. As facies data for the upper shoreface are still limited, the monitoring of some beach-to-offshore transects of oriented box cores at distinctive sites along the western Netherlands coast could prove to be very elucidating.

ACKNOWLEDGEMENTS

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APPENDIX

Dating the IJmuiden Haringhaven section

The IJmuiden section was dated by ^{14}C analyses of two samples (Figs 2, 12). Dating results call for some comments. The 2295 ± 40 y BP is only very slightly younger than the 2310 ± 35 BP of the IJmuiden sluices exposure 1.5 km to the east. It is considered very unlikely that the coastline prograded over this distance in just 15 ^{14}C years (compare Roep, 1984). Especially in the time range within which the two samples are situated, calibration of ^{14}C results is extremely difficult (Stuiver & Pearson, 1986). This implies that it is impossible to assess the time that elapsed between the deposition of the two sections. Fortunately, there was another way to date the Haringhaven section. Terrestrial gastropods (*Cepaea nemoralis*) occurred in the shallow blow-outs at +2 m NAP; their dating yielded a result of 2170 ± 110. After calibration (using the updated version of the calibration programme by van der Plicht & Mook, 1988) this result indicates an age ranging from 370 cal BC to 110 cal BC, while the 2295 ± 40 dating is calibrated at 402 to 366 and 278 to 262 cal BC. For the Haringhaven section, the 2170 ± 110 dating is considered more realistic than the 2295 ± 40 dating, because the oldest archeological finds on top of the dunes (unit 1) some 1.5 km to the east were dated 2250 ± 45 (Velsen-Hoogovens, GrN 4483; Jelgersma *et al.*, 1970). In addition, peat growth immediately to the north of the Haringhaven section started at 1910 ± 60 BP (Velsen-Vormenhal, GrN 5083; Jelgersma *et al.*, 1970). When one ignores the disadvantages associated with the dating of terrestrial molluscan shells (the incorporation of 'old' inorganic carbon: *e.g.* Goodfriend, 1987), an acceptable age determination has been procured.

If, on the other hand, age anomalies of land snails are incorporated into the evaluation of the 2170 ± 110 dating, it would mean a further age reduction of reportedly at least 700 years (Goodfriend, 1987). In any case, this indicates a coastal progradation of 1.5 km in 140 ^{14}C years, but the period during which progradation occurred, could have been much longer, if the uptake of older inorganic carbon by land molluscs is taken

local no.	species	habitus	context	GrN	age	δ13C(‰)	Shell 14C ± SD (%)	depth (m~NAP)
	Mactra corallina	fresh single valves, also broken	stormplanated beach surface	15157	2295±40	-1.59		+2
	Cepaea nemoralis	whole shells	eolian concentrate	16185	2170±110 (after correction for δ13C)	-6.78	76.32 ±1.04	+2

Fig. 12. Radiocarbon analyses of shell carbonate of two IJmuiden samples (coordinates 62.300/436.100). Age in years BP (Present being 1950 AD).

into account. Extensive systematic research into this subject still remains to be carried out (Burleigh & Kerney, 1982).

However, sedimentation occurring during a much younger stage of coastal development is unlikely on the basis of the result of the 2295 ± 40 on marine shell material at the same height in the same geological sequence, but in different type of environment. This is also documented by the traces of human occupation mentioned above which immediately follow upon the deposition of the coastal sequence and the dating of the start of the peat growth in the region (Pruissers *et al.*, in press).

The fact that the two radiocarbon dating results of the IJmuiden-Haringhaven section are so close may indicate that coastal dune *Cepaea nemoralis* takes up inorganic carbon that has a much more 'contemporaneous' stable isotopic composition than, *e.g.* in a Chalk (late Cretaceous) landscape, in which 'old' inorganic carbon occurs profusely. The inorganic carbon in the dune landscape is provided by contemporaneous shell fragments from the beach, transported inland by wind, together with the dune-forming sand. The (delta) ^{13}C measurement of the GrN 16185 is indicative for this, when compared with the lower (*i.e.* more negative) values for *Cepaea nemoralis* of the Chalk landscape (Burleigh & Kerney, 1982). This interpretation certainly to be checked through studies on sections similar to that at IJmuiden, preferably in sections with mixed types of datable material and supplemented by recent monospecific snail data (cf. Burleigh & Kerney, 1982).

CHAPTER III

ESTIMATES OF PHYSICAL DISTURBANCE OF THE SEAFLOOR IN THE SHALLOW SOUTHERN NORTH SEA ATTRIBUTABLE TO NATURAL CAUSES

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CHAPTER III

ESTIMATES OF PHYSICAL DISTURBANCE OF THE SEAFLOOR IN THE SHALLOW SOUTHERN NORTH SEA ATTRIBUTABLE TO NATURAL CAUSES

ABSTRACT

In the present paper the natural causes of physical disturbance in the shallow (< 20 m) southern North Sea are discussed in relation to the disturbance by bottom fishery. A semi-quantitative estimate is given of the depth to which these natural disturbances are active. From 0 to -12 m the physical disturbances reach a depth which largely exceeds depths influenced by bottom fishery and occur several times annually. From -12 to -20 m disturbances attributable to fishery equal those due to natural causes and occur frequently, but possibly not every year. The transition is gradual.

INTRODUCTION

Lately, increased attention has been given to the effects of bottom fishing (beamtrawl, ottertrawl) on benthic faunas in the North Sea. Recently, an extensive study has been published on the effects of beamtrawl fishery (BEON report 13, 1991), from which it appears that beamtrawl fishery disturbs bottom sediments to a depth of at least 4-8 cm. Very few data are available on the physical disturbance of the seafloor due to natural causes. The shallow near-shore zone of the southern North Sea fulfils the same role as a nursery ground for juvenile fish as does the Wadden Sea. The shallow North Sea (less than 20 m water depth) can therefore be considered of equal importance. As the influence of the disturbance due to natural causes of the shallow North Sea bottom increases with declining water depth, it might be important to estimate the contribution of natural processes relative to the total physical disturbance (natural and human/artificial) of the shallow North Sea bottom. The natural disturbance comprises all disturbances other than man-induced causes. Although fishery in the shallow SE (< 20 m) coastal zone of the North Sea is not very intense (limited to vessels of up to 300 h.p.), it is increasing. An increase of fishery influence on the bottom sediments in the near future could lead to overstepping of a certain level of tolerable physical disturbance which could influence the present bioproductivity. The present paper aims at filling part of the data gap with respect to the natural causes. As a result of the lack of recent data from (regularly repeated) boxcore surveys, the subject matter is alternatively approached through the fossil (Holocene) shallow marine coastal barrier sediments. These sediments have the advantage of not having been subject to industrial fishery.

THE HOLOCENE BARRIER SEDIMENTS

During the second half of the Holocene (the period of *c* 5,000 years BP to the present-day), the Dutch coast in the shallow SE corner of the North Sea has experienced a substantial progradation of 8 to 10 km. This progradation of the ultimately *c* 18 m thick, predominantly sandy wedge of sediment took place under conditions of a slowly rising sea level, of up to some 4 m. This wedge formed in a slowly deepening North Sea under climatic conditions assumed to have corresponded to the present-day conditions. Coastal gradients increased stepwise during the progradation (Van der Valk, in prep.). Progradation presumably came to a halt during Roman times (*i.e.* some 1,800 years ago), and changed into erosion shortly after, but not simultaneously along the entire Holland coast (Beets *et al.*, in press).

The result of the progradation is a sedimentary sequence, an example of which is shown in Fig. 1. Full marine sedimentary environments are documented by marine fossils.

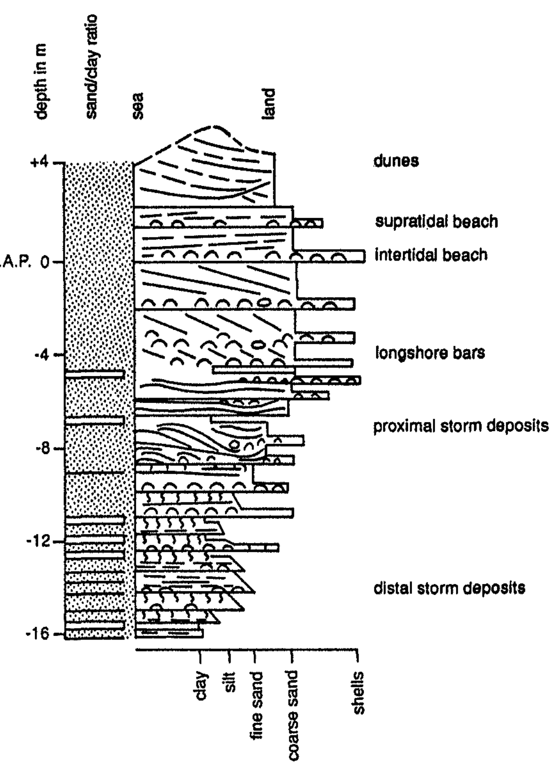

Fig. 1. Generalized Subatlantic coastal beach barrier sequence of the Western Netherlands (Van der Valk, in prep.).

Figure 1 shows that a generally coarsening-up sequence occurs with a maximum thickness of *c* 16 m. The sequence starts with clay-interbedded very fine sands and silts. Higher up, slightly clayey sands prevail. Bioturbation as a whole is less intense than in the fine grained-deposits of the lower part. At a depth of 5 to 7 m below Mean Sea Level (MSL), coarse mega-crossbedded sandy sets occur with many disarticulated shells and few non-bioturbated clay layers. Above MSL, sands with lower amounts of shells reflect intertidal beach conditions, aeolian deposition gaining on marine deposition upwards. The sequence is a result of the prograding shoreline covering older shallow North Sea fully marine subtidal sediments.

NATURAL DISTURBANCES IN THE BARRIER SEDIMENTS

The degree of bioturbation in the barrier sediments can be regarded as a measure of physical reworking of the sediment by other forces, *e.g.* wave action and current action. As might be expected, the distribution of the bioturbation is related to waterdepth and relative shelter. Generally speaking, more extensive bioturbation implies less energy on the seafloor. Bioturbation by worms and molluscs (the only two animal groups whose bioturbation activities could be traced in the barrier sediments) shows a marked decline from -16 m up to -6/-7 m. Above this level very few bioturbation occurs, and mostly ascribed to worms.

Bioturbation traces tend to be obliterated by strong currents, but even more so by strong wave action. From the barrier sediments, it can be deduced that below -16 m clay was rarely deposited in the shallow North Sea, and/or frequently reworked, while above this level clay commonly occurs in thinner patchy layers. It is tempting to attribute this pattern to a change in the relative importance of tidal currents below and above this -16 m level. Below this level, tidal currents might have been strong enough to keep fine-grained sediments suspended or have resuspended them after slacktide deposition. Above this level, forces developed by wave action might have been so strong that they generally surpassed forces developed by tidal action. The ephemeral character of wave action in the North Sea with its high climatic variability explains why the sedimentary environment may change from sand deposition into very quiet clay deposition and bioturbation immediately after a storm passage. From Fig. 1 it may be deduced that the wave action shows several trends with decreasing depth.

. Coarsest grain sizes occur in the upper half of the sequence (a well-known fact in wave-dominated coastal sequences);

. From -16 m up to the -7/-6 m level, set height (a set is defined as the total of sediment deposited after an event) increases from an average thickness of 5-10 cm to several decimetres at the upper limit (*i.e.* -12 m) of sets which are completely fossilized. Above this upper limit, individual sets have frequently been truncated, *i.e.* the upper centimetres (or probably even decimetres) of sediment and fauna are completely removed during the event, and taken into suspension in the case of the finer-grained sediment or transported elsewhere in the case of the coarser elements. In this way, a stack of truncated sets originated. This truncation may attain such a level that the next event will erode to a larger depth than the preceding one, causing erosional lags (shell and other coarse material) to combine into shell layers that become progressively thicker up sequence.

As mentioned above, there is an upward decrease in bioturbation activity. This decrease is thought to be due to at least two causes:
1. Primary non-occurrence in the higher reaches because of greater influence of wave action and,
2. (more limited) preservation potential because of commoner reworking in comparison with the lower part of the sequence.

MECHANISM OF PHYSICAL REWORKING

To estimate physical disturbance occurring in the shallow North Sea, several depth zones should be distinguished:

. 0 to -6/-8 m (zone of beach and breaker bars)
. -6/-8 m to - 12 m (upper part of upper shoreface)
. - 12 m to - 16 m (lower part of upper shoreface)
- 16 m to - 20 m (lower shoreface).

Zone of beach and breaker bars

Reworking of sediments in this zone is intense and frequent. According to Short (1991), a system of rip currents is active during any major wind, causing lateral displacement of the breaker bars. The frequency of reworking is high, which is also suggested by the rarity of bioturbation by worms in boxcores from this zone (Van der Valk, 1991). Maximum reworking depth varies, from at least 0.5 m to a maximum of 1.7 m !

Upper part of upper shoreface

The oscillatory action of the waves near the shore causes physical disturbance. In this zone the depth of reworking could reach to several decimetres in case of a severe storm (of which at present several occur in every season). In case of a less severe storm, shallower reworking is expected. During the progradational phase in the history of the Dutch coast, bioturbated levels occasionally were not eroded, which indicates that possibly the shallow sea bottom was not subjected to erosion every year. Modern conditions in this zone are poorly known.

Lower part of upper shoreface

Underlying the preceding zone, the oscillatory action of (storm) waves generally has a shallower impact: 5 to 10 cm. In addition, the bioturbated surfaces that originate after every (major) storm event are more frequently preserved and covered by the deposits of the next storm event, at least in the prograding beach barrier sequence.

Lower shoreface

Thin sand deposits interbedded with thin clay layers and sandy deposits with shells and shell grit indicate a change in deposition. The rareness of clay preservation (and primary lack of deposition?) and bioturbation indicates that tidal action became increasingly important in the formation of the deposits in this zone.

The most recent approach of the genesis of similar coastal barrier sequences is found in Duke *et al.*(1991), who argued that an interaction between oscillatory bottom currents and a shore-oblique bottom current driven by coastal downwelling is the driving mechanism for this type of coastal sequences. The oscillatory bottom current is by far the most important in this respect. This issue becomes more complex because of the nature of the southern North Sea. Its extreme shallowness (in geological terms) without doubt affects the depositional mechanism. The sequences discussed by Duke *et al.* (1991) cover a much larger vertical range. The extent to which this influence stretches is not well known, because too few wave and current data are known for the Dutch coast. The Dutch coastal mechanism needs monitoring of wave and current action, accompanied by frequent boxcoring.

CONCLUSIONS

The depth gradient off the Dutch coast opposes the gradient in reworking capacity of the average storm active on this coast. The depth at which a certain level occurs on the coastal profile determines the extent to which it is influenced until all influence is wiped out by subsequent tidal processes. The relative importance of wave and current processes in relation to bedforms is poorly known.

In the upper part of the shoreface, the effect of storms is much more extensive than that of bottom fishery: much larger areas are affected to a depth of up to several times the depth to which fishery affects the seafloor, and probably occurs several times annually.

In the lower part of the shoreface, the depth effect of storms is about equal to that of fishery by beam trawls, but in frequency is lower than in the upper shoreface area. The transition between this and the preceding zone is gradual.

As the shoreface (from the Low Water Line down to a depth of -20 m) fulfils the same role as does the Wadden Sea for juvenile fish, an increase of the high natural dynamics of this zone by increased bottom fishing could be of impact to the benthic faunas of this area and consequently to the fish population. At present, bottom faunas appear well adapted to the coastal mechanism, although changes have been reported to take place.

(De Bruyne & Van der Valk, 1991).

Important effects of increased beam trawl fishery could be:
. Uprooting of vulnerable benthic communities in the winter season causing widespread mortality;
. Disturbing settling conditions for the post-larval stages of benthic organisms during early spring and summer.

For comparative research, it is recommended that, similar to the developments in the open North Sea, a closed area for any type of fishery be established along the coast off the western Netherlands.

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2. THE SUBBOREAL/SUBATLANTIC (HOLOCENE) ENVIRONMENT

CHAPTER IV

HOLOCENE EVOLUTION OF THE COAST OF HOLLAND

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CHAPTER IV

HOLOCENE EVOLUTION OF THE COAST OF HOLLAND

ABSTRACT

The Holocene evolution of the coast of Holland was controlled by the complex interaction of such diverse parameters as wave and tidal climate, the rate of sea-level rise, and the morphology of the pre-transgressional surface. The latter, in combination with the rate of sea-level rise, mainly determines the location of sediment sources and sinks, while the hydrodynamic parameters mainly determine the rate and direction of sediment transport. In the early Holocene the low sea-level in the shallow southern North Sea strongly affected wave climate and tidal regime. However, the barrier and back-barrier sedimentary record since 5000 ^{14}C yrs B.P. gives us no reason to assume major changes in these parameters since then, so we conclude that breaks in barrier development are due to variations in rate of sea-level rise in combination with the morphology of the pre-transgressional surface.

The transformation from an open "tide-dominated" to a closed "wave-dominated" coast, which occurred in the Subboreal period, and the concomitant change in barrier movement from transgressive to regressive around 5000 yrs B.P. are the main events in the development of the coast of Holland up to the Middle Ages. The morphology of the pre-transgressional surface gives a shoreline in the late Atlantic which consists of two protruding headlands separated by a large tidal basin.

The southern headland is the alluvial plain of the Rhine and the Meuse, the northern headland constitutes the moraines of the Texel High. The tidal basin in between is connected to the North Sea by a large number of inlets. The rate of sea-level rise at that time (1 m/century) outran the supply of sediment to the tidal basin. After 6000 yrs B.P. the rate of sea-level rise decreased gradually, whereas the rate of sediment supply remained constant. This led to a gradual decrease in the tidal prisms of the inlets as the tidal basin was filled in with sediment. Shortly before 5000 yrs B.P. the first channels silted up and closed; the last tidal channel disappeared around 3300 yrs B.P., leaving two inlets along the coast which were both connected to the river Rhine. The closure of the first inlets occurred at the same time as the barrier began prograding because (1) the rate of sea-level rise diminished considerably, (2) not all the sand supplied by longshore and cross-shore transport disappeared into the tidal basin, but instead could be used for barrier progradation; and (3) ebb-tidal deltas of the closed inlets provided major sand sources.

The prograding barrier sequence enclosed between the two headlands roughly forms a closed system. Using the relationships between tidal prism, cross-sectional area of inlets and volume of the ebb-tidal delta, and the results of modelling of longshore transport along the Subboreal coast under present-day wave conditions, a simple sand budget for the coast of

Holland is given which shows that a large part of the sand now stored in the barrier sequence was obtained by cross-shore transport from the North Sea.

INTRODUCTION

In 1985 a project on the large-scale and long-term behaviour of the Dutch coast called "Coastal Genesis", was started in order to obtain a better insight into the factors and conditions causing coastal change. The main aim of the project is to construct conceptual and physical-mathematical models of the hydrodynamic and morphodynamic processes so that coastal behaviour can be predicted for the coming 10 to 100 years. The Coastal Genesis Project is a cooperative effort between coastal engineers, physical geographers, historians and geologists from universities and research institutes that is financed by the ministries of Transport and Public Works, Economic Affairs and Science and Education.

The basic data for the project are yearly measurements since about 1850 of the position of the dune foot and the mean high and low waterline relative to a fixed reference line, and yearly measurements since 1963 of the coastal profile along about 3000 fixed lines perpendicular to the coast up to 800 m offshore. (Once every 5 years some of these soundings are extended to 2500 m offshore). In addition, the beach and dunes are monitored by aerial surveys, and inlets and other important waterways are regularly monitored by soundings. Although these data give a good picture of the behaviour of the coastline since 1850 and the coastal profile since 1963, we felt it necessary to extend these records with historical and geological data where possible. Although less accurate, these much longer records better reflect the main trends in coastal evolution and as such are important in the formulation of conceptual models to be used for prediction. In this paper the relationship between short-term (since 1850) and long-term (since 5000 ^{14}C yrs B.P.) behaviour of the coast of Holland between Rotterdam in the south and the Frisian Islands is reviewed. Note that all ages, unless otherwise indicated, are given in conventional ^{14}C years.

THE SHORELINE OF THE NETHERLANDS

The shoreline of The Netherlands forms part of a barrier system along the southeastern shore of the North Sea from the northern tip of France up to and including Denmark (Fig. 1). The trend of barriers in The Netherlands varies from almost N-S in the west to almost E-W in the north. The shape of the coastline was inherited from the older Pleistocene morphology, but was strongly modified by Holocene coastal processes.

In the classification of Davis and Hayes (1984) the Dutch coast is a mixed

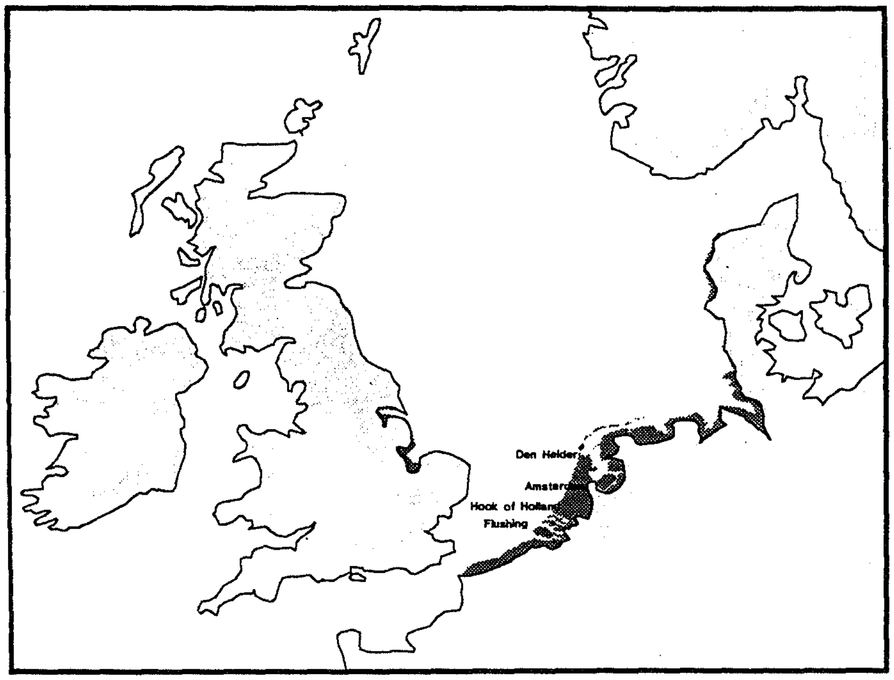


Fig. 1. Maximum extent of the Holocene transgression in the North Sea area.

energy coast, with both tides and waves shaping its morphology. The tidal climate is predominantly defined by the tidal wave coming in from the north and rotating anticlockwise around two amphidromic points, one between The Netherlands and the east coast of Norfolk (U.K.) and the other north of The Netherlands and west of Denmark. South of Rotterdam the tides are also influenced by the tidal wave from the English Channel. This results in a strongly varying mean tidal range along the coast, from 4 m in the south to less than 2 m along the coastal stretch between Rotterdam and the Frisian Islands. Along the Frisian Islands the mean tidal range gradually increases eastwards from 1.35 m near Texel to 2.10 m near the border with Germany (Fig. 2).

Analyses of wind directions along the coast in the period between 1700 and 1940 shows that the southwest is the most common direction (23%), followed by west (16%), east (13%) and northwest (12%) (Kollen, 1987; Stolk, 1989). The dominant wind speeds of over 15 m/s (7 on the Beaufort scale) are mainly from the west and northwest (Sha, 1989). As shown by Van Straaten (1961) there is a close correlation between wind and wave climate. The mean significant wave height is 1.1 m in the south (Kohsiek, 1988) and 1.8 m in the north (Sha, 1989).

On the basis of its morphology the present coast of The Netherlands may be subdivided into three coastal subsystems which basically differ with respect to the dominance of particular physical processes.

In the south of The Netherlands the Zeeland area consists of peninsulas separated by estuaries and inlets. The present morphology was established in post-Roman times by successive and often catastrophic flooding (Van den Berg, 1986). Inundation of large parts of the Zeeland area is considered to be related to peat exploitation and agricultural activitys in the Middle Ages. The present flood defence works in the region were prompted by the flooding disaster in February 1953. They mainly consist of permanent closure works for the estuary arms, and have changed the delta into more or less a relic. One of the arms, the Westerscheldt estuary mouth, is a very active system of bars and channels which has an important impact on the form of coastline undulations on the adjacent coastal stretches.

In the north of The Netherlands the Frisian Islands form a chain of barrier islands separated from the mainland by the Waddensea, a tidal basin with extensive tidal flats. The barrier islands are relatively long and the tidal inlet channels between them are characterized by active delta systems. The present form of the Waddensea was essentially attained a thousand years ago, when important breaches occurred towards the former Almere lagoon in the centre of Holland, thus creating the Zuiderzee. A characteristic feature of the Waddensea region is continuous sedimentation on its tidal flats in order to keep pace with relative sea-level rise, and silting along the Wadden shores. These processes are responsible for an important influx of sand, which is essentially delivered by the adjacent coastal system.

The central part of the coast of The Netherlands is the Holland coast, and the origin and Holocene evolution of this area is the main subject of this paper.

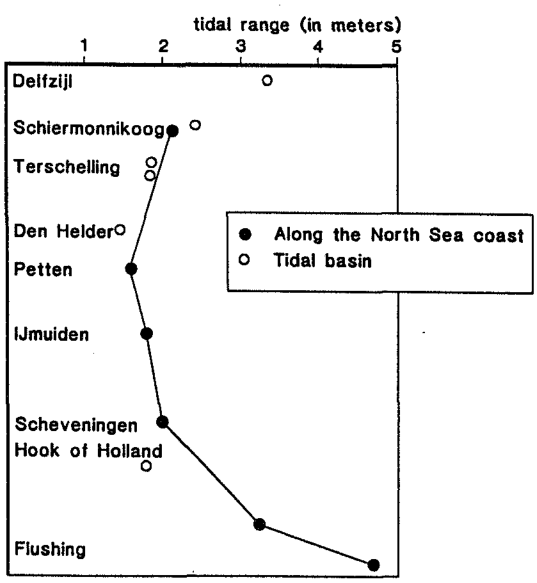


Fig. 2. Variation in tidal range along the Dutch coast (after Stolk, 1989)

THE COAST OF HOLLAND

General description

This area comprises an uninterrupted, slightly curved stretch of coast running SSW-NNE over a distance of almost 120 km from the entrance of Rotterdam Harbour near the Hook of Holland in the south to the port of Den Helder in the North. About midway is the man-made entrance of Amsterdam Harbour near IJmuiden. North of the village of Bergen the barrier is interrupted by the former Zijpe inlet, which was closed in about 1550 by dykes; this is now the Hondsbosse Sea Defence (Fig. 3).

North of this dyke the barrier is narrow and consists of a beach and a few dune ridges. The barrier reached its present position in the 16th century (Schoorl, 1973). South of the Hondsbosse Sea Defence, the barrier is a $\leq$ 10 km wide complex of partly overblown ridges and beach plains formed by progradation after about 5000 ^{14}C yrs B.P. (Van Straaten, 1965; Jelgersma *et al.*, 1970). South of Scheveningen this barrier complex curves westward and is truncated by the present shoreline.

The coast of Holland has a wave-dominated morphology with a steep, concave and barred shoreface. The toe of the shoreface lies at a depth of about 20 m along the northern and southern part of the coast and at about 15 m in the central part. The slope of the shoreface varies from about 1:400 in the north and the south to 1:165 in the central part (Van Alphen & Damoiseaux, 1989). Bars occur to a depth of 8 m below sea level along the entire coast, except for the area south of Scheveningen. The number of bars varies from two to five, including the intertidal bar.

The beach is generally 100 to 200 m wide, measured between the low water line and the dune foot. The slope of the beach between the high and low water line varies between 1:35 and 1:60. The morphology of the beach is dependent on the wave conditions. Quiet conditions promote the construction of a berm, and an intertidal bar, separated from the berm by a runnel. Storm waves will flatten the beach and destroy berm and bar (Reineck & Singh, 1973; Van den Berg, 1977).

Coastal dunes flank the beach over the entire length of the coast. The dune complex varies in width from a few hundred metres to more than 5 km. Dunes may become as high as 50 m, but those flanking the beach generally have a maximum height of 20-30 m. The mean grain size in the shoreface, beach and flanking dunes is 125-250 μm, 250-300 μm, and 200-250 μm respectively (Eisma, 1968; Stolk, 1989).

At present, the coast of Holland is retreating between the Hook of Holland and Scheveningen in the south, and between Bergen and Den Helder in the north. In the central part the shoreline is prograding slightly (Fig. 4). The rate of retreat is about 0.35 m/yr in the south and 0.70-0.95 m/yr in the north. These rates are statistical means based on the yearly measurements of the position of the dune foot and high and low water line since 1850 (Van Vessem, 1989). Initially, this pattern of erosion and progradation was explained by Edelman & Eggink (1962) as being predominantly due to gradients in longshore transport caused by the curvature of the shoreline. However, on the basis of heavy mineral analyses of coastal sands, Eisma (1968) stressed the importance of cross-

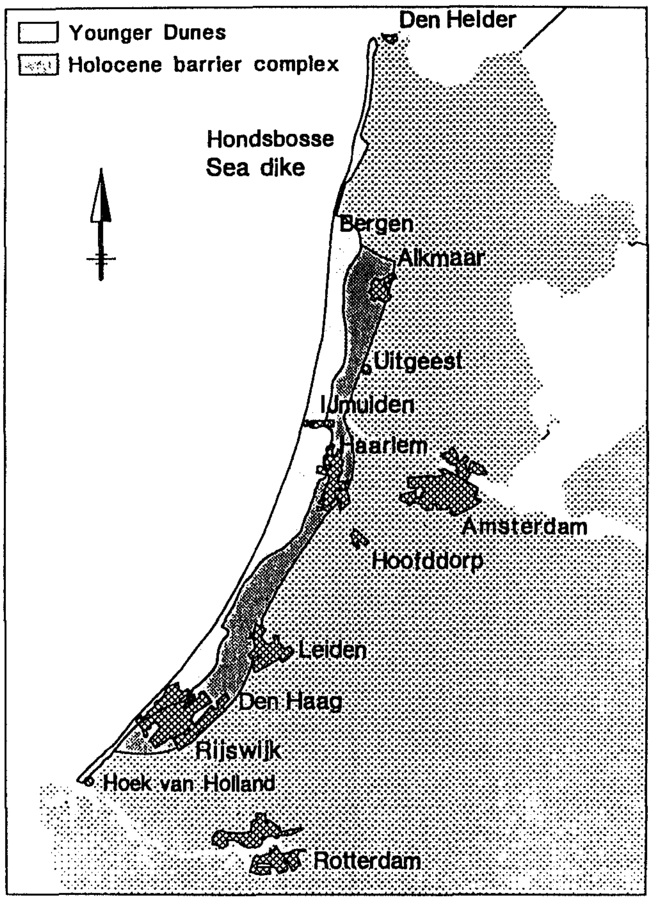


Fig.3. The Holocene barrier complex along the coast of Holland. The Younger Dunes are the medieval and younger coastal dunes covering the older barrier complex.

shore transport on the coast of Holland. At present, this latter view is quantitatively supported in the sense that cross-shore transport, not only within the breaker zone but including the exchange of sand between the shelf and the shoreface, is responsible for most of the progradation along the central part of the coast of Holland (Wiersma & Van Alphen, 1988; Stive, 1987, 1989). Erosion in the north is thought to be largely due to loss of sand to the Wadden Sea by way of the Texel Inlet (Stive, 1989) in response to a relative sea-level rise of 0.15-0.20 m in the past 100 years (De Ronde, 1982; Van Malde, 1984). The present erosion in the south is ascribed by Dijkman *et al.* (1990) and Stive *et al.* (1990) to net northward longshore losses due to wave and tidal motion, enhanced by the harbour moles and entrance channels of the ports of Rotterdam and Scheveningen.

As has already been concluded by Van Straaten (1965), long-term geological development indicates that both cross-shore and long-shore processes have played an important role in the evolution of the coast of Holland. Although (as will be discussed below) their relative magnitudes and response scales have shown some variation through geological time, the long-term orders of magnitude of these processes are approximately equal. At present, however, it appears that due to human interference and regulation measures segmentation of a large part of the Holland coast is being created, which suppresses net long-shore losses.

The long term development also shows that the present pattern of erosion and progradation of the coast of Holland has a long history, and chiefly arises from morphological differences in the pre-transgressional surface.

The Pleistocene surface of the western Netherlands

A simplified picture of the top of the late Weichselian surface beneath Dutch Ordnance Level (≈ Mean Sea-Level) is given in Fig. 5. The surface has a distinct E-W structure and consists of two wide, shallow valleys separated by low divides. The southern valley, which has its deepest part in the Rotterdam - Hook of Holland area, is the Late Glacial course of the rivers Rhine and Meuse. During most of the Holocene the rivers continued to follow this course. Only during the Subboreal and Early Subatlantic did the main tributary of the Rhine shifts its position temporarily, After which it returned to its original course after Roman times (Zagwijn, 1986; Pruissers & De Gans, 1988). A 40-50 km wide, flat divide separates the Rhine/Meuse valley from the northern valley, which is the confluence of a number of small streams draining the area which surrounds the northern valley. The present remnants of these streams are the Overijsselse Vecht in the eastern part of The Netherlands, and the Eem in the central part. The Texel High, an E-W ridge of Saalian pushed moraines (Jelgersma, 1961; Pons *et al.*, 1963; Ter Wee, 1983) is the northern divide of this valley.

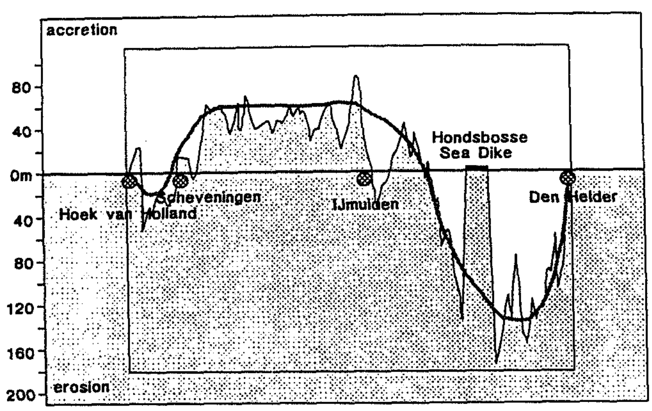


Fig. 4. Hundred year mean coastline changes along the Holland coast (simplified after Edelman & Eggink, 1962)

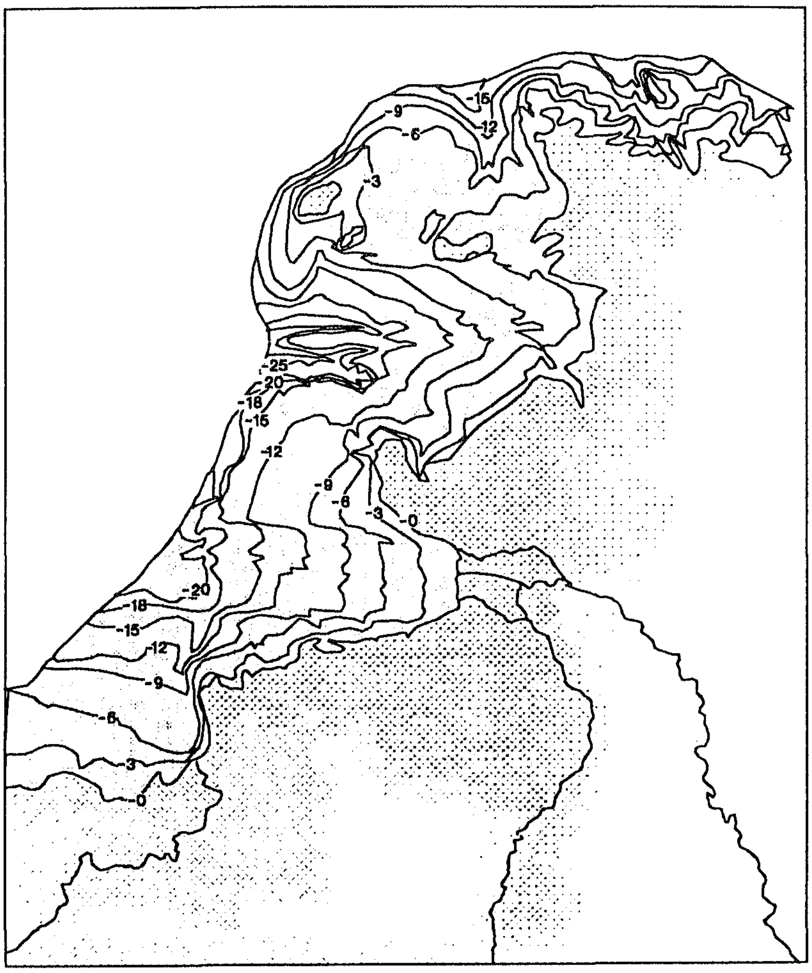


Fig. 5. Morphology of the Late Glacial surface (after Zagwijn, 1986). Contours in metres.

The outcropping Pleistocene sediments consist predominantly of aeolian cover sands and coarse sandy river deposits of Weichselian age. Consequently, the Pleistocene surface provides sufficient sand for barrier construction. Although the westerly extent of the Texel High is uncertain because of destruction by the landward migration of the barrier, it seems likely that this ridge, because of its protruding nature, was a major source of sand during the Holocene barrier evolution. As the Rhine and Meuse followed their original course throughout most of the Holocene, and fill up their alluvial plain in response to the rapid sea-level rise, this area becomes another source of sand to feed the barrier. The discharge of the local streams of the northern valley decreases strongly at the start of the Holocene, and, unlike that of the Rhine/Meuse, this valley changes into a tidal basin which becomes a major sink of sand and mud (Pons *et al.*, 1963;

Pons & Wiggers, 1959-1960). Consequently, the main trend throughout the Holocene is erosion of the Texel High and the Rhine/Meuse estuary and deposition in the area in between - in broad terms the pattern of progradation and erosion of today. Eventually, this pattern of progradation and erosion erased the E-W structure of the late Weichselian surface and replaced it by a smooth SSW-NNE coastline, which, at first sight, has little in common with the original morphology.

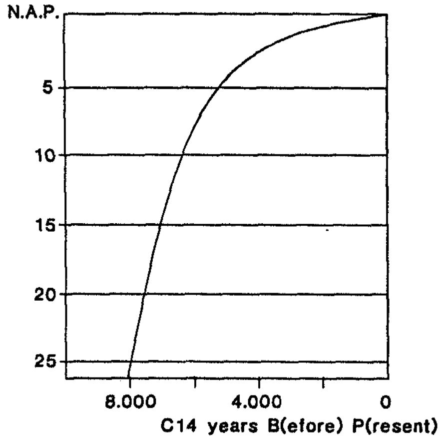


Fig. 6. Curve for the Holocene sea-level rise around the western Netherlands (after Jelgersma, 1961 and Van de Plassche, 1982). N.A.P. = *Nieuwe Amsterdamse Peil* (sea-level).

Holocene relative sea-level rise

On a time scale of several thousands of years, relative sea-level rise is one of the most important factors controlling barrier evolution. The sea-level curve for the western Netherlands is shown in Fig. 6. It is largely based on the data of Jelgersma (1961) and Van de Plassche (1982). More recent data (Roep & Beets, 1988; Van de Plassche & Roep, 1989) improve its accuracy in the range 5500-2000 ^{14}C yrs B.P., but do not add elements which are essential to this paper. The curve shows a rapid sea-level rise (> 1 m/century) until about 6000 ^{14}C yrs B.P., after which the rate gradually decreased to 0.05 m/century during the past 2000 years. As mentioned earlier, a rate of sea-level rise of 0.15-0.20 m/century has been measured since systematic monitoring started around 1850.

Note that at the start of the Subboreal, when progradation of the barrier complex of the coast of Holland started, mean sea-level was still 5 m below the present level.

Paleogeography of the shoreline shortly before progradation

Stabilization of the transgressive barrier system started shortly before 5000 yrs B.P. east of Haarlem and east of The Hague (Fig. 7). South of Haarlem the barrier was offset by a tidal inlet, which, in the next 1000 years, developed into the main mouth of the River Rhine (Pons *et al.*, 1963; Zagwijn, 1986; Pruissers & De Gans, 1988). Southeast of The Hague the barrier bent westward and at present is truncated by the shoreline 10 km north of Hook of Holland. The exact position of the coastline north of

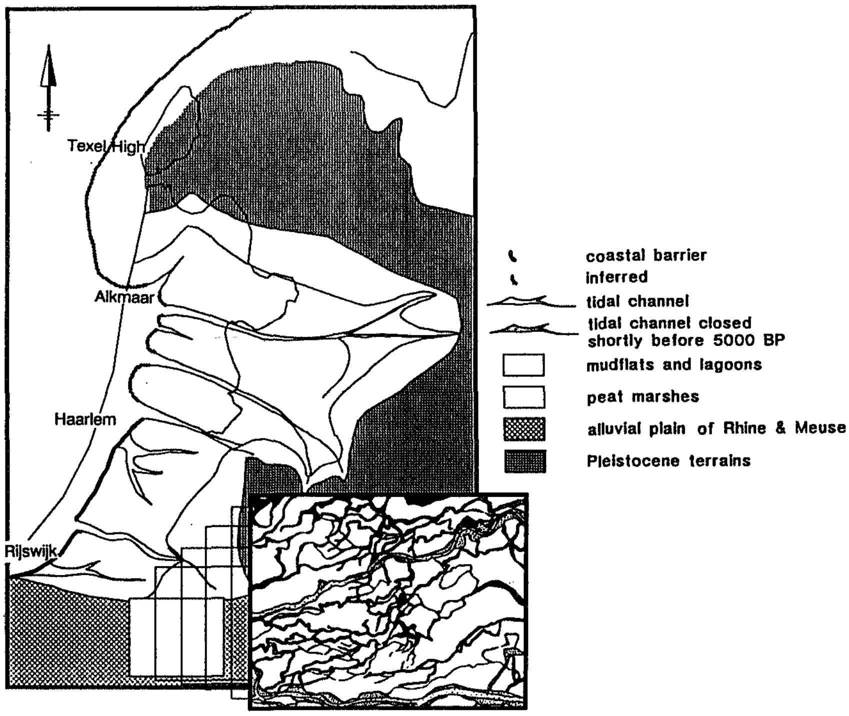


Fig. 7. Paleogeography of Texel High, the tidal basin of Holland, and the oldest preserved barriers around 5000 yrs BP. Inset is also shown in Fig. 11.

Haarlem is unknown, as it was still shifting eastwards at that time. The oldest preserved linear barrier in this area dates from about 4500 yrs B.P. (Westerhoff *et al.*, 1987). At 5000 yrs B.P. the coast north of Haarlem was made up of a number of barrier islands separated by major, E-W channels. Slightly before this time more channels cut the coast when there were tidal inlets at Rijswijk (Van der Valk *et al.*, 1985) and south of Haarlem (Haans, 1954), so the coast of Holland was "open" around 5500 ^{14}C yrs B.P. (Beets *et al.*, 1985). As will be described below, between 5500 and 1500 yrs B.P. the channels successively silted up and at the same time their inlets closed. Due to these events an important mechanism was created for the progradation of the barrier system. This mechanism was very similar to that observed recently after the closure of the Grevelingen estuary in the Zeeland region (Kohsiek, 1988). The basic process involves cross-shore sand transport induced by wave asymmetry (Stive, 1986), and the major sand source contained in the ebb-tidal deltas is used for the barrier progradation. An additional argument in support of this process is the hindcast of the wave climate in the period up to 5000 yrs B.P. as made in Stive (1987). As Fig. 8 shows, strong increase is expected to have taken place in the values of various wave characteristics, and especially in the wave skewness, which is an important, near-linear measure of sand transport induced by wave asymmetry.

The large number of inlets on the coast of Holland between 6000 and 5000 yrs B.P. occurred as a consequence of the size of the tidal basin, and was not due to a larger tidal range as was initially thought (Beets *et al.*, 1985). The tidal range along the coast was 10-25% less than at present, as may be seen from modelling of the tidal conditions in the North Sea at lower sea-level stands (Franken, 1987). The large size of the tidal basin was primarily due to the morphology of the Pleistocene surface. In addition, the rate of sediment supply prior to 6000 yrs B.P. was insufficient to compensate for the fast sea-level rise, so around 5000 yrs B.P. the valley of the Overijsselse Vecht was still recognizable in the shape of the tidal basin (Fig. 7).

Table 2 gives an estimate of the collective cross-sectional area of the inlets on the coast of Holland between 6000 and 5000 yrs B.P., using the relationship between cross-sectional area of tidal inlets and their mean tidal prisms (O'Brien, 1969; Van den Berg, 1986). The mean tidal prism depends on the size of the tidal basin at mean high water and the tidal range at the inlet. However, because of the presence of intertidal flats, which reduce the volume of the basin and dissipate the tidal wave energy, the product of size of the tidal basin and tidal range at the inlet places an upper boundary on the mean tidal prism. Because the paleomorphology of the basins is insufficiently understood, we have tried to correct the overestimation by an indirect approach. In Fig. 9 we have plotted the measured mean tidal prisms of the inlets of the Dutch part of the Wadden Sea versus their theoretical tidal prism obtained by multiplying tidal range at the inlet and the size of the tidal basins (for data see Table 1). This plot shows that the tidal prism of most of the recent inlets is roughly 80% of that calculated from tidal range and size of basin. We have used this factor to estimate the mean tidal prisms of closed inlets. Accordingly, the cross-sectional area of the combined inlets north of the line Haarlem-Amsterdam is estimated to have been 190,000 m^2, whereas that of the combined inlets south of this line is 90,000 m^2 (Table 2). The Texel Inlet and the Vlie, two of the major inlets of the present Wadden Sea, have cross-sectional areas of 70,000 and 60,000 m^2 respectively.

Of course, these are very rough estimates, but the order of magnitude of the outcome of the calculations strengthens the geological data and confirms that major channel systems developed to feed the large tidal basin formed from the former valley of the Overijsselse Vecht. As mentioned earlier, the channels subsequently silted up, so that sand from the ebb-tidal deltas became available for the progradation of the barrier system. In Table 2 an estimate of the amount of sand stored in the ebb-tidal deltas of the former inlets of the Holland coast is given using the

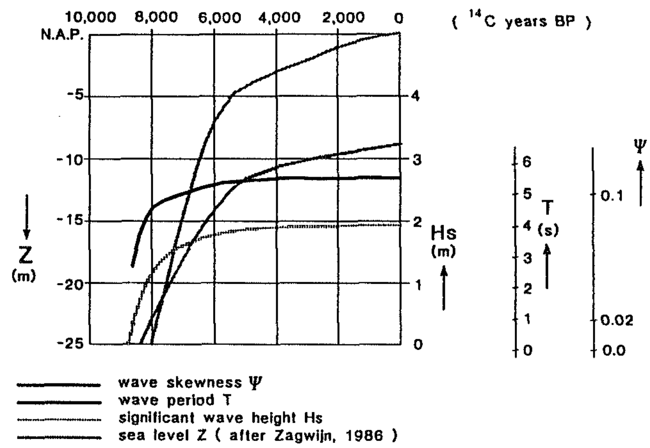


Fig. 8. Estimated variation in wave characteristics in the Holocene on the central Holland coast (after Stive, 1987)

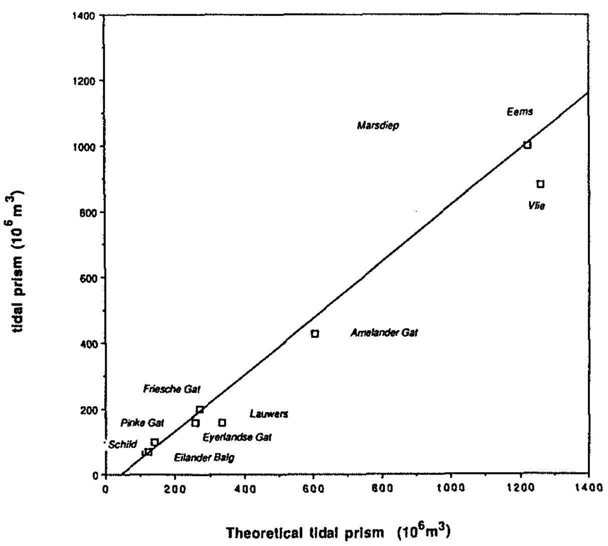


Fig. 9. Relationship between measured tidal prism and theoretical tidal prism of the Dutch Wadden Sea inlets. Theoretical tidal prism is calculated by multiplying the size of the tidal basin at mean high water (m^2) by the tidal range in the inlet (m)

relationship between tidal prism and volume of ebb-tidal delta as developed by Bruun (1978).

Closure of the channels occurred because of a decrease in tidal volume, which was basically due to slackening of the sea-level rise (Fig. 6). The channel near Rijswijk (Van der Valk *et al.*, 1985) and the one south of Haarlem, the Hoofddorp channel system, closed between 5500 and 5000 yrs B.P.. Between 5000 and 4500 yrs B.P. this was followed by silting up of the large Uitgeest channel (Fig. 7) and a smaller one to the north of it (Westerhoff *et al.*, 1987). At 4000 yrs B.P. only three channels remained: (1) the one near Leiden, which by then had developed into the main discharge channel of the Rhine (2) the Oer-IJ, which developed into another, much smaller branch of the Rhine, and (3) the Alkmaar-Bergen Inlet. The latter closed between 3500 and 3000 yrs B.P., but until that time was the major sink for sand along the coast. Finally, the Oer-IJ Inlet closed around 2000 yrs B.P. and Leiden Inlet around 1200 AD (Zagwijn, 1986; Pruissers & De Gans, 1988; Roep, 1984; Westerhoff *et al.*, 1987).

At 5000 yrs B.P. this developing barrier sequence was enclosed between the Texel High north of Bergen and the cuspate delta plain of the rivers Rhine and Meuse south of Scheveningen. Both sandy, soft-rock promontories have been worn away, so their history can only be reconstructed indirectly.

At 5000 yrs B.P., with the sea-level 5 m below present, the Texel High still comprised an E-W ridge that separated the tidal basin of Holland from that of the predecessor of the Wadden Sea (Fig. 7). Its offshore extent is unknown, but, based on historical documents and maps, Schoorl (1973) reconstructed the medieval shoreline at varying distances (on the order of kilometres) offshore of Den Helder, which suggests that at the much lower sea-level of 5000 yrs B.P. the coastline was situated still further westwards. The E-W trend of the hooked spit of Bergen (Fig. 10), which formed the southern boundary of the Texel High and the west bank of the Alkmaar-Bergen Inlet, seems to confirm this.

The strike of the barrier southwest of Rijswijk (Figs. 7 and 10) shows that the alluvial plain of the Rhine and Meuse extended offshore at 5000 yrs B.P.. At present, the rivers carry virtually no sand to the shoreline. Whether they brought sand to the seashore at 5000 yrs B.P. is not known. Considering the high rate of sea-level rise during the Atlantic it is not very likely; most sand was probably deposited in the alluvial plain to compensate for the sea-level rise. The Holocene deposits of the alluvial plain east of Rotterdam (Fig. 11) show a large number of sandy channel fills "floating" in swamp peats and clay-rich overbank deposits. Channel deposits in this area vary in age from early Holocene to recent, but the intricate network of small channel fills of Fig. 11 dates mainly from the Late Atlantic (6000-5000 yrs B.P.; Hageman, 1969; Van der Meene, 1984). Comparable alluvial deposits, but of greater age, must have existed in the present offshore area when sea-level was lower. Due to the fact that the rivers traversed the same general area up to the Subboreal, this diachronous alluvial plain was a major source of sand by reworking of the channel deposits during shoreface retreat. It became a soft-rock promontory because the removal of sand by longshore drift and tidal

TABLE 1

Data for the tidal inlets of the Dutch Wadden Sea

	1	2	3	4	5
Marsdiep	680	1.40	952	1050	820
EijerlandseGat	160	1.60	256	160	81
Vlie	720	1.75	1260	880	660
AmelanderGat	310	1.95	605	430	273
PinkeGat	65	2.15	140	100	45
FriescheGat	130	2.15	280	200	107
EilanderBalg	55	2.25	124	70	29
Lauwers	145	2.30	334	160	81
Schild	50	2.35	118	70	29
Eems	520	2.35	1222	1000	772

1 = Size of the tidal basin at mean high water in square kilometres
2 = Mean tidal range in inlet in metres
3 = Theoretical mean tidal prism: V_t (size of the tidal basin x mean tidal range) in cubic metres x 10^6
4 = Mean tidal prism in cubic metres x 10^6: V_m (mean tidal prism of inlet)
5 = Calculated volume in cubic metres x 10^6 of ebb-tidal deltas: $V_{bd} = 6.57 \times 10^{-3} \times V_m^{1.23}$. V_{bd} = Volume of ebb-tidal delta (after Bruun, 1978 & Eysink, 1990)

TABLE 2

Calculated combined tidal prisms, cross-sections, and volume of ebb- tidal deltas of tidal inlets of the Holland coast prior to 5000 yrs B.P. (See Fig. 7)

	1	2	3	4	5	6
north of the line Amsterdam-Haarlem	2400	1.4	3360	2700	190000	2.5 x 10^9
south of the line Amsterdam-Haarlem	1200	1.4	1680	1300	90000	1.0 x 10^9

1 = Size of the tidal basin in square kilometres
2 = Tidal range in metres
3 = Theoretical tidal prism: V_t (Surface tidal basin x tidal range) in cubic metres
4 = Calculated tidal prism: $V_c \approx 0.8\ V_t$ in cubic metres (Fig. 9)
5 = Combined inlet cross-section $F = 70\ V_c.10^{-6}$ in square metres
6 = Volume of ebb-tidal delta in cubic metres: $V_{bd} = 6.57 \times 10^{-3} \times V_c^{1.23}$

currents was insufficient to compensate for the supply by shoreface retreat at the fast rate of postglacial sea-level rise.

Barrier progradation in the Subboreal

The barrier complex consists of an alternation of ridges and beach plains (Fig. 10), which, on the western side, is buried beneath a much younger cover of dune sands, the so-called Younger Dunes (Jelgersma *et al.*, 1970). The main difference between ridges and plains is that the former have low dunes, whereas the latter lack aeolian deposits and have a cover of peat often underlain by mudflat and/or estuarine sediments near the inlets. Based on the study of sedimentary sequences of the barrier complex in pits excavated for construction work around Alkmaar, Beets *et al.* (1981) found that landward dipping, large scale cross-bedding associated with breaker bars were the dominant sedimentary structure in the intertidal reach of the beach plain sequences, whereas horizontal plain beds characterize the intertidal deposits of beach ridge sequences. In addition, ^{14}C dates on articulated shells suggest a difference in progradation rate, with beach plain sequences forming during rapid progradation.

As, at present, the intertidal breaker bars form during fair weather and are destroyed by storms, Beets *et al.* (1981) state that .... "Beach plain sequences form in periods of rapid progradation when the beach gradient is low and the beach is sheltered from onshore storms by shoals ... Dune ridges, on the other hand, are promoted by a higher beach gradient and no or only little progradation of the beach". They point to the similarity with the cheniers and ridges of the U.S. Gulf of Mexico coast and they state that the alternation of ridges and beach plains in the Dutch barrier complex might be due to changes in the sediment supply.

When Beets *et al.* (1981) studied these sedimentary sequences little was known of the coastal configuration prior to 4000 yrs B.P. and the sand necessary for progradation was thought to have been derived from both overstepped barriers offshore and from the "delta" of the Rhine and Meuse (Van Straaten, 1965). Consequently, changes in the supply of sediment either meant variation in the discharge of the rivers or variations in wave climate. However, now that we know that the ebb-tidal deltas of closing inlets are important sources of sand for progradation of the barrier in in the Subboreal, the changes in sediment supply as expressed by the alternation of beach plains and ridges can largely be explained by the succession of inlet disappearance. In this context it should be noted that the cross-shore processes after inlet closure occur relatively quickly and relatively locally, while longshore processes are expected to occur relatively gradually and over greater longshore distances. It is to be expected that the observation of these processes is not straightforward because of the requirement of a high spatial resolution of geological profiles. Keeping in mind that beach plain sequences represent rapid progradation and the supply of large amounts of sand, the maps shown in Fig. 12 show the following history of progradation:

(1) Between 5000 and 4500 yrs B.P. most sand was supplied by sources near Rijswijk and Haarlem. The former was the ebb-tidal delta of the Rijswijk Inlet, which was an important source for the beach plain east of

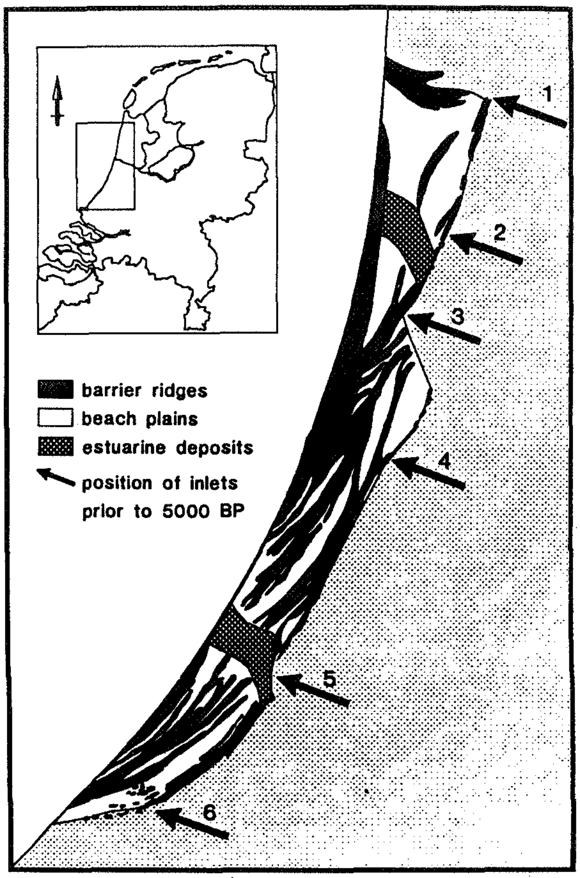


Fig. 10. Beach ridges and beach plains of the barrier complex of Holland. 1= Alkmaar-Bergen Inlet; 2= Uitgeest Inlet; 3= Oer-IJ Inlet; 4= Hoofddorp Inlet; 5= Oude Rijn Inlet; 6= Rijswijk Inlet. After Jelgersma *et al.* (1970), De Mulder & Bosch (1982), Westerhoff *et al.* (1987) and many unpublished data.

The Hague, and the latter was that of the Hoofddorp Inlet, which provided most of the sand for the triangular beach plain east of Haarlem. Both inlets closed shortly before 5000 ^{14}C yrs B.P.. In addition, longshore transport would have brought sand from the cape west of Hook of Holland. Longshore transport forced the inlet of the Oer-IJ towards the north. Note that progradation in the The Hague and Haarlem area started at least 500 years before stabilization of the barrier in the Alkmaar area. This was due to the difference in the size of the back-barrier area. In the Late Glacial the Haarlem/The Hague area was the flat divide between the northern valley and the alluvial plain of the Rhine and Meuse (Fig. 5). Consequently, the back-barrier area which formed during the late Atlantic was smaller in size and was filled more rapidly than the tidal basin east of Alkmaar. The Rijswijk and Hoofddorp channels had a short life span in comparison with the channels in the north. They closed earlier (≈ 5200 yrs B.P.) because of rapidly declining tidal prisms.

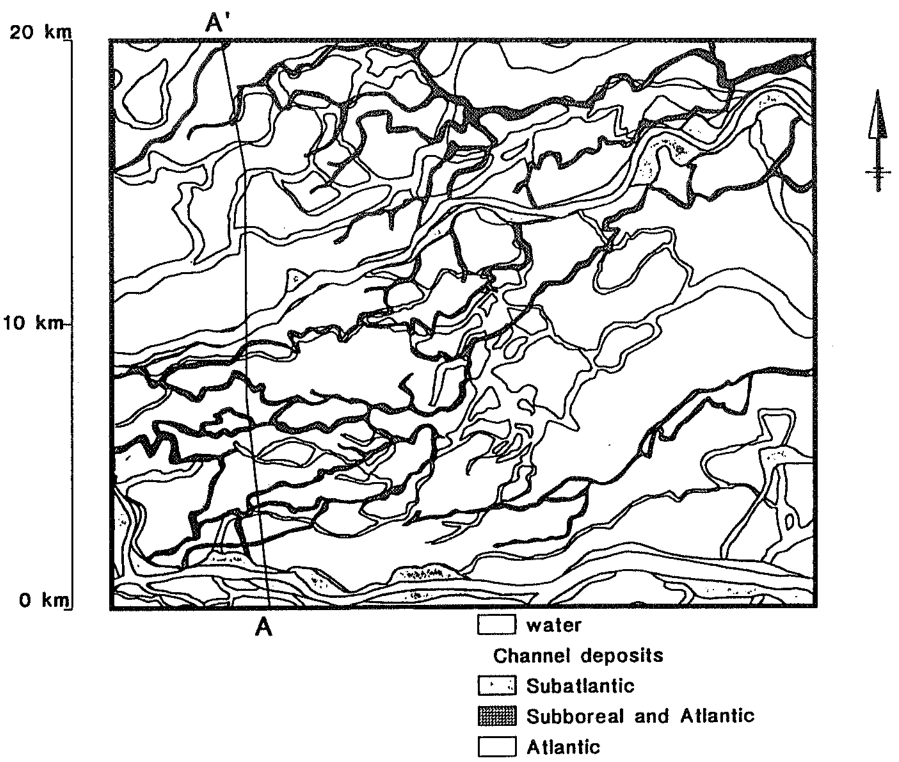
(2) Between 4500 and 4000 yrs B.P. the sand sources did not fundamentally change, except for the area north of Haarlem. Here, the oldest preserved barrier dates from about 4500 yrs B.P. It closed the Uitgeest Inlet and forced the Alkmaar-Bergen Inlet to move northward (De Mulder & Bosch, 1982). Until that time the inlet was a major sink for sand, both from the south and the north. Nevertheless, the amount of sand provided by the Uitgeest ebb-tidal delta was sufficient to cause progradation of the barrier directly south of the Inlet, and the formation of the beach plain south of Alkmaar. The shape of the barriers around Leiden Inlet suggests that this tributary of the Rhine started to bring a modest amount of sand to its mouth from 4500 yrs B.P. onward.

(3) Between 4000 and 3500 yrs B.P. progradation proceeded rapidly over the entire length of the coast. Wide beach plains on both sides of Leiden Inlet show that the supply of sand by this branch of the Rhine increased considerably compared to the preceeding period, suggesting that at 4000 yrs B.P. this was the main or probably the only discharge channel of the river. The 3500 yrs B.P. shoreline in this area was situated near the present coastline. The northward drift of the Oer-IJ Inlet continued. At the same time the Alkmaar-Bergen Inlet narrowed.

(4) For the period after 3500 yrs B.P. we have no data concerning the barrier sequence for the area in the south, as the coastline prograded seaward of the present shoreline. In the central part progradation proceeded slowly: the 2000 yrs B.P. shoreline was situated near the present shoreline. Most of the progradation since 3500 yrs B.P. occurred in the north: the wide beach plain west of Alkmaar was predominantly formed by sand of the ebb-tidal delta of the Alkmaar-Bergen Inlet, and to a lesser degree, of that of the Oer-IJ ebb-tidal delta after 2000 yrs B.P.

For the barrier complex between Rijswijk and IJmuiden (Fig. 10), Zitman (1987) has estimated which part of the progradational sequence could be attributed to gradients in wave-driven longshore transport due to the curvature of the shoreline. The calculations are based on "state-of-the-art" longshore drift formulations with a realistic estimate of the associated bandwidth of accuracy. For the calculations, it was assumed that wind and wave climate between 5000 and 3000 yrs B.P. was similar to those of today, and that the slope of the shoreface to a depth of -10 m was 1:200 instead of the present 1:100. Although the model cannot cope very well with the relatively complicated morphology of the inlet near Leiden, Zitman shows that longshore transport is in no way sufficient to explain the progradation. Of the 6 billion m^3 sand stored in the barrier complex between Rijswijk and IJmuiden, less than 1 billion m^3 sand could have been contributed by longshore transport according to the calculations of Zitman (1987).

Little is known of the development of the barrier of the Texel High in this period. Zagwijn (1986) assumes an uninterrupted barrier from Bergen in the south up to and including the present island of Terschelling in the northeast. Subboreal mudflat deposits behind this barrier are thought to have been fed by channels from the south (Alkmaar-Bergen Inlet) and the northeast. These mudflat deposits are overlain by eutrophic and oligotrophic peat. The collapse of the oligotrophic peat body in the area of Texel



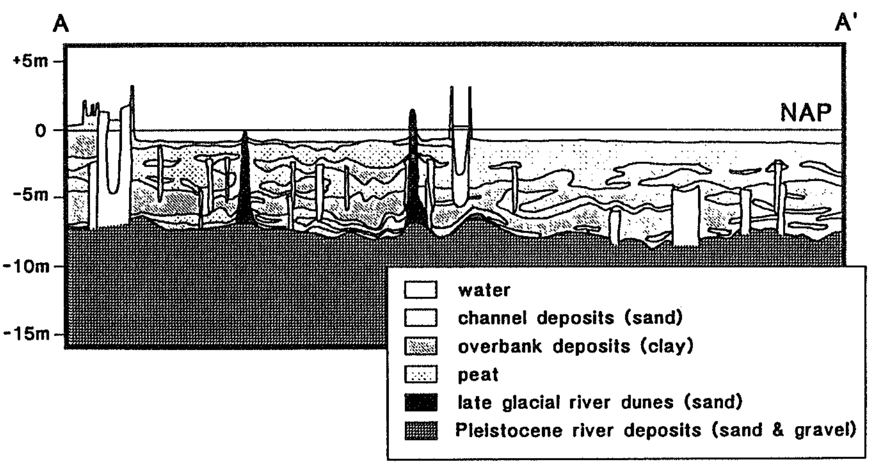


Fig. 11. Holocene alluvial plain deposits in the area east of Rotterdam. For location, see inset in Fig. 7 (after Van de Meene, 1984).

and Den Helder due to drainage by tidal channels from the west around Roman times (Zagwijn, 1986; Westerhoff & Beets, 1987) indicate the nearness of the coastline. Peat is overlain by sandy flood-tidal delta deposits and washover fans of Medieval age fed by a number of channels cutting the barrier, which was then still six or more kilometres west of Den Helder (Schoorl, 1973).

Erosion of the alluvial plain south of the barrier complex continued, probably at an increased rate since 4000 yrs B.P. as the main discharge channel of the Rhine shifted to Leiden. This shift also caused widening of the estuary and after about 3500 yrs B.P., flooding and erosion of the area behind the barrier (Van Staalduinen, 1979).

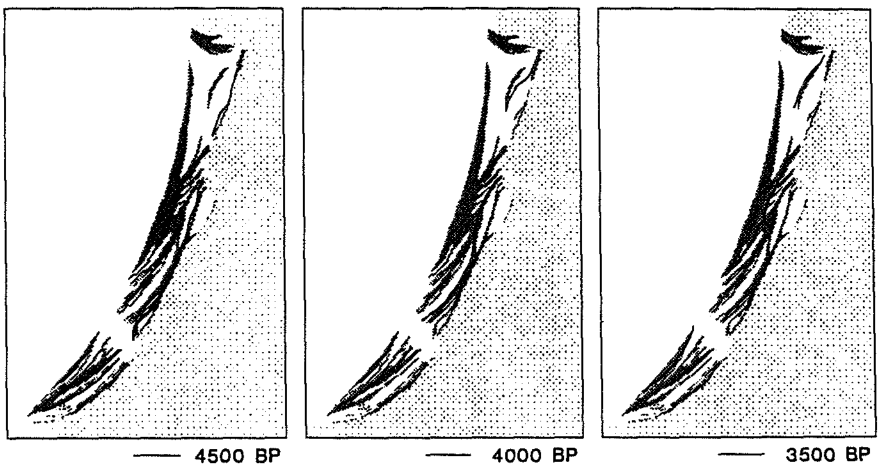


Fig. 12. Isochrons of the prograding barrier sequence of Holland. The isochrons are based on more than 400 ^{14}C dates of shells in the barrier sequence and peat overlying the beach plains. Only some of these dates have been published (see Westerhoff *et al.* (1987), De Mulder & Bosch (1982), Roep *et al.* (1983), Van de Plassche (1982), Van Staalduinen (1979). The others are from the files of the Geological Survey of The Netherlands.

Barrier behaviour since Roman times

With the silting up of the last inlet along the coast of Holland the obvious sources of sand for progradation were exhausted. Moreover, because of the continuous retreat of the Texel High in the north and the alluvial plain in the south and simultaneous progradation along the central part of the coast of Holland, gradients of longshore transport decreased in time. The prograding coast reacted to this decrease in sediment supply by steepening of the upper shoreface. Steepening of the slope of the shoreface since the end of the Subboreal was the logical outcome of the coastal progradation model presented by Van Straaten (1965), which shows low shoreface gradients during progradation in the Subboreal. Although Van Straaten's age control on the reconstruction of the Subboreal shoreface is conjectural, as it involves pollen only, recent work by one of us (Van der Valk) on cross sections of the barrier complex based on undisturbed cores with a large number of ^{14}C-dated isochrons confirms the process of steepening of the upper shoreface, but shows that this occurs more gradually and started much earlier than assumed by Van Straaten (1965). Stive *et al* (1990) point out that along the central part of the coast of Holland longshore net losses in the active zone (extending from the first dune row to a depth of $\pm$ 8 m) are at present so small that the net shoreface feeding of the active zone by wave asymmetry and density-flow driven upwelling can also compensate for the losses due to vertical profile movements by sea-level rise and wind-induced transport. This causes the active zone, including the shoreline, to prograde and the lower and middle shoreface to flatten. As a result, the transition between the active zone and the middle shoreface steepens. The quantitative confirmation of these effects is given by Knoester (1990), where, for example, long-term evolution data (1896-1975) of the -7 m and the -10 m depth contours are presented.

With the inlets closed, the sand of their ebb-tidal deltas remoulded into barrier sequences, and the barrier of the Texel High still a promontory, the coast of Holland became a more or less closed system in the Subatlantic. Steepening of the shoreface implies less dissipation of wave energy on the shoreface and increasing pressure on the breaker zone and the beach. In the classical case of the barrier-lagoon couple, this would lead to breaching of the barrier during storm, landward transport of sand by washover fans or flood-tidal deltas, landward shift of the barrier and a return to the original slope of the shoreface. Basically, this is what happened to the barrier of the Texel High (Eisma & Wolff, 1983). However, in the case of the coast of Holland between Scheveningen and Bergen the barrier and dune complex had reached a width of up to 8 km and, consequently, could not be breached. The gradual closing of all tidal inlets enhanced this process, together with the formation of progressively higher dunes along the successive barrier coastlines.

Although the present process of steepening of the shoreface in the case of the coast of Holland leads to shoreline progradation, the maps of the barrier sequence (Figs. 10 and 12) show considerable truncation of the isochrons. This erosion is due to removal of sand from the shoreline system by aeolian transport. Until Roman times the dunes were low with an extensive shore-parallel and a narrow shore-normal distribution. Shore-normal wind transport was probably inhibited by the "wet" beach plains, where sufficiently wide, and by rapid stabilization of the dunes by vegetation. For reasons which are still not fully understood, the situation changed between 800 and 1000 AD and large-scale overblowing of the barrier complex started (Jelgersma *et al.*, 1970; Zagwijn, 1984; Van der Valk, 1987; Pool & Van der Valk, 1988). Pool and Van der Valk computed that in various steps between 800 and 1850 AD about 1.5 billion m^3 of sand was transported inland between the Hook of Holland and the Hondsbosse Sea Dyke. Rigorous coastal protection, including the systematic planting of marram grass in the dunes bordering the shoreline, started in the middle of the last century and brought an end to overblowing and associated coastal erosion. Yearly measurements of the dune foot and high and low waterlines were started simultaneously and recorded a stable to slightly prograding shoreline between Scheveningen and Bergen since then.

Between 1000 and 1200 AD the barrier of the Texel High, which was situated several kilometres west of the present shoreline (Schoorl, 1973; Eisma & Wolff, 1983), was cut by a number of relatively small inlets, formed by breaching of the barrier during storms. Most of these inlets have small tidal basins and thus closed up soon after by silting. Occassionally, they were closed by damming. However, the inlet west of Den Helder enlarged its tidal basin at the expense of the others by erosion of the peat land behind the barrier (Sha, 1990). When this channel made connection with the Wadden Sea and Lake Flevo, the remnant of the former tidal basin of Holland, its importance increased rapidly. On the basis of historical maps, Sha (1990) demonstrates that between 1500 - the date of the oldest nautical map - and today the tidal prism of the Texel Inlet gradually increased from about 250 to 1100 millions m^3. Today, Texel Inlet has become the most important inlet of the western Wadden Sea, and it is estimated that the loss of sand through the inlet to the Wadden Sea is 4.5 million m^3/yr (Stive, 1989). This development implies that retreat of the barrier of the Texel High continues, although the original cause - its protruding nature - has been eliminated.

Distribution of the early Medieval estuarine sediments in the area south of Scheveningen shows that at that time the offshore barrier sequence had been almost completely eroded.

Sinks and sources

If we take the length of the barrier complex between Scheveningen and Bergen at 75 km, its mean width at 8 km, and the mean base of the sequence at 15 m, it contains about 9×10^9 m^3 of sediment below present sea level. If we correct for some clay in the lower half and, locally, overblown peat on top of beach plain sequences, the total sand content is estimated to be about 8×10^9 m^3. As shown by Pool & Van der Valk (1988) the Younger Dunes covering the barrier complex contain another 1.5×10^9 m^3. A rough estimate of the sand deposited between 5000 and 3000 yrs B.P. in the tidal basin of the Bergen-Alkmaar Inlet is 0.5×10^9 m^3. This implies that 10 billion m^3 of sand were deposited in the barrier sequence and associated mudflats of Holland since 5000 yrs B.P.

Demonstrable sources of the sand are the ebb-tidal deltas of the closing inlets, the retreating headlands south of Scheveningen and north of Bergen, and the delta of the River Rhine near Leiden.

As shown in Table 2, the collective ebb-tidal deltas in front of the coast of Holland shortly before 5000 yrs B.P. contained about 3.5 billion m^3 of sand.

Sand from the Texel High and from the alluvial plain south of Scheveningen would have been transported to the prograding barrier sequence by longshore drift. As mentioned earlier, Zitman (1987) calculated that between 5000 and 3000 yrs B.P. about 0.8×10^9 m^3 of sand was deposited from longshore drift in the prograding barrier sequence between Scheveningen and IJmuiden. A very rough extrapolation gives 1.2×10^9 m^3 for the same period over the entire prograding barrier coast (Scheveningen to Bergen), and twice that amount if we extrapolate un to today (note that ^{14}C years are not solar years). In his calculation Zitman (1987) did not take the Texel High into account as this source was separated from the barrier sequence by the Alkmaar-Bergen Inlet. However, after closing of the inlet some sand from the north would also have been incorporated into the barrier sequence from longshore transport, so we estimate that the total amount of sand introduced from the retreating capes by longshore transport is around 3×10^9 m^3.

From 4500 yrs B.P. onwards the tributary of the Rhine debouching west of the present city of Leiden started to build a modest delta. In time this tributary developed into the main branch with a delta, which in part was situated in the present offshore area but which has been removed by later coastal erosion. By extrapolation a deltaic sand body can be reconstructed which contains about 0.5×10^9 m^3 of sand if we place its base at a depth of 15 m. In conclusion, we can state that if we assume that all sand stored in the ebb-tidal deltas of the closing inlets can be used for barrier progradation, and we assume a Rhine delta depth of 15 m, 7 billion of the 10 billion m^3 of sand stored in the Holland barrier complex can be obtained from clear and demonstrable sources. The remaining 3 billion m^3 must have come from reworking of Pleistocene sands in the southern North Sea (*i.e.* the inner shelf and lower shoreface) and from landward transport by shore-normal processes (Eisma, 1968; Wiersma, 1985; Wiersma & Van Alphen, 1988). This does not appear unrealistic because it would imply a net cross-shore sediment transport rate of the same order of magnitude as the 8 to 14 $m^3/m/yr$ derived by Roelvink & Stive (1990) for the present net cross-shore transport rate at the 10 m isobath of the coast of Holland based on a combination of calculations and observations.

SUMMARY AND CONCLUSIONS

The long-term history of the coast of Holland is basically one of smoothing and straightening of a gently undulating Late Weichselian landscape. The system operated by erosion of the headlands, removal of the sand by longshore transport and deposition in the gap between. In this respect the Holland coast is very similar to other retreating barriers of the world (*e.g.* Nummedal, 1988; Morton, 1979; Kraft *et al.*, 1987). However, in addition to the longshore drift, there were also very efficient shore-normal processes which brought in sediment from the North Sea. The rough sand budget given above indicates that at least 30% and, when we include all sand of the ebb-tidal deltas, at most 65% of the 10 billion m^3 of sand stored in the barrier complex was derived from the North Sea. The sands of the mudflat deposits behind this barrier also originated predominantly from the North Sea, so the total amount of sand transported landwards by shore-normal processes would be still greater.

Although transport across the shoreface in most cases is the result of "waves and currents acting in concert" (Wright, 1987), it can safely be stated that in the case of the coast of Holland tidal flow locally dominated cross-shore transport in the late Atlantic, when the shoreline was cut by a large number of inlets, and a major part of the sand later to be used for progradation was stored in the ebb-tidal deltas of these inlets.

With the progressive closure of the tidal inlets from the south to the north, and the simultaneous progradation of the barrier, the conditions along the coast from Scheveningen to Bergen changed significantly. Closure of the inlets ended the E-W directed tidal flow, probably implying a drastic reduction in shoreward transport of sand from the North Sea shelf and shoreface. Progradation changed the barrier into an 8 km wide complex, which, under the prevailing wind and tidal climate, became a more or less closed and rigid system. These changes resulted in a gradual steepening of the shoreface. Although supply of sand from the shelf decreased, net shoreward transport along the shoreface continued and brought sand into the breaker zone at a rate surpassing its removal by longshore transport, rip currents and aeolian processes. As the barrier was fixed this resulted in steepening and progradation. Steepening leads to reduced dissipation of wave energy and results in increasing wave attack of the shoreline. This is probably one of the causes of erosion of the shoreline and of aeolian overblowing since medieval times.

Simultaneously with progradation of the central part of the coast of Holland, the two enclosing headlands retreated by shoreface erosion. Although the original cause of retreat (*i.e.* the protruding nature of the headlands) has by now been eliminated, shoreface erosion in the north continues because the barrier of the Texel High, unlike the barrier complex south of Bergen, is and was a narrow coastal strip which could easily be breached during storms, so that eventually the connection with the Wadden Sea was established by way of the Texel Inlet, now a major passage for sand.

ACKNOWLEDGEMENTS

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CHAPTER V

GEOLOGY AND SEDIMENTOLOGY OF LATE ATLANTIC SANDY, WAVE-DOMINATED DEPOSITS NEAR THE HAGUE (SOUTH-HOLLAND, THE NETHERLANDS).
A reconstruction of an early prograding coastal sequence.

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ABSTRACT

The geology and sedimentology of the sandy coastal deposits of the Late Atlantic just north of the main river outflow of that time are described. The study area is situated in the western part of the Province of South-Holland and it represents the earliest progradational coastal development of the Holland coastal barrier complex. The sequence shows a general coarsening-up trend in the southern part and has a sheet-like appearance. Further north, is shows a fining-upward character and is incised into the subsoil. In the southern area a section in a large construction pit was studied. The study of the sedimentary sequence in addition to molluscan taphonomy played an important role in the interpretation of the upper part of the sequence on the basis of data yielded by the temporary exposure. The deposits situated more northerly were studied in cored sections; they are interpreted as tidal channel deposits. In an Appendix, some methodological remarks are presented on the interpretation of radiocarbon dates of peat and shell material from the area.

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1. INTRODUCTION

The aim of the present paper is to reconstruct the coastal development during the Late Atlantic in the Rijswijk-Zoetermeer area, South-Holland (Fig. 1). In this area an extensive sandy deposit (the Rijswijk-Zoetermeer (RZ) sands: a sheetlike deposit in the south and sandy channel fills to the north) formed during the Late Atlantic as an onlap sequence on fluviatile and estuarine clayey sediments of Early and Middle Atlantic age (Pruissers & De Gans, 1988). Based on observations in a large excavation near Rijswijk in the topmost part of the sand sheet, an integrated picture of facies (sedimentology), faunal (molluscs and ostracods) and floral (diatom) relationships was drawn. The depth of the excavation allowed some insight to be gained into the full amplitude of the tidally influenced depositional tract. A brief discussion of the methodology and sampling strategy of radiocarbon dating of coastal deposits will be found in an appendix. The stratigraphy of the deposits encountered is schematized in Fig. 2.

Atlantic tidal channel deposits and associated coastal deposits in the province of South-Holland have only occasionally been studied in recent years. The main reason for this is the age of the deposits, i.e. older than 5000 years, and consequently the depth at which the deposits are situated, namely generally lower than several meters below surface.
Evidently, the sea-level rise that took place during the second half of the Holocene in the western Netherlands buried the Atlantic deposits under younger layers of peat and clay (Jelgersma, 1961; Van de Plassche 1982).

The South-Holland tidal channels are shallow based, mostly less than 10 m deep (De Gans et al., in prep; Fig. 3)). This indicates that the tidal volume, which passed through these inlets, cannot have been very large. Consequently, the back-barrier area is not very broad: some tens of kilometres. Another important factor is the presence of major outlets of the River Rhine and to a far lesser extent of the Meuse immediately south of the coastal area discussed here. These river branches provided large quantities of freshwater and a large volume of mainly fine-grained sediment, but more important
is the presence of large quantities of sand immediately in front of the River Rhine outlet, that were deposited by Boreal and Early Atlantic Rhine outlets (De Groot & De Gans, in press; Beets et al., 1992). Presumably, this volume of sand was in the process of reworking during the formation of the RZ sands.

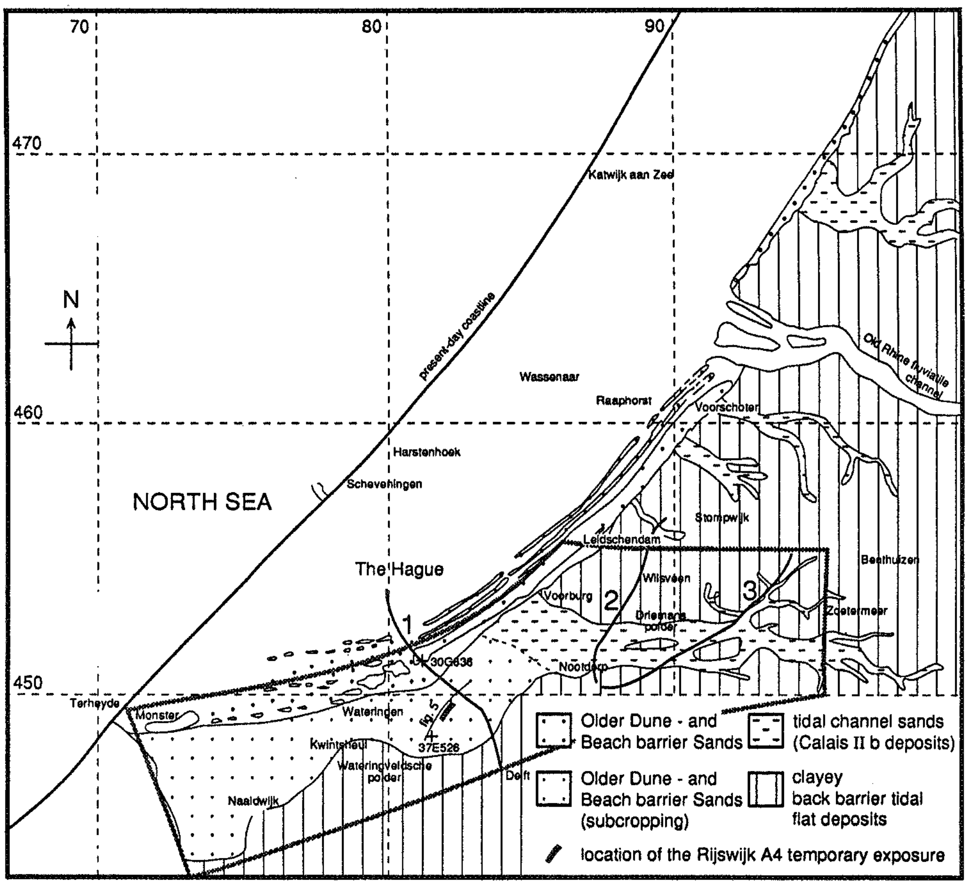


Fig. 1

Palaeogeographical map of the Late Atlantic and Early Subboreal coastal deposits in South-Holland. Topographic names and location of sites and sections are indicated. The position of the temporary excavation Rijswijk A4 is indicated by a black bar. After Pruissers(not published), Van Staalduinen(1979) and Kok(pers. com). Grid sides are 10 km.

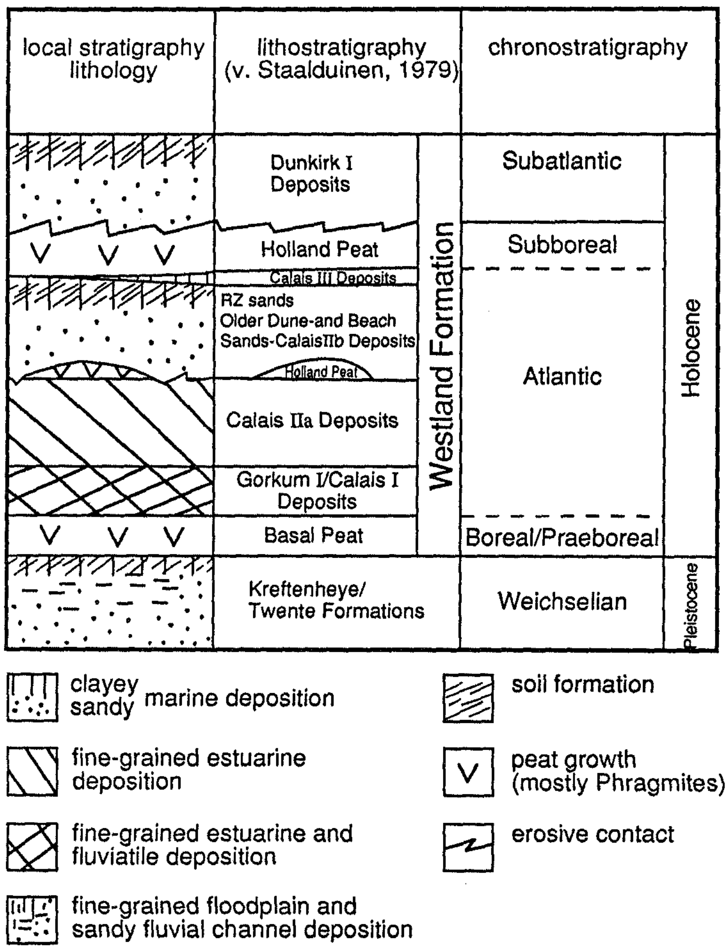


Fig. 2

Local stratigraphy (Upper Pleistocene and Holocene) of the study area, the southern part of South-Holland. The Rijswijk-Zoetermeer (RZ) sands are subject of this study.

2. GEOLOGICAL AND PALEOGEOGRAPHICAL SETTINGS

Sedimentation in the coastal plain of the western Netherlands was strongly governed by sea-level rise. Sea-level was situated at approximately 25 m below NAP (= Dutch Ordnance Datum, which about equals present-day Mean Sea Level (MSL)) at 8000 BP and -7.5 m at 6000 BP, implying a rise of 0.7 to 1 m per 100 radiocarbon years. This coparatively rapid rise lasted until about 5000 BP. Following 5000 BP, it dropped down to 0.2 to 0.1 m per 100 radiocarbon years (Jelgersma, 1979; Van de Plassche, 1982). The change occurred gradually.

The studied deposits are situated between the cities of The Hague and Delft, just inland of the Early Subboreal initial barrier coastline (Fig. 1), which is thought to have been in place from 5000 BP onwards (Van Straaten, 1965; Zagwijn, 1965). Prior to this, between 8000 BP and 6000 BP (possibly up to around 5000 BP) mainly clay was deposited in the southern part of the area by west flowing River Rhine & Meuse branches (De Groot & De Gans, in press), although some fine sandy channel fills were also found (De Gans & Pruissers, 1988). These Early Atlantic river branches (transporting water and mainly fine-grained sediments), flowed from east of Zoetermeer to a coastal area west of the present-day coastline. A transitional zone from fluviatile clayey deposits into estuarine clayey deposits is found south of the city of The Hague. This indicates that during the Atlantic the mouth of the estuary was situated in the present-day North Sea.

Shortly before 6000 BP, mainly marine-brackish, fining-upward channel fills were laid down rapidly. The channel fills themselves are sandy (the median grain size of the sand generally < 150 mu) at their bases, but are fining-up quickly into a clayey top layer at the present height of 10 m below NAP. Towards the south the sediment contains an estuarine diatom flora with a large freshwater input (De Wolf, 1986a). These estuarine deposits covered the southern part of South-Holland completely (De Groot & De Gans, in press). North of the Rijswijk area, a different type of sediment is found. Here, Early Atlantic deposits consist of tidal flat and some lagoonal fine-grained sediments (Pruissers & De Gans, 1988). Clayey and fine sandy fills of tidal channels are known to occur below the coastal barrier sands near the city of The Hague (Van Straaten, 1965). These more northerly fills presumably continue into the Late Atlantic (De Jong, 1978; Van der Valk, unpublished data). This age is confirmed by a radiocarbon dating of 6240 ± 90 years BP (GrN 12748; see Fig. 18) of articulated *Mytilus edulis* shells from a borehole near Scheveningen. Lithologically, these fine-grained fills do not resemble the younger RZ channel sands. Usually the channel fills of the period preceding the RZ channel period are clayey to a high degree and contain a monospecific *Mytilus* fauna. Moreover, mapped occurrences of the Basal Peat and the top of the Pleistocene deposits (Fig. 1) indicate little erosion of both this peat and Pleistocene deposits, only in the area north of The Hague and under the extreme southwest of this city (De Mulder et al., 1983). This means that tidal scouring must have been restricted to a zone immediately east of the Middle Atlantic coastline, which was presumably situated in the present-day North Sea. These northern clayey channel fills are coeval in time with estuarine deposits (more strongly influenced by the presence of fresh water) further south of the city of The Hague (De Groot & De Gans, in press), suggesting that somewhere in the present North Sea a barrier island must have been situated which separated the more northerly tidally influenced area from the more southerly estuarine area.

Subsequently peat started to develop on top of these estuarine and fine-grained marine deposits. The start of the peat growth was dated 5,890 ± 80 y BP at Nootdorp (GrN 2268 ; Zagwijn, 1965; see Appendix). It is not known when the peat growth came to an end, presumably before 5600 BP (see Appendix).

Continued sea-level rise caused further eastward movement of the coastline. Several large tidal systems developed in the study area after 5600 BP (Fig. 2). These late Atlantic palaeo-channels lie roughly at an angle to the present-day coastline. They usually consist of medium to fine-grained sands. Westernmost parts genetically belonging to these deposits (e.g. ebb-tidal deltas and barrier island coastlines) were probably removed by erosion prior to barrier formation underneath the present-day towns of Wateringen, Rijswijk, Voorburg etc. (Fig. 1). Remaining parts, north of the Naaldwijk-Kwintsheul area were called Older Dune and Beach Sands by Van Staalduinen (1979). The question arises how the sand sheet between Rijswijk and Naaldwijk should be interpreted and in how far the channel to Zoetermeer is related genetically with the above- mentioned sand sheet.

The RZ sands are shown (both the sand sheet and the channel fill) to be of about the same age as the Naaldwijk-Kwintsheul Older Dune- and Beach Sands. First, the results of the study of the sandy deposits, belonging to the sand sheet are discussed. These deposits could be studied in a temporary exposure south of Rijswijk (Fig. 1).

3. PALAEOGEOGRAPHY OF THE RIJSWIJK-ZOETERMEER SANDS

Having briefly defined earlier coastal history predating the deposition of the RZ sand body, the boundaries of the sheet-like sand body are here discussed. Three sections are given to illustrate these boundaries (Fig. 3.1 to 3.3). The RZ sands are underlain by a generally fine-grained estuarine and fluviatile sequence, assigned to the Calais IIa/I and Gorkum Deposits (Fig. 3a) and with a wide lateral distribution (De Mulder et al., 1983). At the present, the RZ Sands are assigned partly to the Older Dune- and Beach Sands (Van Staalduinen, 1979 and Kok, pers. comm.) and partly to the Calais II (De Mulder et al., 1983). Towards the east, the RZ sands grade into clayey tidal flat (see Mulder (1989) for the soil map of the area) sediments (Calais IIb/III Deposits). Towards the north, the RZ sands also pass into clayey deposits. The latter are underlain by a peat layer which covers the older fine-grained tidal Calais IIa Deposits. The start of the peat growth is dated at about 5900 BP (see Appendix). This peat level is also present to the south of the RZ sand complex (De Groot & De Gans, in press). The lithological boundary of the RZ sands at the southern edge of the complex shows a clear-cut contact with the peaty and clayey sediments in the hinterland (Figs. 3 & 4). This indicates erosive action prior to the deposition of the RZ Sands.

No more than a thousand metres southwest of the excavation the correlative deposit of the Rijswijk pit showed marked facies changes (Fig. 5, core 37E526)). The deposit is also markedly thinner there.

To the west lithologic change is difficult to trace. Here, the prograded barrier complex occurs. Surface expression of the barrier dune sands offers some possibilities for a distinction, but these become restricted westerly RZ sands equally show dune morphology on top, as is the case underneath the area of Naaldwijk-Kwints-

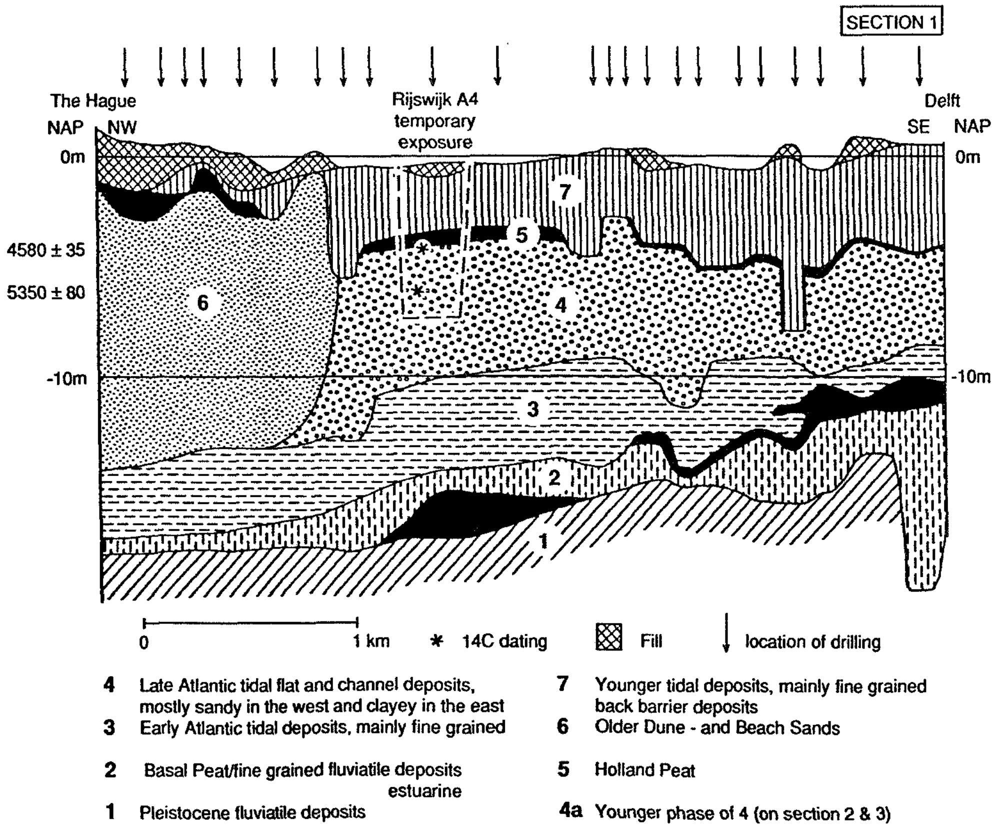


Fig. 3

Three sections in the Late Atlantic and Early Subboreal coastal sequence in the Province of South-Holland. For location, see Fig. 2. See Fig. 1 for stratigraphy. For radiocarbon datings, see figs. 18/19.

Fig. 3.1: section 1

The Hague-Delft, perpendicular to the post-5000 BP coastline. Note gently sloping Pleistocene surfaces. The Rijswijk A4 temporary exposure is indicated.

Fig. 3.2: section 2

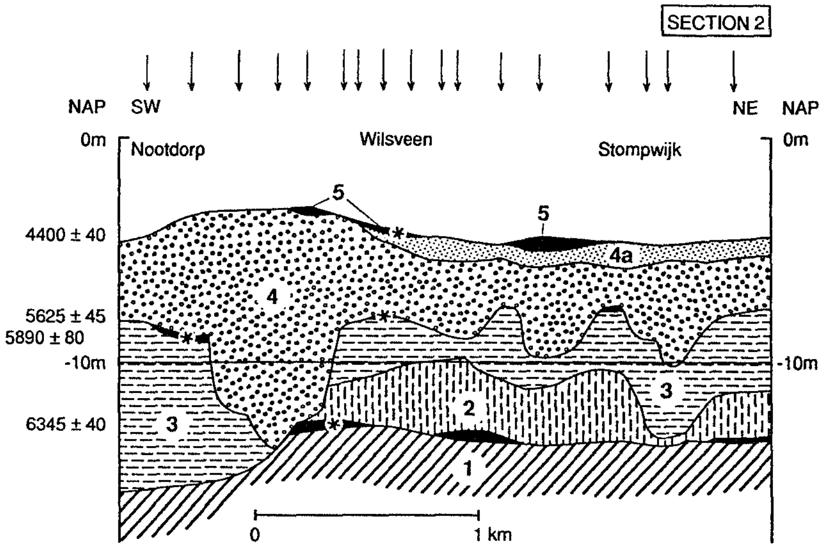
Nootdorp-Stompwijk

Only fragments of the former Holland Peat cover, which was thicker than four meter, remained due to natural erosion and human peat extraction in historic time for fuel consumption.

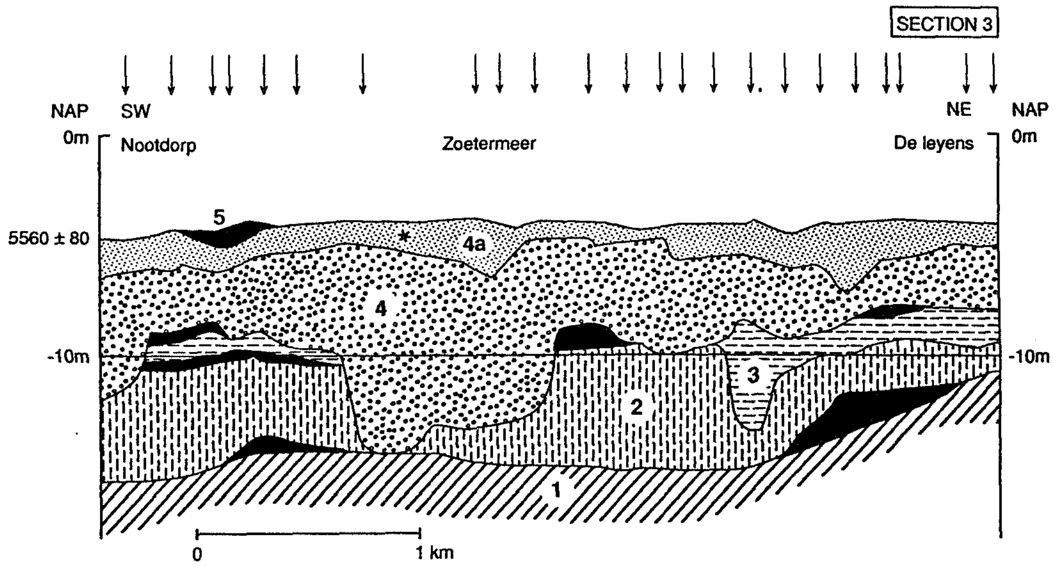
Fig. 3.3: section 3

Nootdorp-Zoetermeer

Note generally less sandy character of this more easterly section in comparison with section 2.



SECTION 2
NAP
SW
NE
NAP
0m
Nootdorp
Wilsveen
Stompwijk
0m
5
5
4400 ± 40
4a
4
5625 ± 45
5890 ± 80
-10m
-10m
3
2
6345 ± 40
3
1
0
1 km



SECTION 3
NAP
SW
NE
NAP
0m
Nootdorp
Zoetermeer
De leyens
0m
5
5560 ± 80
4a
4
-10m
-10m
3
2
1
0
1 km

heul and also in the excavation discussed in this paper. A core (30G836: Fig. 6; see for location Fig. 1) in the oldest Subboreal barrier shows a coarsening-up barrier section above -10.5 m. Below, a tidal channel sequence occurs which has to be older, but which also already resembles a North Sea environment with regard to facies and faunas. The close time relationship could also be deduced from the diatom zonation. Below and above the -10.5 m NAP boundary, the same subtidal nearshore diatom flora occurred (De Wolf, 1990). Finally, the fill is slightly coarsening upward which means that storm waves may have been able to transport increasingly larger quantities of sand from the adjacent shore into the basin. The early (Subboreal) barrier sands resemble the RZ sands to a great extent. It indicates that rapid depositional processes probably may have been resposable for this. This phenomenon is not unusual in coastal sequences (e.g. Curray et al., 1969).

4. RIJSWIJK A4 TEMPORARY EXPOSURE

4.1 GENERAL

The Rijswijk pit was dug into the sandy sheetlike deposit near to transitional area to the zone of deposition in tidal channels (see Figs. 1 & 4). A distinction between this deposit and the younger barrier sands to the west can be made by the combined data of the lithologic sequence and coastal morphology. During the Atlantic, a general WSW-ENE trending coastline existed in this coastal region because of the position of the outlets of the Rivers Rhine and Meuse directly south of the studied area. The Rijswijk pit approximately parallels this trend (Fig. 1). The excavation reached a depth of -7.5 m NAP, exposing some 4 m of the RZ sand deposits.

A peat bed on top of the marine sands was found at about -4 m in the eastern half of the 700 m large excavation. Towards the west this peat layer and the upper part of the post 5000 BP barrier sequence were eroded by a younger tidal channel of Pre-Roman age (Dunkirk I Deposits). Predating this erosion, the 'Holland' peat reached a thickness of some 4 m, at least prior to compaction (Kok & De Groot, 1990). Most peat in the area was obviously removed by erosion (Figs. 3 & 5).

4.2 SUBSOIL

Borehole data and core penetration tests (CPT) are available for the immediate subsoil below the Rijswijk pit (Fig. 5). The above-mentioned peat bed is considered to be part of the so-called Holland Member of the Westland Formation (Doppert et al., 1975). The depth of the Pleistocene sandy subsoil varies from -15 to -17 m. On top of it, a compressed peat layer (the so-called 'Basal Peat') is present, which is covered by a fine-grained (clayey) layer some 4 m thick. This clay layer is characterized by low cone resistance values (< 2 Mpa = MN/m2).

The sandy Calais Deposits may be subdivided into three units, based on CPT's:

A. Subtidal sandy deposits (between 4 and 6 m thick). Interstratified layers of fine sand and thin clay, of generally rapidly changing cone resistance values (qc) in the CPT's.

B. High subtidal and intertidal sediments (between 3 and 4 m thick). Few thin clay

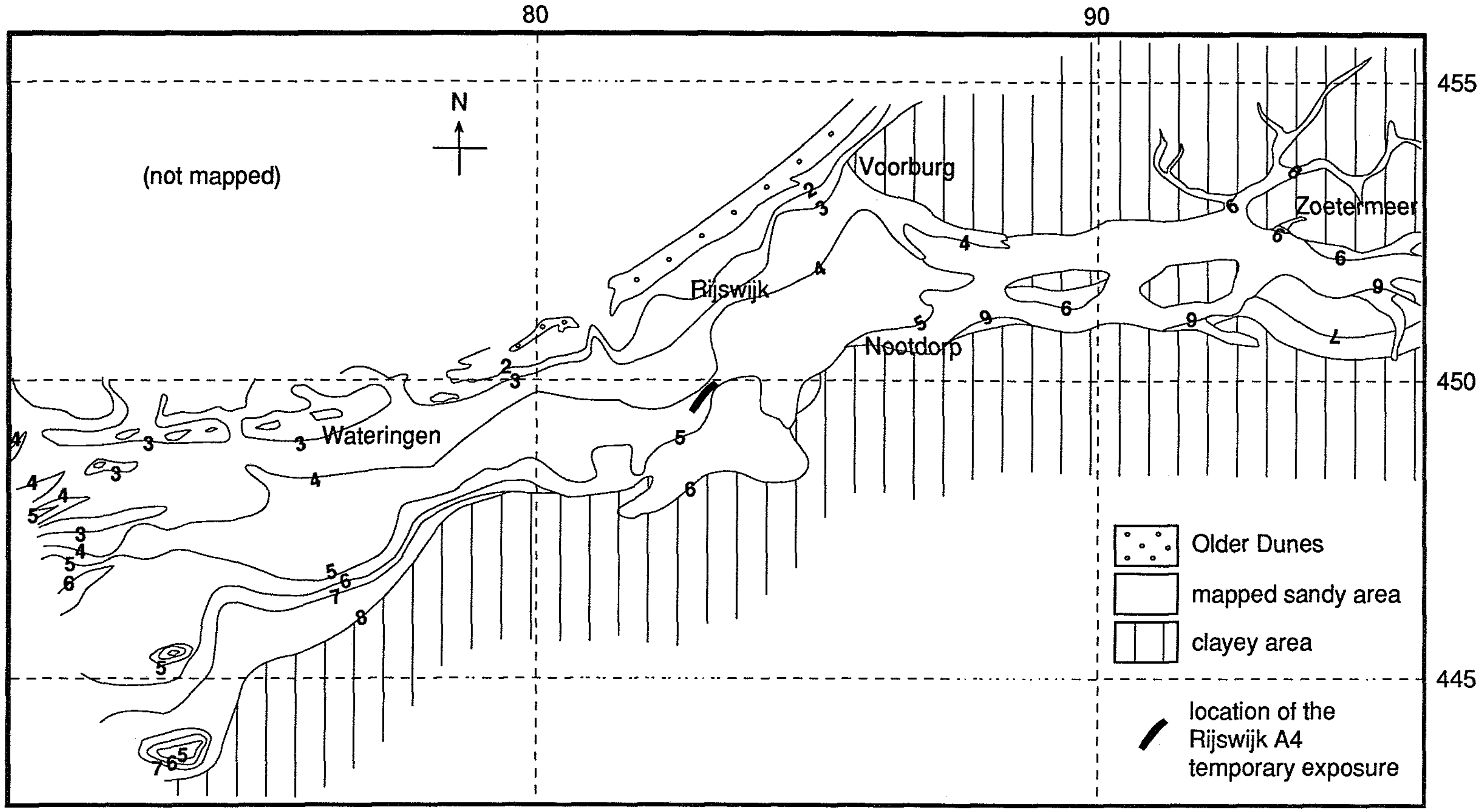


Fig. 4

Depth contours (in m below NAP) of the surface of the Older Dune Sands and sandy Calais Deposits in the southwestern part of South-Holland. The position of the excavation is indicated by a black bar. Grid size is 10x5 km.
After Van Staalduinen (1979), Pruissers and Kok (pers. comm.).

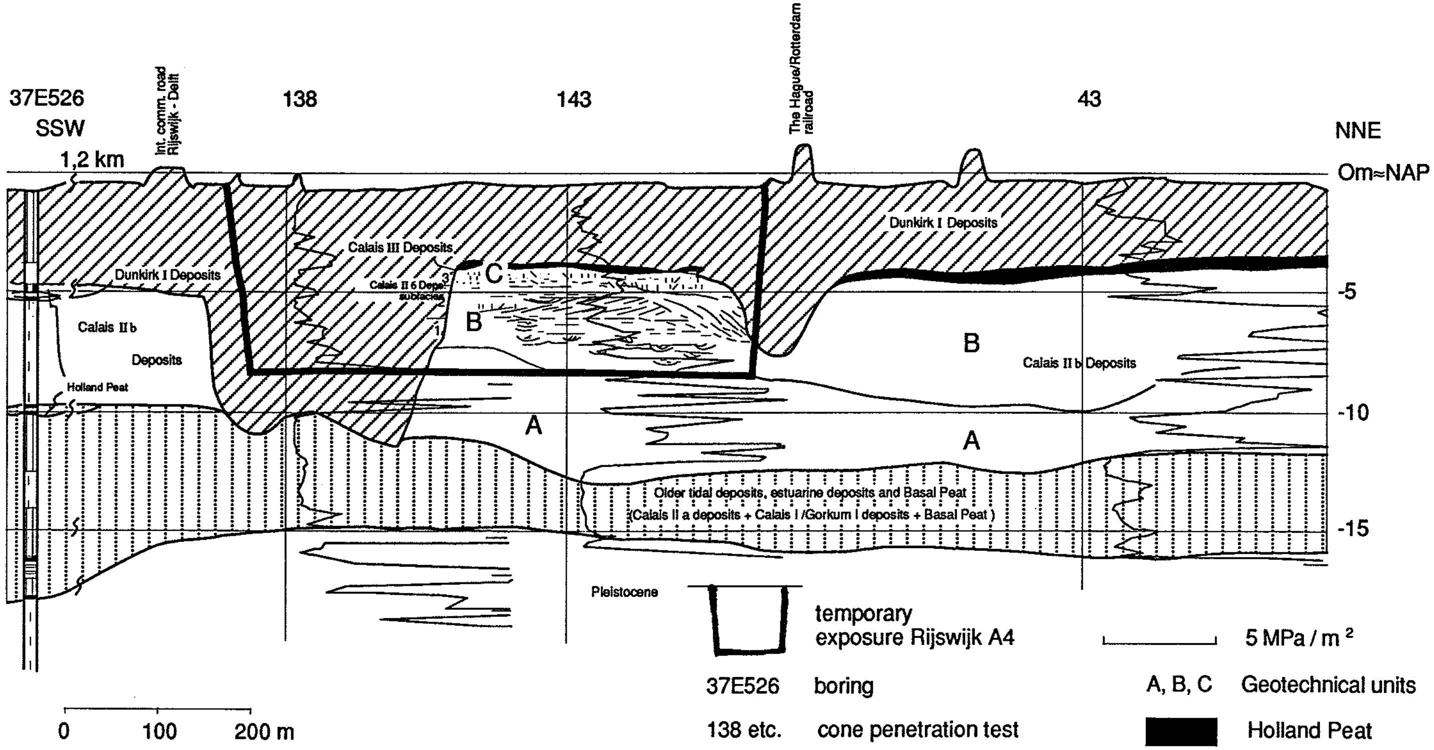


Fig. 5

Schematic geological and geotechnical section along the A4 Motorway, southeast of Rijswijk. The Rijswijk A4 temporary exposure is indicated by a broken line. To the southsouthwest, boring 37E526 is situated.
After Rijkswaterstaat ZH TX 83.9033.

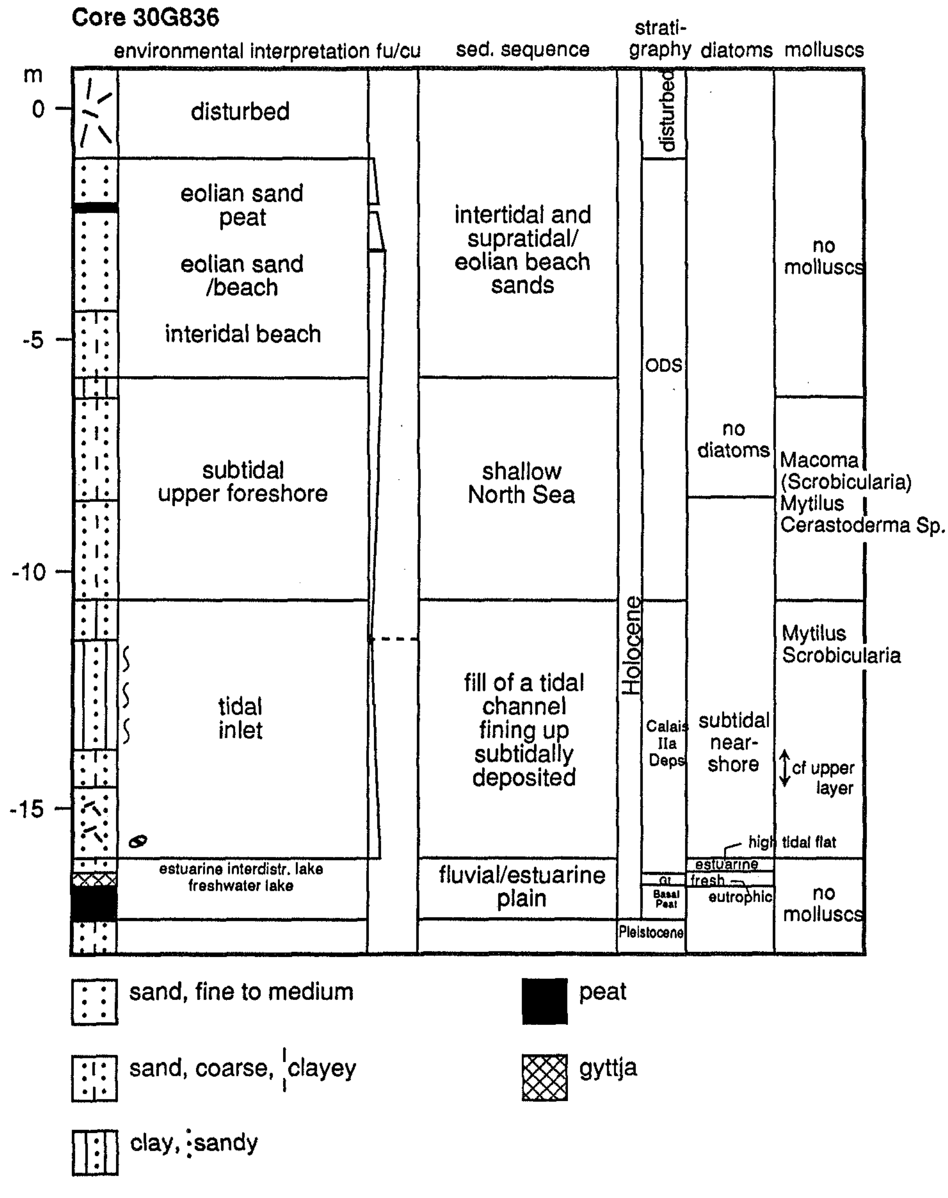
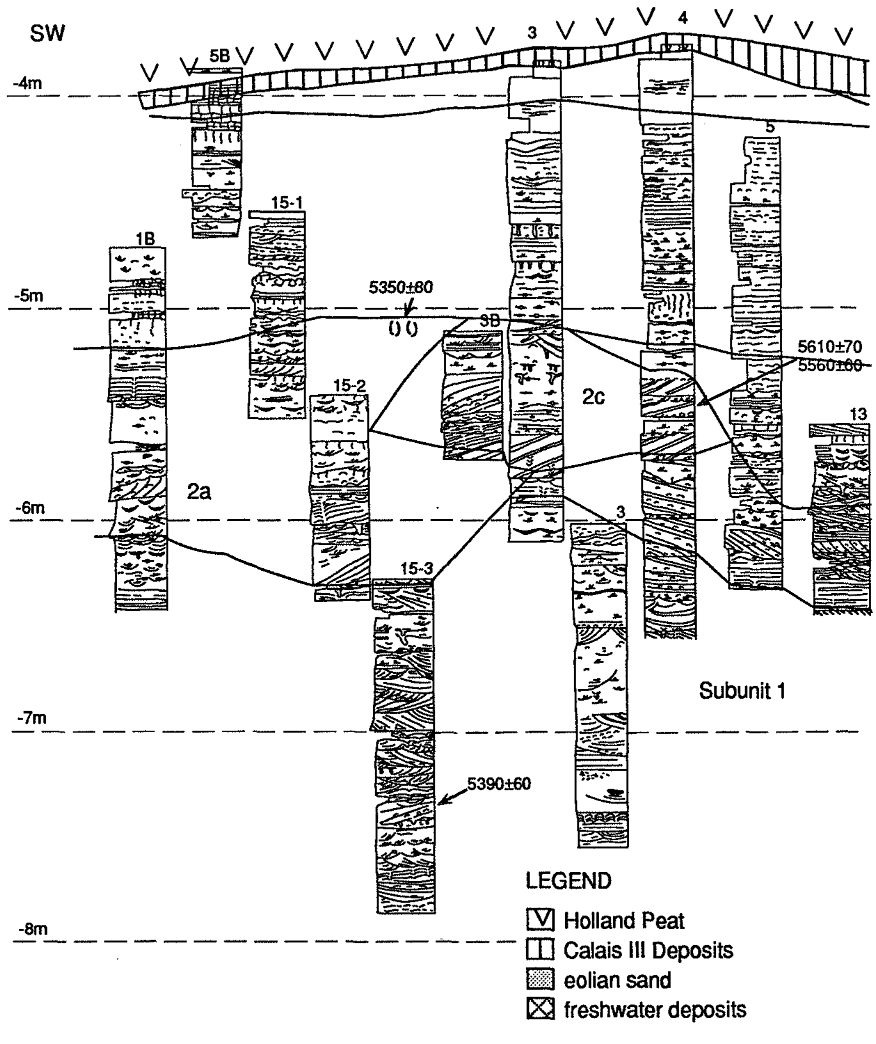


Fig. 6

Stratigraphy of the cored boring 30G836 (Rijswijk 05), showing the gradual change of older tidal sediments into barrier sands at -12 to -10 m NAP.



SW
5B
3
4
-4m
5
15-1
1B
-5m
5350±80
3B
5610±70
5560±60
15-2
2c
13
2a
-6m
3
15-3
Subunit 1
-7m
5390±60
LEGEND
Holland Peat
Calais III Deposits
eolian sand
freshwater deposits
-8m

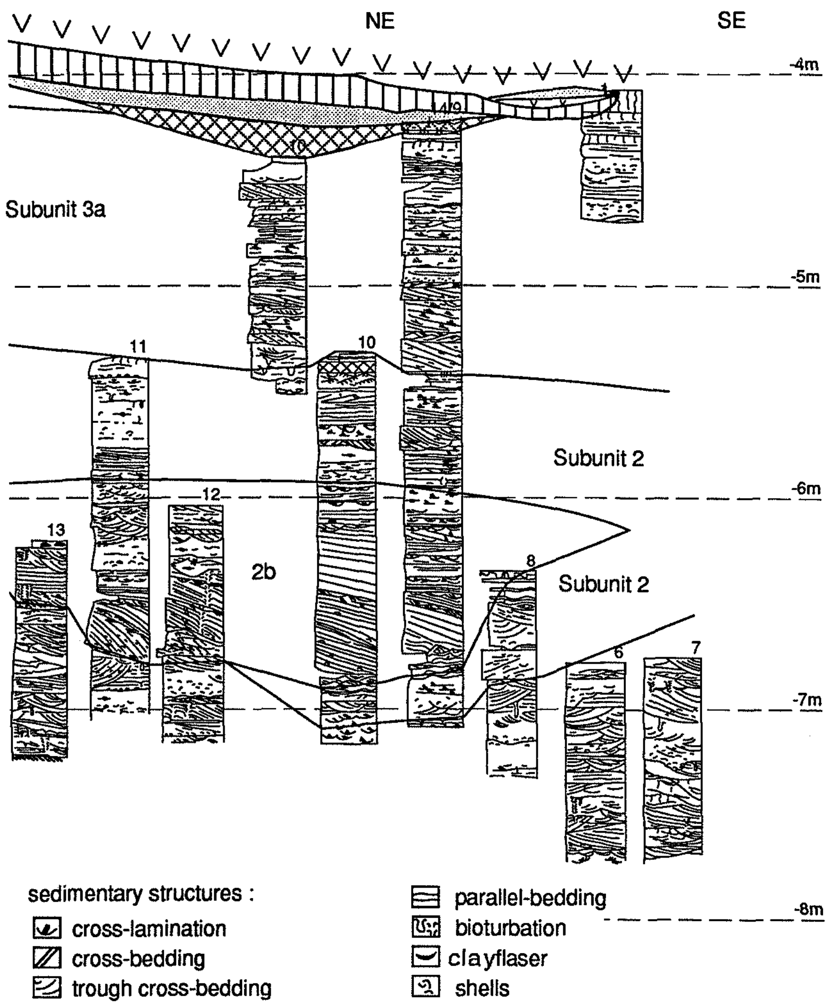


Fig. 7

Composite sedimentological outline of the temporary exposure Rijswijk A4: sedimentary structures and subunit.

Fig. 8

Rijswijk A4 temporary exposure: subunit 1 and 2,
gradual transition in the part of the exposure that did not show runnel and swash bar formation. Spade handle scale: 10 cm. Orientation approximately southwest-northeast.
Fig. 7 loc. 13. Photograph RGD.

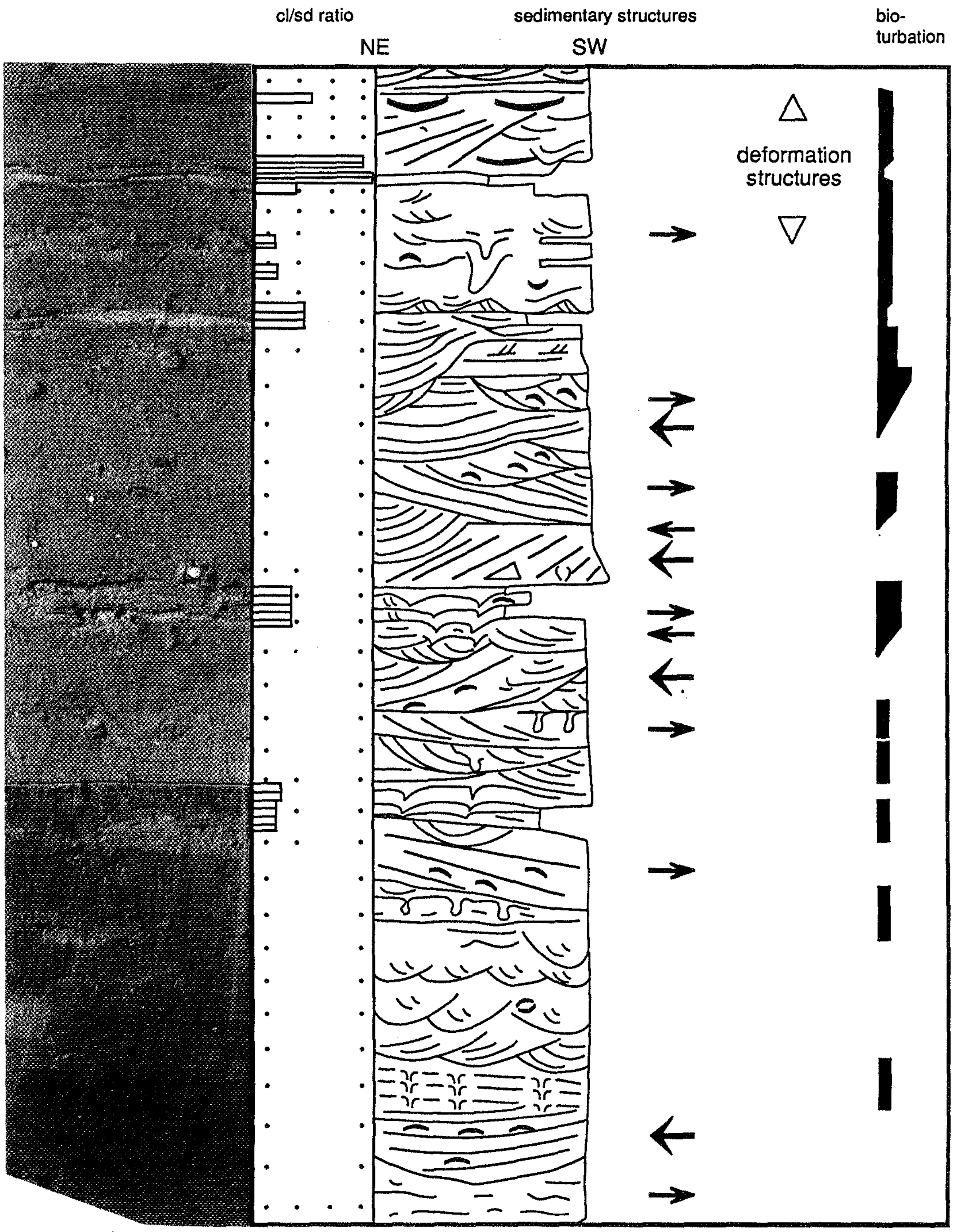


Fig. 9 Rijswijk A4 temporary exposure: subunit 1: trough cross-bedded fine sands. Lacquer peel and drawing. Note frequent bioturbation and also frequent erosive bed contacts. See also Fig. 8; Fig. 7: location 15-3. Legend: see Fig. 7.

layers are present. Sands offer high resistance values. Wave energy is considered responsible for these high values (see below).
C. High intertidal and supratidal sandy sediments (between 1.5 and 2.5 m thick) with generally lower cone resistance values.
In the pit, the top of unit B and unit C could be studied. These units are described below.

4.3 SEDIMENTOLOGY

In the excavation units 4, 5 and 7 of Fig. 3.1 were exposed as the base of the pit reached to -7.5 m. On the basis of sedimentological characteristics three subunits were distinguished (Fig. 7):
Subunit 1. Generally below -6 m, consisting of fine sand characterized by trough shaped crossbedded units separated by slightly bioturbated levels.
Subunit 2. Between -6 and -5.4/-5.1 m, locally eroding into subunit 1 to -7 m, consisting of medium to moderately coarse sands with horizontal parallel lamination and large-scale cross bedding. Subunit 2 was further subdivided into three units: 2a, 2b and 2c.
Subunit 3. Between -5.4/-5.1 and generally -4 m, consisting of horizontally bedded and crosslaminated fine sands with occasional thin clay beds, which are often burrowed. The top beds consist of very low-angle crossbedded clean sands, showing positive topography of the upper surface. Subunit 3, further subdivided into units 3a and 3b) is overlain by a freshwater gyttja (in depressions only), an aeolian sand sheet and regionally by a thin clay layer. Micromorphological analysis showed that this clay layer postdates the earlier subunit 3 by several centuries (Mücher, 1985).

4.3.1 **Subunit 1**

It consists of fine to medium sand of uniform average grainsize, slightly coarsening up. Bioturbation traces occurs frequently, presumably stemming mostly from worms. At least three types of this kind of bioturbation were distinguished.
1. *Arenicola* type (diameter > 0.5 cm), 2. intermediate type (in size between 1 and 3), and 3.*Heteromastus filiformis* type (diameter 1-2 mm). No molluscs in life position were observed. Occasional clay layers are soft and often contain sand lenses. Peat detritus is common as are smaller rounded and flattened peat lumps.
Bedding type: planar bedding of 0.3-0.5 m scale. These plane beds are often covered or slightly truncated by a bioturbated surface (Fig. 8, lower part; Fig. 9; Fig. 15, lower part). Within the beds frequent formation of low angle to trough-cross bedded sand occurs, accompanied to a minor degree by flaser bedding, below -7 m NAP. The foresets are concave-upward, changing from slipface into low angle foresetting. Last stages of infilling usually carry laminae of peat detritus, wood remains and remains of *Echinocardium* and molluscs (Fig. 15, lower part). Foresetting of these lunate megaripples is generally to the SSW (Fig. 10a). On the basis of palaeogeography this is roughly perpendicular to the strike of the contemporaneous coastline.

The lamination of the sand layers is sometimes disturbed in such a fashion that it resembles disturbance as a result of entrapment of air into the sediment, called "bubble sand formation". This type of deformation could be related to the tidal working (Reineck & Singh, 1980). This type of deformation generally occurs to depths of -6.5 m in the Rijswijk pit, but occasionally down to -7 m. No channel-like features or spring-neap cycles were found, nor were double layered sediments. This implies that a strictly tidal origin for this subunit is not very likely.

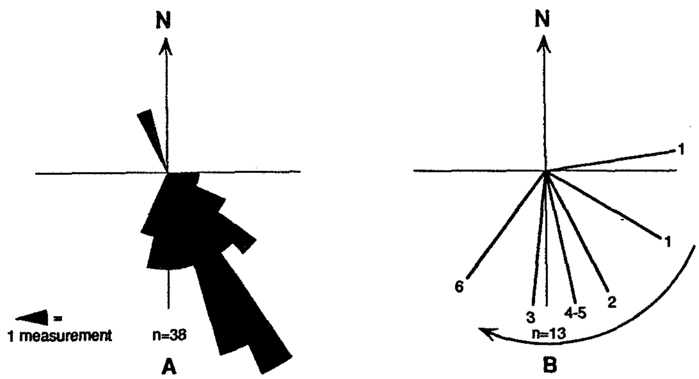


Fig. 10

Rijswijk A4 temporary exposure: rose diagrams
a) subunit 1 lunate megaripples
b) subunit 2b runnel fill phases. Order of formation indicated.

If the disturbed lamination indicates entrapment of air and thus emergence during low tide, its presence then implies the working of tides, occasionaly reaching down to -7 m.

The sandy layers in this subunit are generally well-sorted (Ruegg, 1985). This indicates that wave influence must have been prominent, but not all-overwhelming as some clay layers (Fig. 9) as well as bioturbation levels occur. This indicates a high-preservation potential, because otherwise bioturbation layers and clay would have been reworked by wave activity. The implication is that rapid aggradation may have occurred, not only vertically (from one bioturbated level to another should account for one year's sedimentation, not counting erosional phases in between) but also laterally, meaning rapid coastal progradation. In view of the direction of foresetting (Fig. 10a), this progradation occurred towards the NNE. On the other hand, the presence of bioturbated levels indicates that the coastal section as observed in the pit, could have been a low-energy type of coastal section, in which animals were lived on the coastal shoreface.

Trough fill structures indicate southerly transport of the fine to medium grained sand under wave approach from the north. Absence of infaunal molluscs and presence of worms in the bioturbated horizons could mean high sedimentation rates with which worms could keep up but not molluscs. Data for recent Wadden Sea macrofauna (e.g. Dekker, 1989) show that most molluscan and worm infauna occurs intertidally. The fauna sedimentary environment in the subunit 3 cannot be compared readily with the subtidal Wadden Sea environment on the basis of faunal composition. The lack of infaunal molluscs in the bioturbated horizons of this subunit 1 is thought to be due to several factors. These factors would be the moving substrate and the generally high-energy level in the subtidal zone (clean sands), together with the fact that only very few species are adapted to these circumstances of high rates of sediment reworking. Food restrictions were probably no limiting factor because of the close proximity of the outflow of the River Rhine, supplying large quantities of food particles. Large-scale bedforms such as the lunate megaripples (Fig. 7: a) are formed by a combination of oscillation and (wave-induced) currents. As low-energy bioturbated horizons cap the high-energy deposits regularly, this indicates frequent and rapid changes in sediment movement, which is suggestive of a wave-dominated sedimentary environment.

According to Dalrymple et al. (1978) lunate megaripples (type 2 ripples in their terminology) are produced at velocities exceeding 0.7 m per second in a water depth of more than 2 m. Unfortunately, no information is given on the spatial distribution of this ripple type in the basin. Beets (pers. comm.) reported them however, from a lowest intertidal shoal on a wave-dominated area of the recent flood tidal delta east of the island of Vlieland Wadden environment. This indicates that in the more sheltered position of a recent Wadden Island low intertidal environment, lunate megaripples can occur. The formation of lunate megaripples in the environment of this subunit 1 was common. In its turn, this indicates circumstances like those prevailing around the present-day Wadden islands in the lower intertidal (and presumably upper subtidal) could have occurred during the deposition of subunit 1, causing lunate megaripples to be formed.

In the excavation pit on several locations within subunit 1, structureless sands were observed. This could either indicate a loss of sedimentary structures, or their primary abscence. Loss of structures was partly the effect of bubble sand formation and perhaps other tide-related processes, but the possibility of mass deposition without any formation of sedimentary structures, for example by storms taking up sediment from higher up on the coastal profile and bringing it down amass can not be ruled out. If the bioturbated horizons in this subunit indicate year-to-year rhythms, vertical accumulation should have been rapid, in the order of several tens of centimetres per year.

Summarizing, this subunit is characterized by trough shaped cross-bedded units separated by slightly bioturbated levels. Structures are indicative of a high subtidal to low intertidal wave-dominated environment. The direction of wave propagation is towards the south.

4.3.2 **Subunit 2**

This subunit has a flat top, situated between -5.5 and -5 m (Fig. 7). Lithology , for the subunit as a whole, consists of medium to moderately coarse sands. Few clay layers occur. Only isolated traces of predominantly *Macoma* represent bioturbation throughout the subunit, and in the top *Scrobicularia plana* occurs in life position. Some wood lumps and peat pellets were observed. This subunit consists of three smaller units.

Units 2a and 2c

Bedding types are largely parallel to horizontal or large-scale low-angle, cross-bedded (unit 2a; Fig. 8, upper part). Exceptionally, large-scale convex cross-bedded sands occur (units 2b and 2c; Figs. 12, 14 and 15, middle part). Lamination is predominantly parallel but relatively thin cross-laminated beds were found as well. Foresetting of low-angle mega cross-bedding took place mainly to the south (Fig. 11: lower part; Fig. 14), but directions to the north were also observed. An exceptional case of a runnel fill (unit 2b) shows foresetting towards the east and south (Fig. 12). Unit 2b erodes into unit 2a, but is also covered by unit 2a type sediment. Cross-bedded structures generally flatten upwards, but a major exception exists. A composite bar/swash platform in the upper metre of the subunit steepens during build-up (unit 2c; Fig. 14). High depositional rate causes preservation of convex mega-ripple cross-bedded sets, indicating influence of the rising tidal phase, interbedded by rippled sands, which would have originated during highest stage of the tide. Contemporaneity exists between runnel facies (unit 2b) and at least part of the planar bedded facies (unit 2a; Fig. 7; Fig. 12, lower part).

Unit 2b: Runnel fill (Fig. 12)

The sediment characteristics comprise a change from pure sand deposition to the deposition of sand and clay interlayered bedding, indicating the sheltering effect behind the bar in the runnel. The sedimentary structures show a steepening of progressive sets towards the east in the later stage of infilling, together with tangential attachment of laminae to the runnel bottom. This indicates to increased shelter due to increment of the sheltering bar. Together with the sediment live and fully-grown *Macoma balthica* were washed in. Occasional traces of escaping *Macoma balthica* occur. The direction of the foresetting of the runnel fill phases presumably correlates with a local dominant flood tidal phase (Fig. 10b). Each fill phase comprises a set of plane laminae dipping into the runnel topped by some wave-rippled sand with some clay flasers. The structure as a whole is interpreted as a berm, driven ashore by the waves.

Little (preserved) clay deposition indicates high turbulence of the sedimentary environment. The driving force of the runnel fill, wave energy apparently, changes direction (Fig. 10b) as a result of changing wind conditions both in force and direction. At first, the runnel is filled in from the north, but in later stages from the west. As a consequence of these changes more clay was deposited in later stages of the runnel fill. Subsequent loading by the overlying sand deposit caused the highly incompetent clay to flow and produce extensive distorted features, also by dewatering of the sand deposits between the clay layers. Occasional failure of bank sediment took place, which might indicate a subtidal origin. The wave energy presumably declines during the infilling of the runnel, as indicated by generally less steep foresetting during the later stages of the filling-in and the increase of clay content.

Successive brink points (* in Fig. 12) in the runnel fill rise from -6.1 to -5.6 m.

Fig. 11

Rijswijk A4 temporary exposure subunit 2/3 boundary. Subunit 2: cross-bedded coarse to medium sands with occasional flaser beds, transitional (with a sharp break: Bivalves of *Scrobicularia plana* in situ) to subunit 3 low-angle medium to coarse sands with some wave scours and shallow channeling. The *Scrobicularia* bed indicates freshening of the area. Roots of plants associated with peat growth on top of this section. The southwest is towards the left of the photograph. Trowel handle for scale: 10 cm. Photograph RGD.

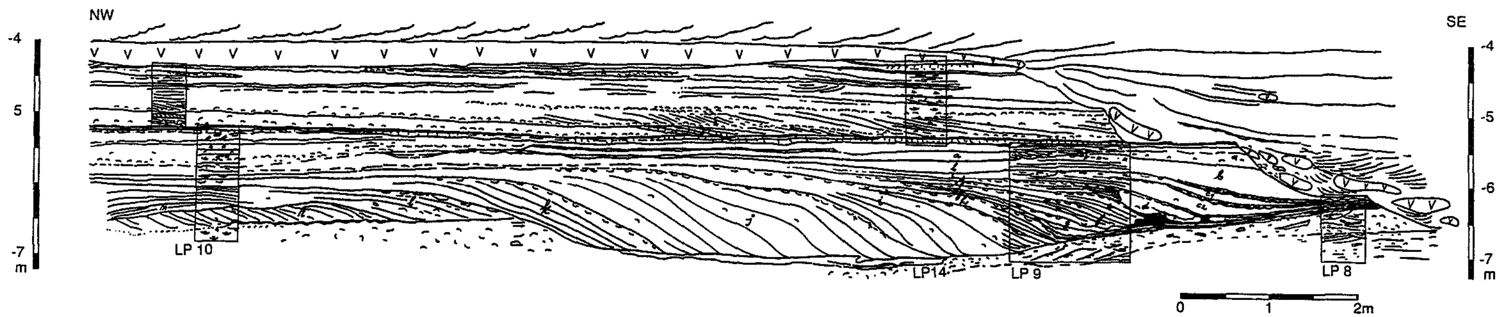


Fig. 12

Rijswijk A4 temporary exposure, mainly subunit 3 (backshore washover deposits; above -5.25 m) and 2 (shallow lagoonal deposits; below -5.25 m). Only thin subunit 1 shoreface deposits are present (in lower right hand corner; below -6 m). * = brinkpoints. sf = subunit. This section contains locations 8,9 and 10 of Fig. 7. After Van der Valk et al, 1985.

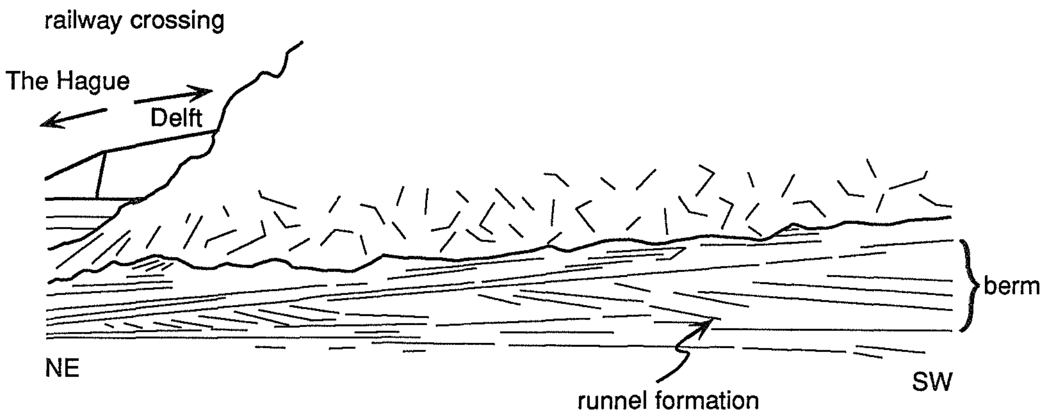


Fig. 13

Southeast face of Rijswijk A4 temporary exposure: subunit 2. Oblique (southeast-northwest) cut through a low-angle bar. Bar height approximately 2 m. Length of profile approximately 50 m. Photograph RGD.

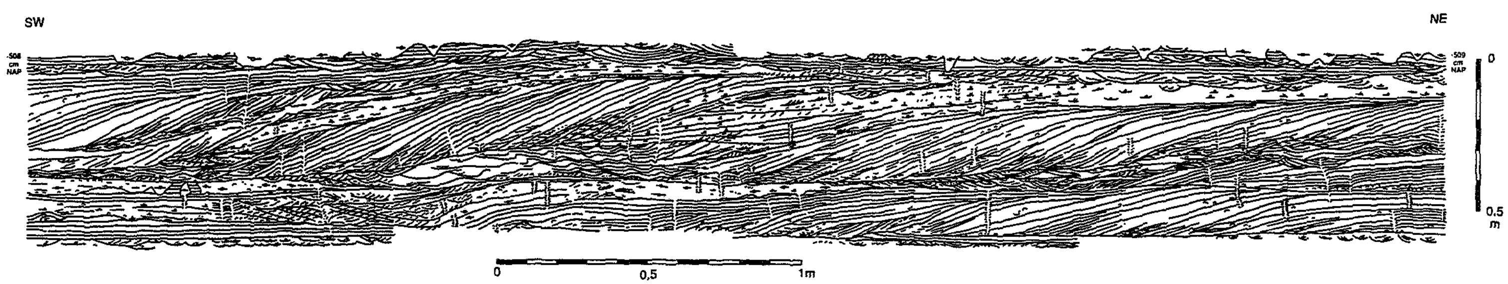


Fig. 14

Rijswijk A4 temporary exposure (subunit 2): convex laminated bar in high depositionary intertidal environment. Laminated sand: breaking waves during rising tide, accompanied by erosion in the toe sets. Cross ripples sand: high tide phase. Bar crest structures deformed by bubble sand. Escape traces by *Macoma balthica*. Drawing after lacquer peel location 3b in Fig. 7.

Also, the runnel bottom is situated a few tenths of centimetres higher in the last stage of the runnel fill. Groundwater level must have risen. This rise, however, is well within natural variations of neap/spring tidal cycles and/or more usual vs. storm waterlevels. A confirmation of the shallow subtidal and intertidal origin of this deposit is found in the occurrence of a low-angle berm-like bar at approximately the same height and of bubble sand above -6.1 m. In view of the structural set-up, the runnel together with the protective bar must have been short-lived phenomena during a later stage of subunit 2.

This subunit is the coarsest grained of all three subunits (see also below). It shows the largest bedding features, probably of a larger dimension than could be encountered in the 100 m x 400 m compartment of the construction pit, which contained the RZ sands. A photograph of the southeast face of the excavation shows a low-angle bar, cut at an extremely low angle (Fig. 13), together with runnel development in a later stage of bar progradation. This type of low-angle bar shows a strong resemblance to the intertidal low-angle bars, which Beets et al. (1981) described from the North-Holland beach plain sequence. This low-angle bar is of a complex inner structure, indicating multi-phased build-up. The individual beds in this low-angle bar presumably are comparable to beds in other profile which were visible in the excavation. Probably due to the orientation of the excavation, the extremely low-angled bar profiles as of Fig. 13 only rarely were apparent in the excavation.

The final phase of this subunit is far less energetic. As mentioned above, the fine-grained top of the subunit is flat. Locally, a *Scrobicularia* molluscan community developed in clay. This environment is comparable to the beach plain environment that prevailed in the area west of Rijswijk-Voorburg (Roep et al., 1983) during the Early Subboreal.

Some concluding remarks on the total structural build-up of this subunit 2: this subunit shows coarsest grainsizes. On the basis of the low-angle bar and other large bedding types, it is argued that subunit 2 as a whole is the low-angle barred zone of an open coastal configuration. The short-lived unit 2b, the runnel fill, fits this model well. Unit 2c, the stacked convex megaripples, represents a shoreward incoming intertidal bar crest or berm, filling the high intertidal beach runnel. It is, however, remarkable that very few parallel bedded swash- and backwash sands have been found, as could be expected in an intertidal wave-dominated environment. Again, this could be due to the angle of cut. Virtually no observations in a direction perpendicular to the presumed ancient shore were possible. In the lower left hand corner of Fig. 12, however, some coarse parallel bedding is present, internally consisting of parallel laminated sands. Also some beds of this nature were analysed for macrofauna (see below), indicating a high-energy environment, interpreted as the swash- and backwash zone. The subunit is topped by sediments laid down in a calm beach plain-like environment.

4.3.3 **Subunit 3**

This subunit occupies the upper 1.3 m of the section (Figs. 11, 12, 15 and 16) and consists of two units. The lower unit 3a is influenced by aquatic deposition, while the upper unit 3b is an aeolian one (Fig. 7).

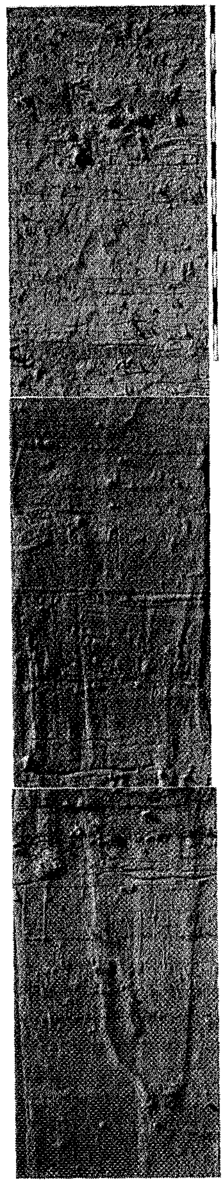


Fig. 15

Rijswijk A4 temporary exposure location 3 (see Fig. 4). Subunit 1, 2 and 3 in the area not dissected by runnel development. Note gradual transition from subunit 1 into 2. Location 3 in Fig. 7.
Photograph RGD.

Unit 3a

Unit 3a (Fig. 12 (top), Fig. 15 (top) and Fig. 16) consists of predominantly flat-bedded fine to medium grained sands and some clay layers of varying thickness. Top clay layers contain pyrite (FeS_2). Fine sandy units are mostly cross laminated. Set boundaries generally undulate slightly. Frequently, erosion occurs during or prior to deposition of a new set (Fig. 16).

The deposit consists of stacked short fining-up cycles (80 %), interspersed by other deposits of the upper tidal zone, which consist of interbedded fine-grained laminated sands and bioturbated clays 20 % (versicolored deposits *sensu* Gerdes et al., 1985).

Frequent worm traces occur up to -4.3 m (Fig. 16), indicating that high-water level was situated slightly higher, together with the presence of bubble sand below that level. A strong contrast exists between generally fine grained sets and

strictly sandy units. Molluscan thanatocoenoses in the sandy units indicate a selection of coarse reworked material, which should be related to wave activity originating from the North Sea. Both this activity and intercalated biological traces point to rapidly changing depositional circumstances. These are very probably associated with intermittent overwash activity because of the flat beds, separated by intermittent biological activity, not from bivalves but probably from root penetration from plants.

Unit 3b

The top of this unit and therefore of this subunit consists of an undulating surface. Sometimes low dunes are present -, sometimes not. In between these low dunes cat-eye ponds were present, which were filled later by organic-rich sediments. The top of the low dunes is usually decalcified for several tens of centimetres. Also iron oxides were transported by infiltrating groundwater, indicating that soil formation processes were active for probably hundreds of years on this surface. Later, after soil formation had taken place, the shallow depressions were filled with clay deposits (see Fig. 7 at -4 m NAP).

4.4 PALAEONTOLOGY-FACIES RELATIONSHIPS

In Fig. 17 a summary is given of the palaeontogical data, together with sedimentologically important data, as well as radiocarbon datings, which were performed on several levels. The main purpose of the palaeontological work was the search for important levels for the interpretation of the sedimentary environment with levels which could possibly be connected with Mean High Water (MHW), MSL or Mean Low Water (MLW) of the period during which the sediments were deposited. A distinction is made between the micro- and macropalaeontological work.

Fig. 16 (see overleaf)

Rijswijk A4 temporary exposure, subunit 3: washover deposits. Note frequent bioturbated horizons capped by cross bedded and plane bedded coarse sands with shells and shell fragments. 'Puckled' appearance of sand due to intertidal (and supratidal ?) bubble sand formation (-o-). Location 10 in Fig. 7; see also Fig. 12. For legend, see Fig. 7.

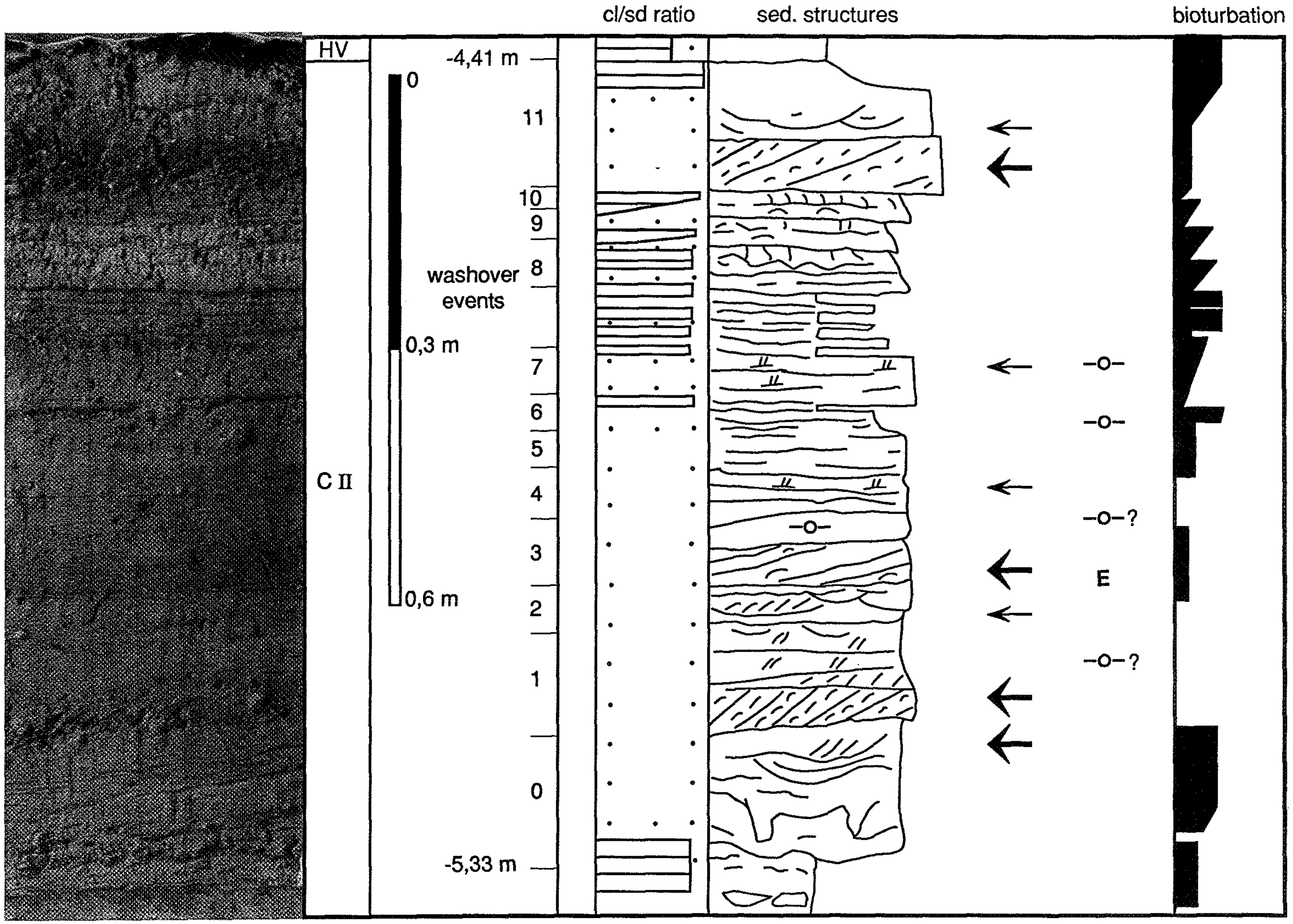

cl/sd ratio
sed. structures
bioturbation
HV
C II
-4,41 m
-5,33 m
0
0,3 m
0,6 m
washover events
11
10
9
8
7
6
5
4
3
2
1
0
E
-o-?

Fig. 16

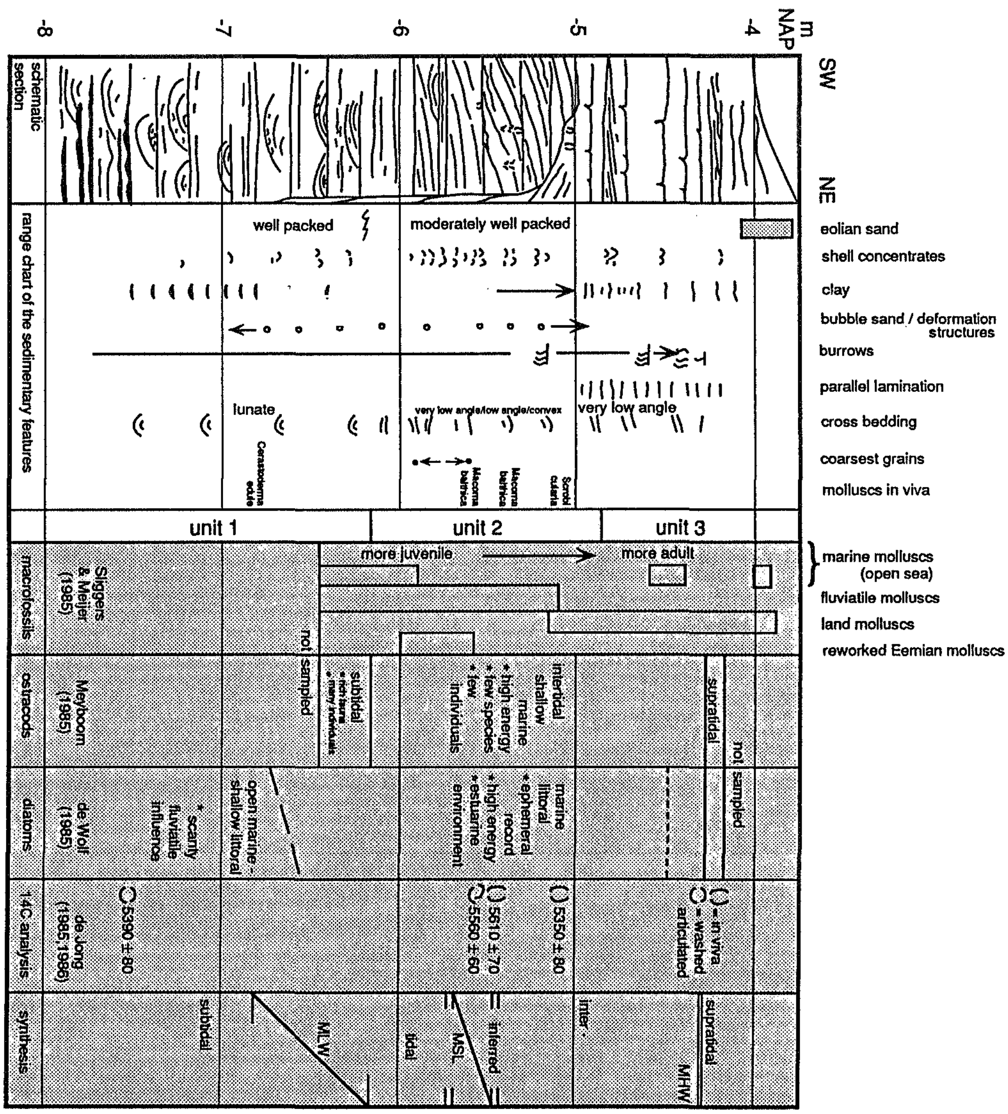


Fig. 17

Schematic section and range chart of sedimentary characteristics of the RZ sands of the Rijswijk A4 temporary exposure.

All micropalaeontologists have reported that their material is allochthonous. From the class of molluscs, autochthonous species are reported, together with a large number of allochthonous species. Therefore, molluscan analysis is treated separately.

As for MHW, this level is easiest to determine. Palaeontological and sedimentological evidence converge in the sense that -4.3 m is a level at which major boundaries occur (diatoms, forams, ostracods and highest bioturbation by worms) (Fig. 17).

MLW is much more difficult to define (e.g. Roep & Van Regteren Altena, 1988). This difficulty becomes even more serious by a lack of biodata in the zone in which they should occur. If the -4.3 m is accepted as a reliable MHW estimate, then MLW should be encountered some two metres lower if tidal amplitude would be about the same at the time of deposition as it is today. No important sedimentological boundaries occur at that level, however, except for the boundary between subunits 1 and 2. As mentioned above, this is only an arbitrary boundary.

Distortion of ripple cross lamination by the possible formation of bubble sand, presumably due to tide-related processes took place to a depth of nearly -7 m, while highest clay layers thicker than 0.5 cm only occur below -7.2 m (not counting the clay with the *Scrobicularia* shells). This suggests that MLW should be found somewhere between -6.3 and -7.2 m. It is suggested that faunal evidence is of limited help in determining this level. Major boundaries in the diatom, foram and ostracod records occur in a zone 0.5 m below the subunit 1-2 boundary, generally at -6.2 m. Still, sedimentological evidence is considered the strongest argument in the determination of the MLW. This suggests that MLW should occur at a depth of -6.2 m to -6.8 m.

Molluscan evidence is twofold, as mentioned above. The par-autochtonous component is composed of a few species well adapted to the sedimentary environment: an occasional *Cerastoderma edule* (juvenile), some washed-in *Macoma balthica* below the -5 m level and the *Scrobicularia plana*-level at -5 m. Nowadays these species mostly occur in a Wadden-type environment. All other species probably would be allochthonous and should not be used as environmental indicators. They can be used, however, as indicators of the energy-level in a sedimentary context. In that case they reflect various degrees of washing and sorting. It is in this way that the molluscan evidence (Sliggers and Meijer, 1985) is interpreted.

The empty molluscan shells generally lie concave down, i.e. in position of greatest stability. In lacquer peels the molluscan thanatocoenoses are dominated by *Macoma balthica*, accompanied by varying amounts of *Mytilus edulis*, *Cerastoderma edule*, *Spisula sp.*, *Peringea ulvae* and *Mactra corallina*. Single or articulated valves of *Unio pictorum* occur, indicating a fluviatile connection. Erosion of older fluviatile sediments can be ruled out, otherwise the *Unio pictorum* bivalved shells would have become disarticulated. Largest concentrations of shell fragments and of reworked Eemian species occur in this zone.

It is remarkable that concentrations of Eemian shell material were found. This implies that the Late Atlantic tidal currents or waves were able to erode Eemian deposits. This agrees with data from Van Regteren Altena (1937), who reported that this material occured at the bottom of the North Sea below -20 m. Van Staalduinen (1979) indicated a provenance of this material from below -27 m NAP for the subsoil west of the present study area.

A gradual transition occurs at the -5.4 m level. Above this level less riverine-and more land-molluscs are present. It is also the level above which no bedding types occur, attributable to a continuous high-energy level. This implies a major break in energy-level, which could indicate the mid-tide level. The *Scrobicularia*-level at -5 m is a strong expression of a drop in the general energy level. Througout the sampled section (-4 m to -6.4 m), levels occur in which no spatfall was found. Invariably, these levels pertain to strictly horizontally laminated sands. These sand beds may be associated with breaking and spilling waves, causing maximum agitation and, hence, removal of all spatfall and a great number of the smaller sized molluscan shells (e.g. *Peringea*), non-marine molluscs and *Bryozoa*.

In this context, it should be mentioned that the section at Benthuizen, that has been analysed by Raven and Kuijper (1981), shows on the basis of molluscan evidence that no connection existed of the RZ channel with a fluviatile channel in the Hinterland. This indicates that the shell material in the RZ sands for a large part came from the North Sea. All the same, alder carr plant seeds drifted. There seems only one way for these seeds to have arrived at this location: out of the river mouth, through the shallow North Sea by long-shore currents and transported landinward, all the way up to Benthuizen. The same transport way is supposed for the *Unio pictorum* bivalves, indicating low energy conditions.

The dominant presence of *Macoma balthica*, but also the persistent presence of *Spisula subtruncata* in the section is known from the barrier sediments as well (compare Van Straaten, 1965).

It is concluded that molluscan evidence can provide valuable information on sedimentary conditions in intertidal and subtidal environments. The importance of information on species composition is subordinate to sediment-related parameters such as size, weight and shape of the molluscs. The fact that in the Rijswijk A4 pit subunit 2 maximum occurrence of reworked Eemian molluscan shells takes place, is no coincidence. It shows that particulary in this zone of high sedimentary dynamics shell material from the North Sea bottom washes up into the intertidal zone.

5. AGE OF THE DEPOSITS

Establishing the duration of activity during which the RZ sands were formed, was done by means of radiocarbon analysis. In the western Netherlands a substantial amount of radiocarbon data indicative of the start or the end of peat growth is available. This peat dating the top and base of the peat bed, is called Holland Peat of the Westland Formation (Van Staalduinen, 1979). Therefore, these data indicate the beginning and the end of the process of peat growth in the coastal plain and not the age of the clastic deposits in between these peat layers. The clastic deposits in the Rijswijk pit were dated by radiocarbon analysis of molluscan shells preferably sampled in life position. A short methodological discussion is devoted to the particular aspect of radiocarbon analysis on molluscan shells (see Appendix).

The beginning of marine activity is indicated by the Nootdorp dating of c. 5,900 BP of the Holland Peat layer underlying the RZ sediments (Fig. 18, no.1: GrN 2268; Zagwijn, 1965). The end of sandy sedimentation in the Rijswijk-Zoetermeer area is indicated by the radiocarbon dating of 5,560 ± 80 BP on molluscan shells near Zoetermeer (Fig. 18, no. 5). Shortly after this moment the tidal marsh reached maturity. This is suggested by a tidal creek and low marsh pattern which was mapped during a recent soil survey (Mulder, 1989). Further south, west of Delft (Van Staalduinen, 1979), the start of the growth of peat on top of sandy Calais II Deposits was dated as 5,470 (GrN 6497; Van Staalduinen, 1979) to 5,270 BP (GrN 6500; Van Staalduinen, 1979). These Calais II Deposits are tentatively correlated with the RZ sands. As a consequence any peat layers formed on top of this deposit postdate the maximum transgressive activity and the fixation of the easternmost border of the sandy deposits south of Naaldwijk-Wateringveldsche Polder (Figs. 1 & 4). Hence, the formation of the sand sheet of the RZ deposits can be dated c. 5,500 BP or slightly older.

Summarizing, the RZ sands were deposited in the period between c. 5,900 and 5,500 BP, i.e. some 400 (or somewhat less) radiocarbon years. This period may become be shorter when the radiocarbon datings on shell material from the Rijswijk pit are interpreted alternatively (see Appendix)

6. DISCUSSION AND CONCLUSIONS

6.1 TIDAL AMPLITUDE

Depositional processes locally caused rapid aggradation covering subtidal and full tidal amplitude ranges. Based on sedimentary structures range charts, the tidal amplitude is 2.1 to 2.8 m, 2.4 m on average. This figure is indicated by the range of sedimentary structures and the distribution of the fossils in the section studied in the Rijswijk pit (see Fig. 17). As may be seen, the uncertainty is some 0.7 m; this uncertainty is due to the quality of the sedimentological data, that do not permit a further narrowing down of the intertidal range. Taking into account that the tidal amplitude at the part of the present-day Dutch coast west of the excavation is 1.8 m, it follows that, if our assumptions are correct, the tidal amplitude has diminished by 0.8 m starting from the Late Atlantic. This is in agreement with Roep & Beets 's data (1988). MSL for the deposits the Rijswijk pit is situated approximately at -5.5 m to -5.7 m NAP with an uncertainty of ± 0.4 m according to the uncertainty of the tidal range (Fig. 17).

Franken (1987) argued that the tidal amplitude in the southern North Sea never diminished, but instead always grew. Franken's data pertain to the open sea-situation, while it is clear that in the case presented here a coastline close to a tidal channel is under discussion. In these areas all kinds of resonance problems may be expected. Hence, the 2.4 m tidal amplitude is considered not unrealistic, though local, probably influenced by resonance in estuarine environment of the area; there is certainly a need for support by data from other areas.

6.2 DEPOSITIONAL ENVIRONMENT, RATE OF DEPOSITION AND SEA-LEVEL RISE

In the coastal environment of the Late Atlantic, the Rijswijk pit offered an insight into a wave-dominated part of this environment. The presence of such deposits may be deduced from the palaeogeographical position of the exposure relative to the coastline configuration of that period. The section that accessible in the Rijswijk pit showed a rapid coarsening-up sequence, also fining-up rapidly above the level of inferred MSL. Diatom data showed a succession (Fig. 17) from open marine to marine littoral. As this sequence is covered by dunes (Fig. 7), this may be interpreted as an open coastal sequence.

Micropalaeontological research and diatom analysis were performed on the sediments. Because of the allochthonous character of these micro-organisms their value for the reconstruction lies mainly in providing regional images. Molluscan analysis, however, yielded data concerning the sedimentological interpretation of the deposits. Especially the way in which thanatocoenoses were put together, was highly instructive for the interpretation of the sedimentological record. Parallel laminated beds (high energy of breaking waves) show the selection processes of the swash and backwash: for instance, no spatfall stadia are present.

In the section as a whole, few infaunal molluscan species occur and when they do, only highly adapted ones are found. *Macoma* can survive high sedimentation rates (up to 0.5 m/hour) provided water temperatures are not too low. *Scrobicularia* enters this system only when a considerable drop in energy level has been effectuatedted. This species can withstand varying salinities but not large amounts of sediment cover. The drop in energy level is effectuated when sheltering barrier and dune deposits reach a position immediately west of the excavation. Immediately, desalination takes place by large volumes of water brought in by rivers and by precipitation.

When comparing this coastal sequence with other coastal sections reveiling similar structural build-up (e.g. Clifton et al., 1971), it appears that the present section is situated in an open coastal environment. From the sedimentological record it is inferred that the preservation potential of the sandy deposits can have been extremely high once laid down. Lunate megaripples are rarely found in coastal sequences (Reineck and Singh, 1980), but here they occur, separated by probably seasonally induced bioturbated horizons, 30-40 cm apart. The lunate megaripples did not originate in a tidal environment, but in a wave-dominated open coastal configuration. This is indicated by the absence of clay drapes in the lunate ripple deposits and the transition from fine sand to shell hash and peat detritus.

The deposition of sediment is mostly influenced by waves. Main deposition of sand is towards the south related to the west-east trending coastline. From the presence of several layers of tidally induced disturbed bedding (e.g. bubble sand) a local rise in low-water table of -7.0 to -6.2 m during the deposition of this sequence (which is thought to have taken several hundreds of years) is observed. This amount of rise (0.8 m) is considered not exceptional for the Late Atlantic. However, this difference could also have been caused by fluctuating (neap-spring) low tidal levels during deposition of the sequence. Computed sea-level rise from peat data amounts to 0.7 - 1.0 m per 100 radiocarbon years (Jelgersma, 1979; Van de Plassche, 1982). This figure does not conflict with radiocarbon data from the RZ deposits. It is not possible however, to estimate aggradational rates due to the effect that lowest and highest datings showed no significant age differences, not even after calibration (Van der Plicht & Mook, 1988). Furthermore, the effect of isotopic fractioning may well have led to a younger age to be assigned to the sand sheet deposits after the appropriate correlation relative to the degree of fractionation.

Comparing the radiocarbon data from the basal strata from peat layers covered by sediments from the RZ system with the radiocarbon data from shell datings of the deposits themselves, it can be conclued that only three hundred years, or slightly more, were available for the formation of the sandy deposits.

The Rijswijk pit offered good opportunities for sea-level rise studies (Roep & Beets, 1988, their fig. 3 & 4, site no. 19). Probably no compaction or subsidence occurred subsequent to the sandy marine sequence. This is because underlying deposits had been subject to compaction during the deposition of the sequence itself. At the time the top layers were deposited, allmost all compaction would already have taken place.

Summarizing, the sedimentary environment can be characterized as an open coastal one. It differs from the coastal sequence from the barrier area further to the west. Firstly, the lunate megaripples present in the Rijswijk pit (and on the present-day Wadden island low intertidal beaches) were never found in that area and secondly, where two or three stacked longshore bars and/or a berm can be found in the barrier area (Roep et al., 1983), here only one berm-like bar was found. This indicates that the coast in front of the area of the Rijswijk pit must have been well sheltered against wave attack. Presumably the presence of a large ebb-tidal delta belonging to the tidal channel leading into the Zoetermeer area was of importance here, sheltering the beach to the southwest.

The RZ sand sheet is interpreted to be the earliest sign of coastal progradation along the northern shore of the Rhine estuary. Progradation in this early stage of coastal evolution is connected with the downdrift activity of the Rhine estuary bordering the island to the south. The sand probably originating from the shallow North Sea in front of the River Rhine outlet, as most authors agree that the River Rhine was not able to bring sand to the sea during the Atlantic (Kruit, 1963; Zagwijn, 1986; De Groot & De Gans, in press). Next to this sand source, another source may have been present, namely the ebb-tidal delta mentioned above. Both sources contibuted to the appearantly fast initial progradation.

The sequence visible in the Rijswijk pit shows a type of coarsening-up development, which indicates an open coastal configuration, to which waves had direct though attenuated access. The direction of the coastal progradation is towards the north, which is in agreement with the postulated situation of the coastline before 5,500 BP. The coastal profile as a whole reaches down to -13 m at the site of the exposure, indicating a sea depth of about 8 m.

6.3 COASTAL DEVELOPMENT

The sand body to which the RZ sand sheet belongs is a deposit laid down in a period during which sea-level rise took place at higher speed compared to the subsequent one thousand years. The transport of sand was probably mostly longshore, the sand being provided by reworking of the former River Rhine delta sands (Beets et al., 1992). The deposit is interpreted as the earliest prograding sequence in the western Netherlands. Probably the best reason for the early occurrence of progradation is the presence immediately east of the former delta sands and south of the ebb-tidal delta sands belonging to the channel leading to Zoetermeer. In this way, the RZ sand sheet formed the progradational southern border area to this tidal channel. It prograded because of the readily available sand sources. As far as we know the northern border area is still eroded during the same time as the RZ sand sheet was formed.

From the general morphology of the coast (small part of which is given in Fig. 1), an estimate can be made of the length of the Atlantic barrier islands. A length of 8 to 10 km seems reasonable. In this way three barrier islands could have been present, bordered by four tidal inlets between the present-day Haringvliet and present-day Old Rhine. The southern inlets were connected with fluviatile water while the northerly inlets were not.

Coastline movements during the Atlantic were directed inland. The conditions appear to have been: no sediment influx from rivers into the coastal area and a high rate of sea-level rise. Only in the Late Atlantic, when the tidal basins had been filled to a great extent and, consequently, tidal volume had decreased dramatically, did coastal configuration change into a progradational coastline as the south- (= shore-) ward displacement of sand by waves continued. The sand used earlier for filling in the tidal basins could now be used for barrier progradation. This more or less coincided with the decline in the rate of sea-level rise (Beets et al., 1992).

The oldest preserved barrier chain presumably rolled inland and removed a Holland peat bed and, to a lesser degree, marine and estuarine deposits underlying this peat layer. After this oldest barrier line had become fixed along the line Naaldwijk-Kwintsheul, coastal progradation immediately started to use this as a base-line. The barrier progradation was fed by sediment provided from the North Sea floor and/or by coastal longshore drift, originating from the Rhine estuaries. It is not known exactly when this early coastal progradation started, but radiocarbon datings from the Rijswijk pit suggest that it could have started as early as 5,800 BP, which is some 800 years earlier than generally accepted (e.g. Roep et al., 1983). However, when the effect of fractioning present in the shells (Fig.18) is taken into account, the outcome of the datings could be several hundreds of years younger. This issue will be treated in a paper by Van der Valk & Mook (in prep).

The barrier sands were topped by eolian dunes. These now buried dunes cover sandy sediments of the RZ sand sheet. Assuming that transport capable winds blew generally from the southwest during the Atlantic (just as they do now), this indicates aeolian coastal drift towards the northeast. Dune subcrop and outcrop patterns indicate rapid thinning of the barrier complex towards the northeast (Fig. 1), implying rapid decrease of influence of longshore transport in this direction. Therefore, the source area of the sediment of the prograded RZ sands should be the shallow North Sea area west of Hoek van Holland. It is assumed that this progradational phase for the coastal area between Naaldwijk and the River Rhine estuary with a major impetus from the south, lasted until at least 4,750 BP (Roep et al., 1983; De Gans et al., in prep). The phase of coastal development as documented in the RZ sand sheet is seen as a transitional phase between a period with many tidal inlets prior to 5,500 BP (or even 5,900 BP) and a period of 5,000 BP or younger with fewer tidal inlets. Progradation during this transitional phase was extremely rapid, as a consequence of the presence of large volumes of sand available in the former River Rhine Delta and as ebb-tidal delta sands in the shallow North Sea area in front of the RZ sand sheet.

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APPENDIX

CONVENTIONAL RADIOCARBON DATING ON MOLLUSCAN SHELLS

Shells of molluscs are a readily available material of almost all aquatic depositional environments. Especially in coastal areas shell material in large quantities. In high- energy environments, in tidal channels and on beach face profiles, virtually no locations are stable enough to support molluscs in life position for a number of years, let alone allow fossilization in this position. It is well known that the preservation potential of the most bivalve (98 %) molluscan communities is not very high (e.g. Eisma, 1966). Bivalve communities in the North Sea coastal zone usually are dominated by a single or a few species, but the bivalve species present usually occur in great numbers. The shells are removed out of their life position either by currents or by waves, become disarticulated and sorted with respect to shell form and weight according to the hydrodynamic situation at that particular site. High-energy of both waves and currents washes them into thanatocoenoses. These accumulations also contain transported already (sub)-fossil shell material and other organic and lithic material which were subject to the same hydrodynamic conditions. It is clear that these molluscan shell accumulations are not suited to be collected for radiocarbon analysis.

There is, however, a category of molluscan shells from these high-energy environments that can be used for radiocarbon analysis: transported bivalves with periostracums still present, preferably but not necessarily articulated. The Rijswijk pit offered valuable material for testing this method. For most bivalve species it is sufficiently well known that bivalved specimens quickly become disarticulated, especially in high-energy environments. Usually this is a matter of just days. Therefore, this material is considered qualitatively equal to articulated bivalve shells in life position. In the Rijswijk pit, articulated *Macoma* shell pairs were collected, which were generally not in life position. For the uppermost shell-sample, in situ *Scrobicularia plana* were collected.

A disadvantage of the analysis of shell carbonate in not fully marine coastal settings is the probable presence of freshwater admixture in the coastal waters. In the case of the shell carbonate datings reported uponhere, it is very likely that some percentage of freshwater has indeed been present. Remarkably, diatom

Table I. C14 - Datings in the immediate surroundings of the Rijswijk-Zoetermeer sands

Cat. 1 Holland Peat datings (and 1 dating on shell material) predating the RZ sands.

	location and coord.	local nr.	GrN	C14-years	depths	sample composition	δ C13/C14	reference
1	Nootdorp 88.400 - 452.150		2268	5890 ± 80	8.05 (-)	peat		Zagwijn, 1965
2 3	Leidschendam- Wilsveen 89.135 - 454.475	3 4	9807 9808	5625 ± 45 6345 ± 40	7.02 - 7.04 (-) 11.32 - 11.34 (-)	peat gyttja		De Mulder et al., 1983 De Mulder et al., 1983
4	Scheveningen Harstenhoek 80.430 - 458.870	3	12748	6240 ± 90	18.20 (-)	hinged Mytilus edulis	- 3.85	this publication

Cat. 2 Datings from the RZ sands.

	location and coord.	local nr.	GrN	C14-years	depths	sample composition	δC13/C14	reference
5	Zoetermeer Driemanspolder 90.500 - 452.500		15111	5560 ± 80	5.00 (-)	**Scrobicularia plana in viva**	- 4.73	this publication
6 7 8 9	Rijswijk Plaspoelpolder 82.200 - 449.500	1-1 2-6/1 2-6/2 37	12846 12848 12849 13490	5350 ± 80 5610 ± 70 5560 ± 60 5390 ± 60	5.05 (-) 5.45 (-) 5.45 (-) 7.50 (-)	**Scrobicularia plana in viva** **Macoma balthica hinged not in viva** **Macoma balthica, Zirfaea not in viva** **Macoma balthica hinged not in viva**	- 7.85 - 5.0 - 4.70 - 5.32	De Jong, 1985 De Jong, 1985 De Jong, 1985 De Jong, 1986

Cat. 3 (Mainly) Holland Peat datings postdating the RZ sands

	location and coord.	local nr.	GrN	C14-years	depths	sample composition		reference
10	Rijswijk Plaspoelpolder 82.275 - 450.300		2267	4670 ± 65	4.00 (-)	basis Holland peat		Zagwijn, 1965
11	Rijswijk Plaspoelpolder 82.200 - 449.500		12847	4580 ± 35	3.93 - 3.95 (-)	basis Holland peat		De Jong, 1985
12	Zoetermeer Dorp 94.075 - 452.310		13461	4440 ± 60	4.50 - 4.56 (-)	basis Holland peat		De Jong, pers. comm.
13 14	Leidschendam Wilsveen 89.135 - 454.475	1 2	9428 9429	4400 ± 40 5045 ± 40	5.07 - 5.09 (-) 6.00 - 6.02 (-)	basis Holland peat gyttja		De Mulder et al., 1983 De Mulder et al., 1983

Fig. 18 C14-datings in the immediate surroundings of the Rijswijk-Zoetermeer sands.

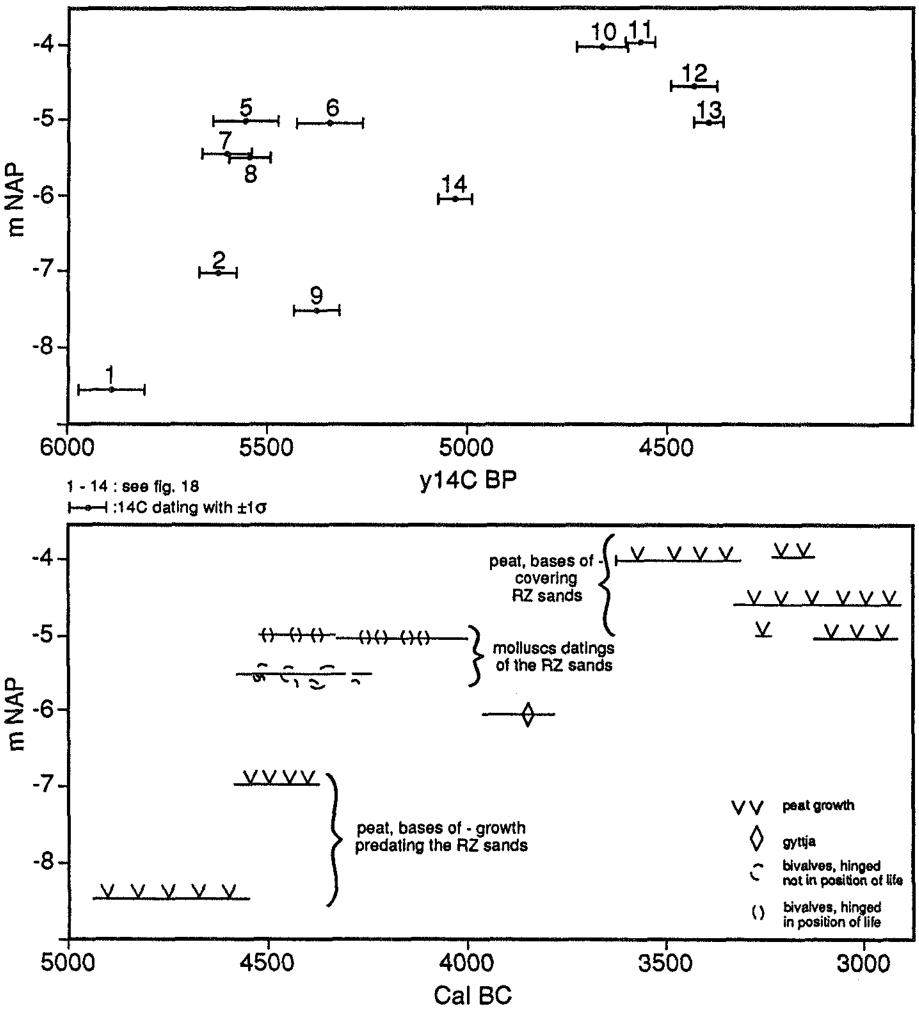

Fig. 19

Radiocarbon datings in connection with the Late Atlantic coastal deposits in South-Holland :
a) time (yBP)-depth diagram
b) time (cal BC)-depth diagram

analysis showed this effect only minimally (De Wolf, 1986b). δ13C values of -4.71 to -7.85 per mil with regard to the PBD standard however (Fig. 18), are suggestive of this freshwater admixture. The value of fully marine sea-water is 0 to -1 per mil δ13C. The effect of the admixture of freshwater is that it renders the datings relatively too old, 16 radiocarbon years per mil deviation from - 25 per mil, the 'continental' standard for δ13C (Mook & Van de Plassche, 1986).

Shell material involved in dating was treated in the usual way (cf. Mook & Waterbolk, 1985). Some 30 % weight of the sample was lost during the pre-treatment due to diluted HCl solution to remove secondary $CaCO_3$. The remaining shell material was dated.

Shell carbonate datings as published here in this paper were compensated for the apparent age effect of surface ocean water (Mook and Van de Plassche, 1986) but not for the delta 13C age effect.

Results and comments

Fig. 18 shows the datings in three categories:
1) peat datings, predating the RZ sands;
2) datings from the RZ sands, all shell carbonate;
3) datings mostly on peat overlying the RZ sands.

Fig. 19a shows the dating results in years BP, while Fig. 19b presents the intervals of grouping of the data after calibration (cf. Van der Plicht and Mook, 1988 and associated computer program by Van der Plicht, CIO Groningen).

It is remarkable that yhe youngest conventional peat datings of Category 1 only just predate Category 2 datings (when the latter are not corrected for δ13C). This is remarkable because Category 1 samples reflect bases of the strongly compacted peat layers predating the RZ sands and not the (usually eroded) top of these peat layers. It is generally thought that it takes at least some centuries for such peat layers to form. Category 2 datings can become much younger when corrected for δ13C values, as these are between -4.70 and -7.85 per mil (Mook & Van de Plassche, 1986). This widens the gap between Category 1 and Category 2 dates. Category 3 datings postdate Category 2. A solitary date on a gyttja is intermediate in time between Category 2 and 3 datings, but postdates the tidal system and is therefore incorporated into Category 3.

In Fig. 19b, the depth/cal BC diagram, the overlap between Categories 1 and 2 is even clearer. Secondly, it is obvious from this diagram that a distinct period of some 400 years elapsed between the period of active sedimentation in the tidal system as documented by the molluscan shell datings and the start of peat growth on top of the deposits themselves (and slightly younger clay sheets deposited against the sandy channel fills of the tidal system). As the sea level still rose moderately rapidly, it is unlikely that peat growth did not start due to low groundwater levels. An emerged position of sampling locations can be the only alternative solution to this problem). Clay sheets are known from the flanks of the tidal channel, with locally one or two standstill phases in clay sedimentation (e.g. Van der Knaap, 1959). These phases were not dated, but it is likely that they at least fill part of the gap between Categories 2 and 3. The thin clay layer just below the peat in the Rijswijk pit is part of this complex. Local freshwater lakes also may have existed (dating f; Fig. 7: gyttja) during the entire period. Just before peat growth started at Rijswijk Plaspoelpolder (dating c), locally dy formed by precipitation of humic matter in ponds in the brackish environment (Zagwijn, pers. comm.).

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CHAPTER VI

COASTAL BARRIER DEPOSITS IN THE CENTRAL DUTCH COASTAL PLAIN

L. Van der Valk

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ABSTRACT

Following preliminary work with Core Penetration Tests, a transect in the coastal barrier area between the Older River Rhine outlet and the Oer IJ tidal inlet was cored. The relationships between various lithological e.g. grainsize, sedimentological structures and palaeontological features (diatoms, forams, molluscs and pollen) are discussed. The chronostratigraphy of the transect is based on radiocarbon datings of reworked shell material of which the freshest habit was selected. Pollen analysis reveals possible source areas of the pollen and the fine-grained sediment contained in the barrier sediments.
Despite a sea-level rise of 3 to 4 m, the coast at the site of the transect experienced a stepwise progradation. During this progradation the shoreface gradient steepened, i.e. it deviated from the Bruun rule of shoreline retreat during sea-level rise. Below the longshore breaker bar zone, coastal sedimentation is storm-dominated; a model is presented here. The coastal development is seen to be related to evolution of tidal inlets in the area.

CHAPTER VI

COASTAL BARRIER DEPOSITS IN THE CENTRAL DUTCH COASTAL PLAIN

1 INTRODUCTION

1.1. GEOLOGICAL FRAMEWORK

1.1.1 **Setting**

The coastal zone of the western Netherlands is characterized by a more or less continuous barrier. In the southern part of the Netherlands (the province of Zeeland), this barrier is cut by several large estuaries, some of them connected with river outflows. With the completion of the Delta works, some of these estuaries were cut off from the sea by artificial barriers. The central part (the Holland coast) is essentially closed over a distance of 120 km, while the northern part (the Wadden area) again shows tidal inlets. The barrier zone is separated from the mainland by an area filled in with Holocene tide and fluviatile deposits and peat. The tidal range at the coast varies from 1.7 m in the central part to some 3 m near the tidal inlets of the Zeeland and Wadden areas. Therefore, the Holland coast may be described as micro- to mesotidal in character. For this coast, wind and waves are considered dominant formative factors, in combination with some tidal action. The horizontal tidal action is slightly larger during flood (bottom value 0.85 m/s to the north) than during ebb (0.75 m/s to the south) on the Holland coast (Van der Giessen *et al.*, 1990). Mean wind directions are westerly, whereas northerly wind causes the highest waves in the shallow (depth mostly less than 40 m) North Sea. Mean visually registered wave height is about 1.2 m (Hoozemans, 1990). For a recent survey of North Sea hydrographic conditions, see De Wolf (ed., 1990). Major rivers (Rhine, and, to a far lesser extent, Scheldt and Meuse), flow into the southern North Sea.

The climate of the western Netherlands is temperate. Average rainfall is between 700 and 800 mm per annum. The wind climate is highly variable. During winter, spells of moderate easterly winds or no winds at all are followed by fierce storms from directions between northwest and southwest. During summer modest southerly and southwesterly winds predominate.

1.1.2. **Regional geology**

The study area (Fig. 1) is situated in the central part of the Holland coast. The western Netherlands belong to the depocentre of the southern North Sea Basin, which has been subsiding ever since the Carboniferous (Zagwijn, 1989).

During the Middle and Late Pleistocene, the southern part of the North Sea experienced two or three glaciations and deglaciations. The present-day coastal region was flooded by the sea three or four times during interglacial highstands. During the Saalian, the continental ice sheet just reached the study area, and a substantial relief was created between ice-pushed moraines and scooped-out tongue basins (De Gans *et al.*, 1987). The last two interglacial phases (the Eemian and Holocene) have left distinctive coastal plain depositional sequences. Tectonic subsidence is the cause of the difference between the altitudes of Eemian (highest occurrences at present at -8 m NAP) and Holocene coastal deposits (Zagwijn, 1983). Between these two interglacials, the Weichselian glacial period generally left an unconformity as a result of (peri)glacial weathering and/or erosion. During this glaciation, a large part of the North Sea was cut off from marine influence, leaving continental geological processes to be active here. River Rhine waters had diverted towards the Channel area since the Weichselian until the deglaciation in the central and northern North Sea at *c* 11,000 y BP.

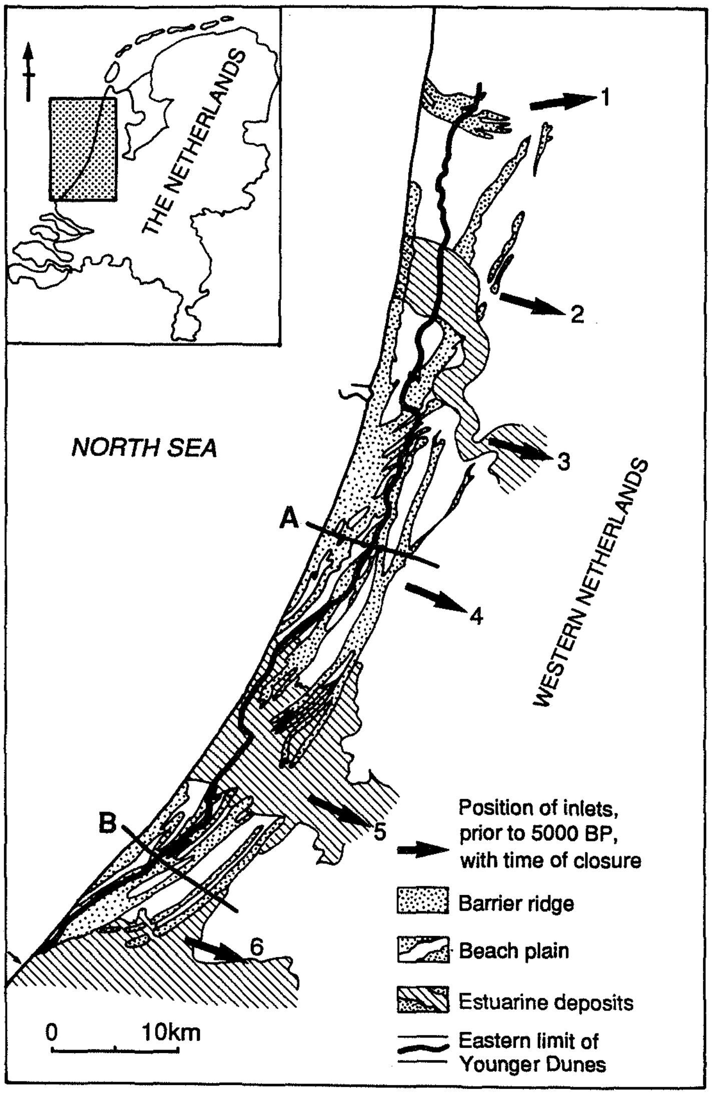
Deglaciation led to a sea level rise; the sea entered the southern North Sea Bight some 13,000 years ago, which is several thousands of years later than in other, more northerly areas. This phase of eustatic sea level rise lasted until *c* 6,000 y BP (Jelgersma, 1979). Subsequently, the combined effects of eustatic sea level rise, tectonic/isostatic- and soil subsidence caused a further rise of relative sea level of about 5 m in the western Netherlands (Jelgersma, 1979; Van de Plassche, 1982; Van de Plassche & Roep, 1988).

During the last six millennia, the coastal development in this central area has been different from the southwestern and the northern part of the Netherlands (Zagwijn, 1986). Essentially, the development is a long-term redistribution of available sand masses in the eastern coastal area of the southern North Sea. Erosion of headlands and progradation of the area in between, the central Holland coast, took place. This area became a rigid sand barrier during progradation, thereby progressively closing its tidal inlets (Beets *et al.*, 1992).

The main contributing factors that may be distinguished are:

- the presence of large volumes of fresh discharge waters of the rivers Rhine and Meuse. Only the River Rhine contributed sediment to the coastal plain deposits prior to 7,000 BP (De Groot & De Gans, in press);
- the existence of river valleys prior to inundation during the Atlantic, *i.e.* the pre-Holocene surface;
- the different exposure to wind, waves and currents of the SSW-NNE trending coastline;
- the very limited amount of tectonic subsidence in this period of time; and, most importantly,
- the availability of large volumes of sand in the coastal area.

The joint effects of these factors caused the coastline to behave in the way it did. Instead of moving inland, as many a coastline would do when experiencing a similar sea level rise of about 1 m per 1,000 years, the coast started prograding. A series of beach barrier ridges and -plains were deposited, the oldest in the east, the younger in the west. The beach ridges became covered with dunes (the so-called Older Dunes) and the beach plains were later filled in with peat (Van Straaten, 1965; Jelgersma *et al.*, 1970; Roep & Beets,1988).



1 Alkmaar / Bergen (3300 BP)
2 Uitgeest (4500 BP)
3 Oer IJ(2000 BP)
4 Hoofddorp (4000 BP)
5 Oude Rijn (1100 AD)
6 Rijswijk (5500 BP)

cross-sections
A: near Haarlem
B: near The Hague
(van Straaten, 1965)

Fig.1. The coastal barrier area of the western Netherlands. Modified after Roep *et al.* (1991).

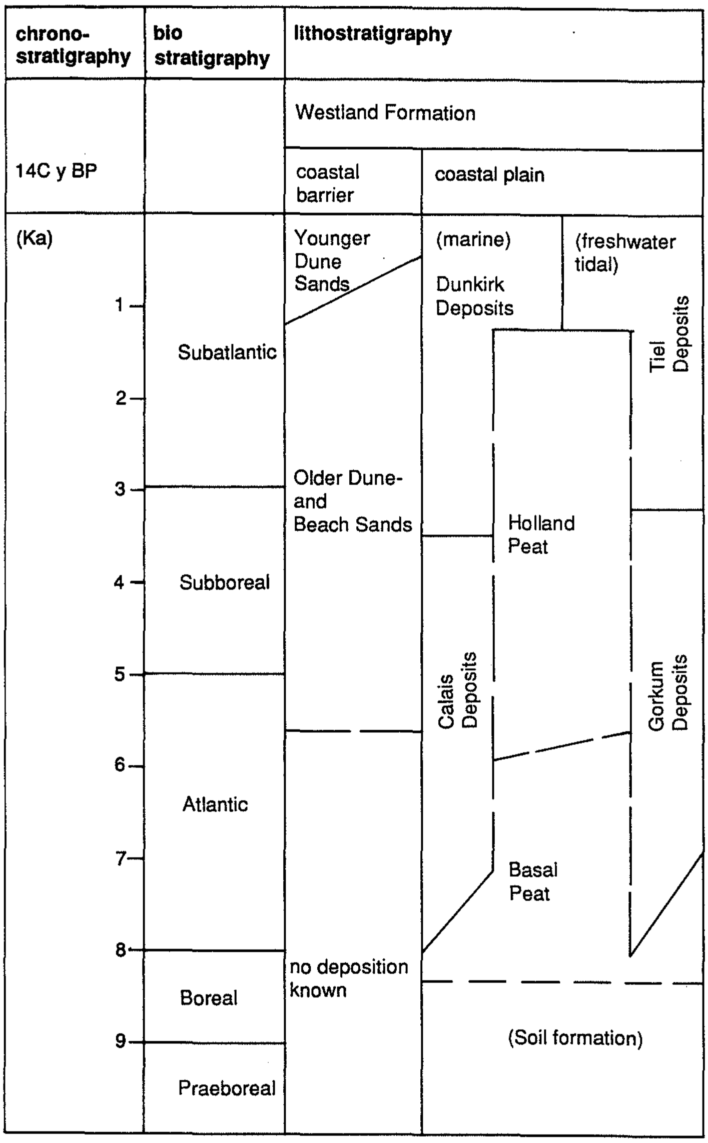


Fig. 2. Holocene stratigraphy of the western Netherlands. Modified after Zagwijn (1986). The Holland Peat interfingers with both marine and freshwater-tidal deposits and occurs also in and on top of the coastal barrier deposits.

All marine deposits to which reference is made in this paper are members of the Westland Formation (Holocene) (Fig. 2). Stratigraphical nomenclature is discussed by Zagwijn & Van Staalduinen (1975).

1.1.3. Local geology

1.1.3.1. *Previous work*

The coastal barriers of the western Netherlands have long since been recognized, mostly on morphological grounds (covered as they are by dunes in most places), while the sandy subtidal and beach deposits have been demonstrated to have originated from the North Sea on the basis of their fossil content. From the 1950s onwards it has been possible to investigate the deeper lying subtidal barrier deposits by means of cored boreholes. Until that time only bailer or flush boreholes were available. Cored boreholes provided the opportunity to study the sedimentary structures of lower barrier deposits. Van Straaten (1965) reconstructed the coastal development by studying the barrier sediments of the western Netherlands by means of cores from the southern part of the beach barrier complex near The Hague, in addition to temporary exposures and actualistic data from the North Sea. During the early phase of barrier formation, the shoreline retreated. When the pace of sea level rise slowed down, younger barriers started to form seaward of the oldest, covering offshore sand ridges belonging to the oldest phase of barrier formation. Fast progradation was subsequently initiated by the presence of an extremely shallow North Sea in front of the barrier and on top of the overstepped offshore bars (Van Straaten, 1965).

Based on data collected from temporary exposures, Beets *et al.* (1981) proposed a different mode of barrier formation. Beach plains would form during phases of low gradient of the North Sea shoreface, while beach ridges would develop when shoreface gradients were steep. Thus they rejected Van Straaten's hypothesis (1965), which said that offshore bars could emerge and be the cause of coastal progradation. The main reason for the changes in coastal progradational rate would be a different rate of sediment supply, which resulted in different gradients associated with the two modes of barrier sediments deposition (Beets *et al.*, 1981). Recently, however, a reconstruction of the Bergen inlet has been undertaken, also based on subsurface borehole data (Beets *et al.*, in press). A general model which incorporates all features of the barrier complex based on geological evidence has not yet been proposed.

1.1.3.2. *Recent work*

Recent mapping by the Geological Survey has provided a much more accurate picture of the morphology and geology of the barrier deposits (De Mulder (ed.), 1983; Westerhoff *et al.*, 1987; unpublished data of the Geological Survey). However, data on the geology of the deeper part of the barrier complex are still very limited, the Alkmaar area being an exception (Jelgersma, 1983; Westerhoff *et al.*, 1987; Beets *et al.*, in press). The Geological Survey and the Quaternary Geology Department of the Free University (Amsterdam) have decided to investigate the barrier deposits by means of cored boreholes, also in connection with the "Coastal Genesis" (Kustgenese) project, which is under the auspices of Rijkswaterstaat. This research was conducted by the present author.

The main reason for locating the transect of cored boreholes south of the city of Haarlem has been the lack of data on deeper barrier deposits in comparison to other areas *e.g.* around The Hague and Alkmaar. Another reason has been the numerous data available on the formation of the Older and Younger Dunes (Fig. 2) in this area (Jelgersma *et al.*, 1970; Zagwijn, 1984). The transect is situated some 20 km north of the mouth of the pre-medieval River Rhine and 10 to 25 km south of another former coastal inlet (the so-called Oer-IJ)(Fig. 1), also previously connected to the Rhine system. This inlet shifted its mouth considerably in a northerly direction during the time of formation of the coastal barrier complex (*e.g.* Zagwijn, 1971; Westerhoff *et al.*,1987). The location of the section can be compared directly with that of the more southerly section near The Hague studied by Van Straaten (1965). The latter transect was also situated approximately half-way between two outlets (the combined Rhine/Meuse outlet west of Rotterdam to the south and the Rhine outlet at Katwijk to the north; Fig. 1).

The shallow North Sea area adjacent to the shoreline has not been mapped yet. The sea-floor sediments are known to have a size-graded shoreface and a coarser sandy upper shelf zone, both with occasional clay layers. The present-day shoreface is distinctly barred and highly dynamic (Short, 1990). Modern coastal sequences closely resemble fossil Subatlantic sequences (Van der Valk, 1991), but differ in some respects compared with early Subboreal coastal sequences (this paper; Beets *et al.*, 1981; Beets *et al.*, 1992).

The barrier deposits in the transect (Fig. 3) rest on:

1. Older Tidal Deposits of Holocene age (mostly sands) and Basal Peat
2. Pleistocene deposits of presumably Weichselian (sands) and Eemian age (sands (?) and clays). The subsoil of the immediate surroundings of the transect was mapped hydrogeologically by Stuyfzand (1987) to a depth of about 100 m; these data been taken into consideration in the present study.

2. AIMS AND METHODS

2.1. AIMS

The purpose of this study has been to investigate the formation of the coastal barrier deposits in the mid-Holland area and to analyze the factors that have determined this development. The main factors are: sea level rise, climatic evolution, possible identification of sedimentary processes involved in barrier complex formation, the availability of sand, the main constituent of the barrier sediments and the influence and significance of the factor time involved in the formation of the barrier sequence. The aim has been to obtain a more detailed picture of the longer term dynamics of the Holland beach barrier coast.

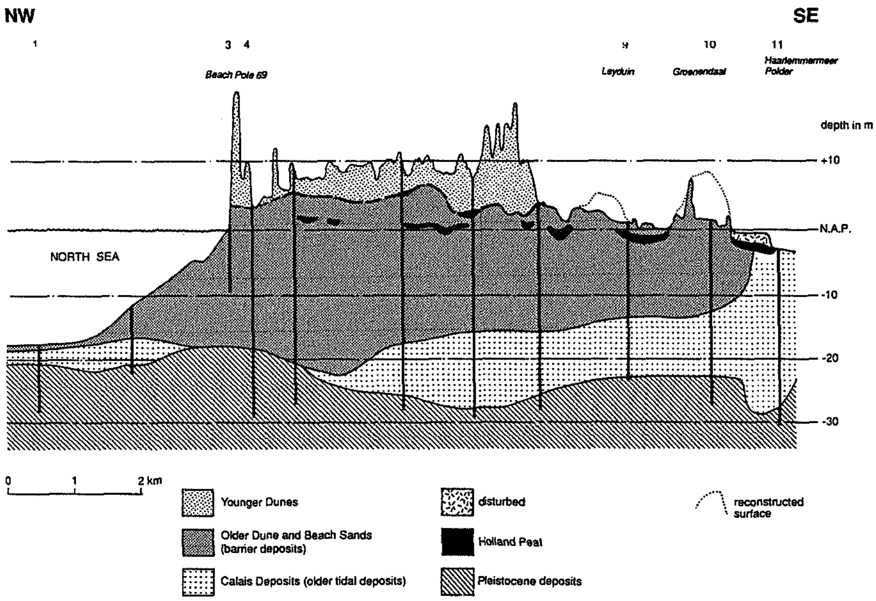


Fig. 3. Cross-section south of the city of Haarlem showing Holocene and undifferentiated Pleistocene deposits.

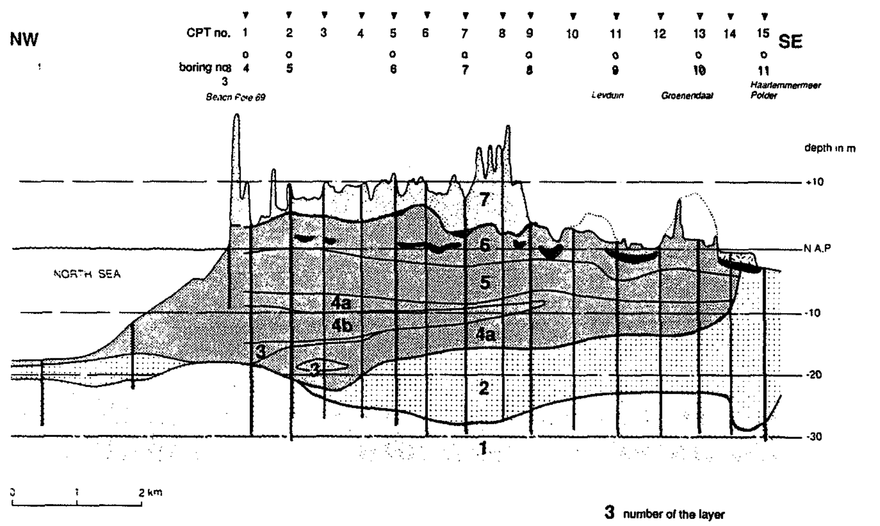


Fig. 5. Preparatory cross-section of geotechnical units, based on Core Penetration tests. Bold numbers refer to layers; for explanation see text and Fig. 6. For legend of background, see Fig.3. From RGD data (J. Blokzijl).

Understanding the genesis of the barrier sequence may also assist in predicting future coastal development.

2.2. METHODS

2.2.1. Preparations

The study area comprised the region of IJmuiden-Velsen-Hoofddorp-Noordwijkerhout and the adjacent shallow part of the North Sea (Fig. 4). The most important data evaluated in this study were supplied by a transect of cored boreholes about perpendicular to the recent and ancient shoreline. The positions of the cores were selected on the basis of the results of a previous geotechnical cross-section based on Core Penetration Tests (CPTs). CPT data are useful for reconnaissance activities and may make geological mapping easier (Westerhoff *et al.*, 1987; Beets *et al.*, in press).

Supplementary data came from additional (sections of) boreholes, mostly from Geological Survey sources. Finally, a number of temporary exposures (mainly civil construction works) were studied. Only the final results of these supplementary data were used in this study, the emphasis is on the information supplied by the cores.

2.2.2. The geotechnical cross-section

At more or less regular distances of 400 to 500 m on the proposed transect, CPTs were performed to a depth of 25 to 30 m. In spite of the large number of borehole data available for the area (a drinking-water catchment area of previously infiltrated Rhine water), few of the borehole descriptions are detailed enough to allow unambiguous assignments of deeper layers to either Pleistocene or Holocene units to be made. Therefore, CPTs were performed to depths of at least 25 to 30 m, penetrating well into Pleistocene deposits, depending on the location in the cross-section (Fig. 5).

A CPT graph integrates several major lithological properties present in the subsoil *e.g.* grain size and grain size variations (including shells and gravel), packing of the grains and syn- or postsedimentary disturbances (bioturbation by animals -marine or terrestrial- or root growth). Naturally, comparable outcomes may be expected, due to the combination of different types of lithological properties. Nevertheless, the method is very useful, as it takes little time and may be indicative of the type of sediments that can be expected at a certain locality. In the CPT graphs several geotechnical units were well visible, units 3 to 6 of which belong to the barrier deposits. The sites of the CPTs are indicated in Fig. 4. The barrier section with the 7 units distinguished is depicted in Fig. 5. A summary of the geotechnical characteristics is given in Fig. 6. On the basis of this section, coring locations were selected. These sites are also indicated in Fig. 5. Another criterion for the selection of coring sites was the mutual distance. Distances should not become too large, to prevent possible coastal slopes from dune to lower shoreface from not being covered by at least two (parts of) boreholes, and to make sure that the quality of the data set would not be influenced negatively.

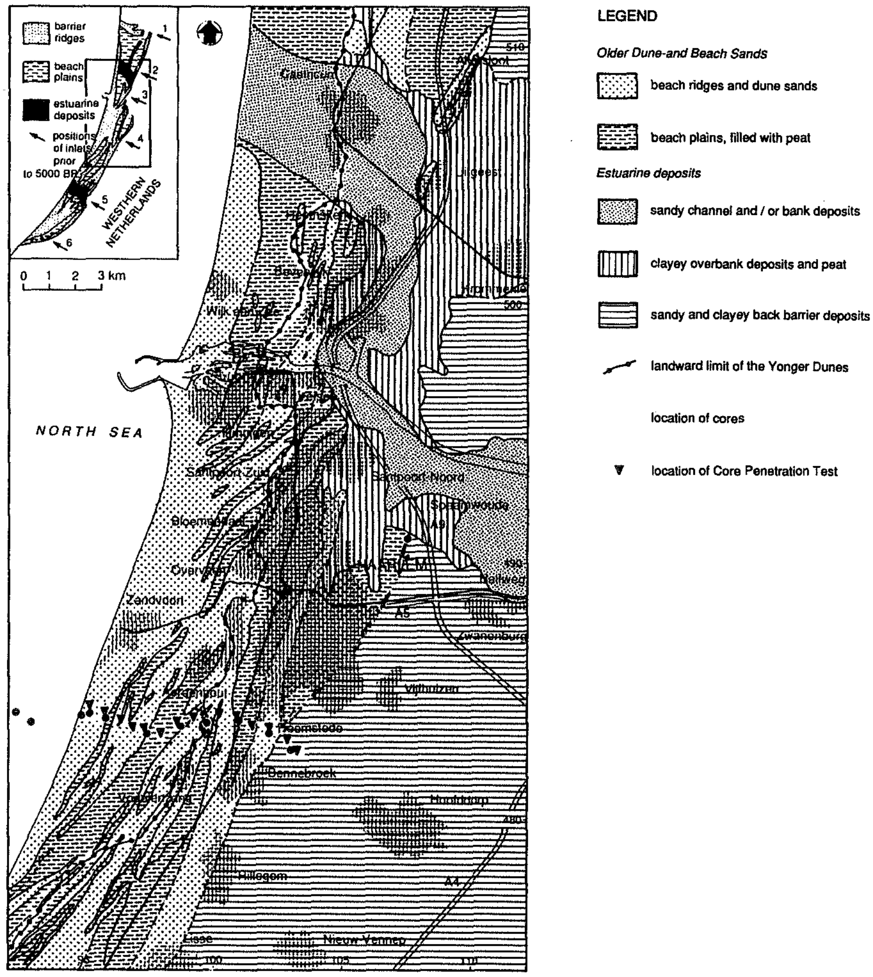


Fig. 4. Map of the Haarlem study area, showing surface geology, with Younger Dune Sands removed and the location of the cross-section. The legend "beach plains, filled with peat" incorporates also primary dune slacks with soils, especially in the northern part of this diagram from unpublished RGD data).

		generalised CPT values in MPa/m²	additional features
Younger Dunes	7	8-16 (or lower)	few exceptions
Older Dune and Beach Sands	6	8-16	highly variable
	5	west: 30-42	max. 75; occ. fall-backs to 10
		east: 16-24	max. 32
	4b	16-32	occasionnaly thin layers 4-16 and > 32
	4a	2-16	occasionally thin 16-32 layers
	3	34-50	max. 54
Older tidal deposits	2	west: 16-32 east: 4-16	both occasional higher and lower values
Pleistocene deposits	1	16-40	max. 52, occ. lower than 16

Fig. 6. Characteristics of the geotechnical units of the preparatory section. Nos 1-7: see Fig. 5. For explanation see text.

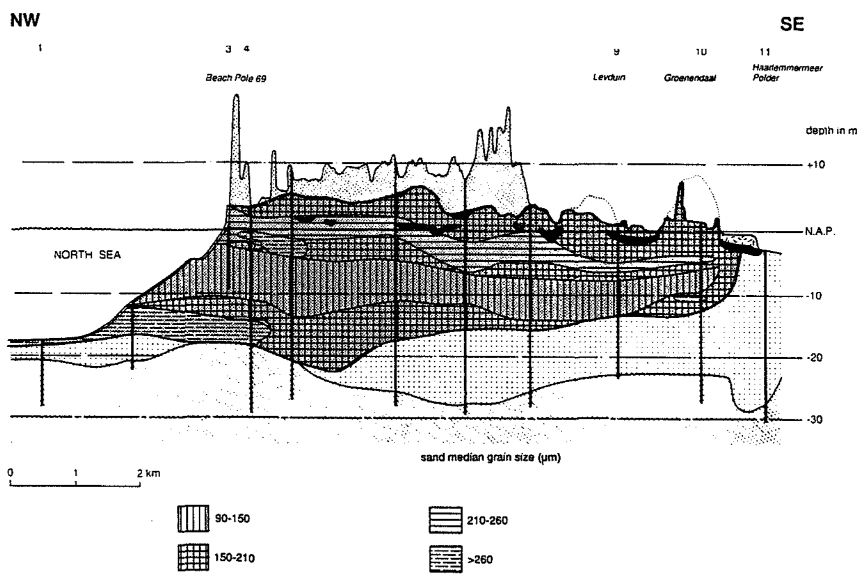


Fig.8. Average median grain size of the sands (four classes) in the Haarlem transect. For legend of background, see Fig. 3.

Few systematic variations occur amongst the general geotechnical characteristics per unit. Only unit 4 shows these variations. A gross bipartition is the result. Some smaller deviations occur in CPTs 1 (cored) and 10 (not cored). The schematic section (Fig. 5) with its units will be compared with the section with the sedimentary units (Fig. 10) in 3.2.3, in view of the relationship between lithology and CPT characteristics as mentioned above.

2.2.3. **Core acquisition**

Of the eleven cores that make up the section, nine were sunk on land and two in the coastal zone of the North Sea. The westernmost core in the North Sea actually is a shallow vibrocore supplemented by a suction borehole and the shallowest core is a suction borehole. The westernmost borehole on land was placed on the beach (Figs. 3 & 4). Except for the latter, the eight cores on land are orientated. The North Sea cores measured 7 cm in diameter, the land cores nearly 10 cm. Penetrated depths varied from 10 m in the North Sea and the beach to a maximum of 37.5 m on land. Six out of twelve cores exceed 30 m in depth. The cores penetrated all Holocene deposits and generally 2 m of the underlying Pleistocene deposits (except for core 3). An overall total of 292 m of undisturbed core material was recovered. The coring on land was done by a type of bailer boring apparatus using 21.7 cm casing. This allowed heavy steel core barrels to be lowered, fixed with core catchers. When the casing was lowered, shell samples per half metre were recovered from bailed out sediment, which was sieved using a 2 mm mesh sieve. Orientation of the cores was done by fixing a square nozzle to the core barrel, which could be directed from the surface with the help of iron pipes with a square section, of which the same side was always directed normal to the shore. The core barrel was fitted with a pvc liner and could contain cores up to 1 m in length. Average recovery of seven cores based on land was 79 %. After coring operations, gamma ray borehole logs were made. North Sea Geodoff II and cored boreholes were ship-based. The borehole on the beach was performed using a worm-wheel type of casing, on a Nordmeyer truck-mounted drilling rig. This type of core taken from underneath the casing cannot be orientated. All cores were provided by the Drilling Department of the Geological Survey.

2.2.4. **Analyses**

To preclude any damage as a result of transport, the land based cores were treated on site. After splitting the cores according to the orientation at an angle normal to the (palaeo-) coastline, the southern half was described lithologically and sedimentologically and kept for photography and storage in water-tight tubing. The northern half was used for making a lacquer peel and samples taken for grain size, diatom, molluscan, foram and heavy mineral analyses. Clay laminae and -layers were sampled for pollen analysis every half metre if possible. A more elaborate discussion of the selection of samples for pollen analysis may be found in paragraph 3.3.4. The cores were kept moist, to prevent the samples from drying out.

Of the samples retained from the bailed-out sediment, a qualitative description of the molluscan fauna was made. Later, these samples were used to select shell material for ^{14}C analysis. Whenever gravel was present in these samples, this was noted. In one exceptional case a gravel count could be performed on 3-5 mm fine gravel (*cf.* Zandstra, 1978).

Laboratory grain size analyses have been carried out on samples from boreholes 5, 7 and 9. These analyses were intended to check core-observed median grain size estimates in comparison with known sieve fractions. Grain size was determined twice every m of a core, or as often as changes in lithology required this. Conventional sieve and pipette analyses were performed, using standard procedures of the Geological Survey. In general, textural analysis results which matched grain size estimates were obtained. Total carbonate content was measured on another part of the original sample, and standard procedures of the Geological Survey were used. Separate samples were taken for macropalaeontological analysis and for diatom analysis.

From the Haarlem section boreholes, a total of 24 shell samples were collected for ^{14}C dating and analysis of the stable isotope ratios ($^{13}C/^{12}C$ and $^{16}O/^{18}O$). These were supplemented by several other samples collected in the area. Where possible, shell samples were taken from *in situ* faunas, but in most cases washed shell material had to be used. In nearby exposures it was usually possible to collect articulated specimens, but in boreholes this was impossible. The relatively large samples procured by bailing from the large diameter casing were used (see above). A selection of this material yielded shell samples of fresh habitus, generally of the bivalve *Spisula subtruncata*, specimens not having been subject to prolonged transportation (see below).

The age of the samples was determined at the Centre for Isotope Research at the State University of Groningen, the Netherlands (with the exception of one dating- not in the section but in the surrounding area-, which was performed by AMS at Svedberg Laboratory, Uppsala University in Uppsala, Sweden). The Libby half-life of 5568 years was used (0.95 x NBS oxalic acid standard). The results will be discussed in section 3.4.

Cored boreholes were described according to the legend system for logging and description of sedimentary sequences (Selley, 1970). Non-recovery zones were small and were not inferred from the core logs, but in the borehole descriptions they were considered to be similar to adjoining undisturbed parts of the core. On request, detailed sedimentary logs of the cores can be provided.

3. RESULTS

3.1. PLEISTOCENE TOPOGRAPHY AND EARLIER HOLOCENE GEOLOGICAL DEVELOPMENT

The subsoil of the area where the transect discussed here is situated, consists of continental Weichselian deposits. The surface slopes very slightly to the north (Fig. 7; De Gans & Van Gijzel, in press). The

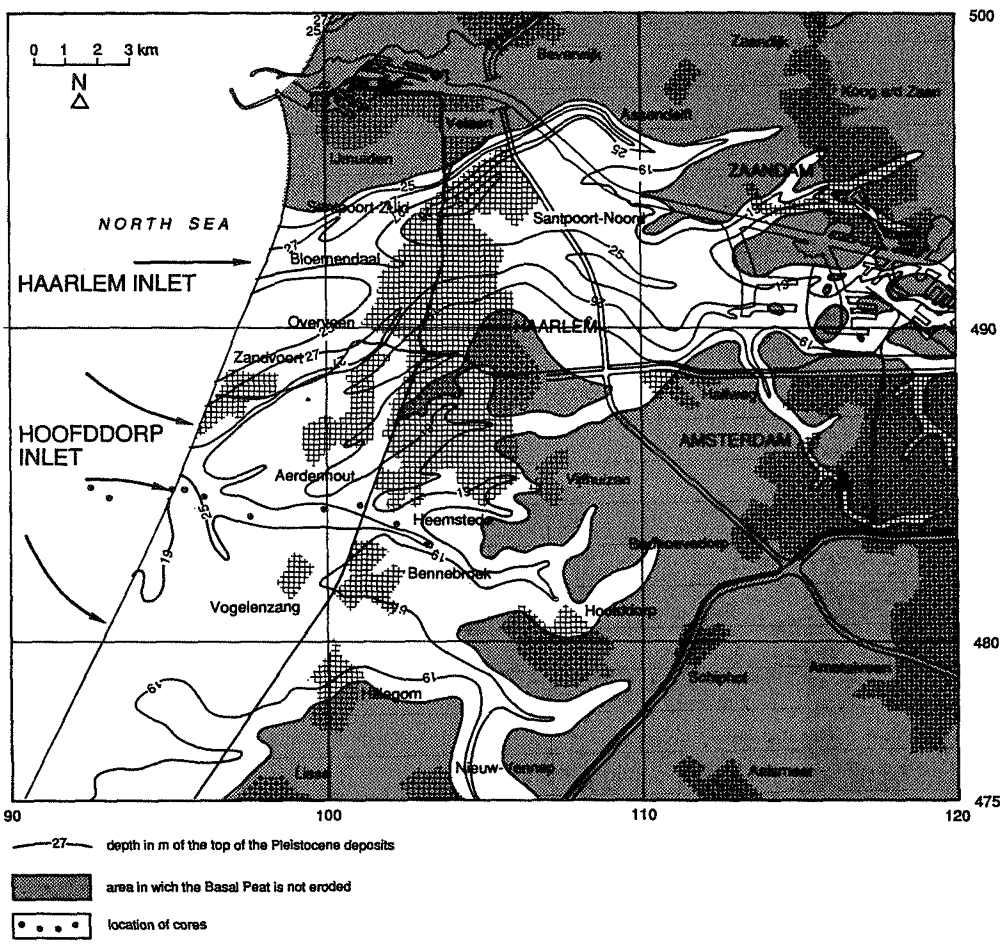


Fig. 7. Contour map of the top of the Pleistocene in the Haarlem area, also indicating Holocene erosion by channelling. Modified after Pruissers & Blokzijl, in prep.

Weichselian deposits are composed either of aeolian coversands or of local fluviatile sands. This gently undulating pattern occurs in a very large area below the mid-Holland Holocene coastal deposits. In non-eroded parts, these deposits are generally covered by a Holocene soil and the so-called Basal Peat. In the area of the section, this gently dipping and undulating pattern is cut between Lisse and IJmuiden by Holocene (Atlantic) channel fills of two tidal channels or channel complexes. Erosional activities of the channels are bounded in the north by the earlier (Boreal and Early Atlantic) Basal Peat/Velsen Clay. The channels are indicated by their scours in Fig. 7.

The southern channel sediments are situated directly below the Older Dune and Beach Sands in the cross-section (Fig. 3) and surface in the Haarlemmermeer polder area (Fig. 1; Haans, 1954). The channels have a WNW-ESE orientation. The deepest scours generally cut down to 21 m in the Haarlemmermeer area and to 25 m further west (Fig. 7). A ^{14}C dating of *Scrobicularia plana* shells (GrN 14211; Fig. 28) from about 1 m below the surface of the clay found on one of the tidal channels indicates that *c* 5,300 y BP these tidal channels had ceased major activity. The fact that the barrier sediments are found on top of the channel sands and ^{14}C dates of shells of the barrier deposits show that barrier sediments postdate these channel sands.

The second channel system is situated further north of the study area. The channel orientation is WSW-ENE. Below the northern part of the city of Haarlem, a depth is reached of 25 m, but slightly more to the west, below Santpoort-Noord a depth of 27 m is attained. The deepest scours, 32 and 35 m, occur in the vicinity of Zandvoort (Stuyfzand, 1987; Cleveringa, 1990). These deepest scours, and, in fact, all deeper parts, are filled with clay (Stuyfzand, 1987) with sand lenses in a facies, similar to the Bergen Clay (*cf.* Westerhoff *et al.*, 1987). This facies is characterized by frequent and rapid changes in sedimentation. Thin beds of shells, shell hash and sands grade rapidly into clay. The facies is associated with a period of major change in tidal volume in the inlet. It is assumed that the so-called Bergen inlet adjusted itself to the reduced tidal volume in that period (Westerhoff *et al.*, 1987).

The dating of the sediments of the more northerly channel is somewhat more problematic than the dating of the channels mentioned previously: the channel sands were not dated by ^{14}C analysis on shell material and the only other (palynological) dating (on an isolated channel fill) can be interpreted in several ways (Cleveringa, 1990; author's data). On the basis of depth and length, superposition and reconstructed palaeogeography, however, (see 4.3), it is most likely that the more northerly second channel was filled several hundreds of years later than the more southerly channel. Like the first mentioned channels, the second channels are overlain by barrier sediments. The oldest barrier crossing the channel fill is dated *c* 5,000 BP or slightly younger (see also 4.3). This indicates that both channel systems can be considered to be closely related: the second generation of channels very probably has taken over functions of the more southerly channels, but has been pushed northwards with its mouth. Exactly what process caused this shift and why the character of the fills of both channels differ considerably from each other, is discussed in section 4.3. The deepening of the more northerly channel scour is also focussed on there.

3.2. LITHOSTRATIGRAPHY

3.2.1. Introduction

In this paragraph, data on lithological and sedimentological parameters are presented. Firstly, grain size data of the predominantly sandy barrier deposits are summarized. These include estimated grain sizes and the laboratory results. Secondly, sedimentary environments of the barrier deposits are described. To conclude all lithostratigraphical information is incorporated into a facies model.

3.2.2. Grain size pattern (sand, gravel, mud)

Sand median grain size was determined every half metre, or as often as changing lithology required. This was done manually, with a grain size comparator as a standard and down to a level of 0.25 phi. The reliability of these data was tested by performing some 70 conventional (pipette and sieve) grain size analyses at the sedimentology department of the Geological Survey. The results of these analyses are in accord with the results of the manually determined mean values, which are shown in Fig. 8, generalized to four 0.5 phi grain size classes. Median grain sizes below the present-day upper shoreface were not reconstructed due to a lack of borehole data. From Fig. 8, it is obvious that the prograded series of barriers shows a consistent pattern of sand median grain sizes. Going downwards from the top of the barrier deposits, first an increase in median grain size occurs, which is followed by a general decrease. Thirdly, below this relatively fine-grained zone, another coarse-grained zone is found (only in the west: core 4) before reaching underlying non-barrier older deposits. The median grain size in the lowermost open marine deposits further east is only slightly coarser than in the deposits above. Grain size analyses revealed a bimodal grain size distribution in samples of the lowermost zones of these deposits. This pattern is also known from the barrier sediments near The Hague (Van Straaten, 1965). General grain size of the barrier sands is not very different from the underlying older Holocene tidal deposits. In the barrier sediments, however, occur many layers with well-sorted fine and very fine graded sands, which differ from the older Holocene (tidal) deposits in the immediate back-barrier environments. These layers will be discussed in section 4.2.

Gravel particles up to a size of 10 cm occasionally occur in a high beach environment as part of the barrier sediments in the area (Jelgersma, 1961; Wieland Los *in* Modderman, 1960-61). Their distribution in the present transect is from -10 m NAP up into the supratidal beach sediments. In the high supratidal storm beach environment, flat gravel shapes often prevail (Jelgersma, 1961; Van Straaten, 1991). Borehole 5 contained enough gravel particles (300) at the level of *c* -3.8 m NAP to allow a fine gravel analysis to be carried out (*cf.* Zandstra, 1978). This analysis showed that the gravel belongs to the group of Rhine Meuse samples (RM.z), indicating a

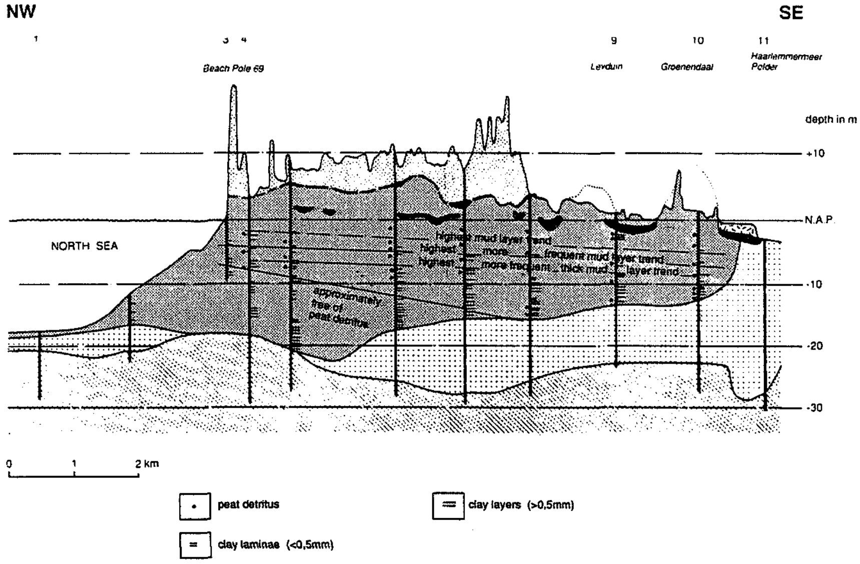


Fig. 9. Mud and peat detritus content of the barrier deposits in the Haarlem transect. Trend surfaces can be seen to rise towards the west. Note the area in the western part of the cross-section, almost free of peat detritus. For legend of background, see Fig. 3.

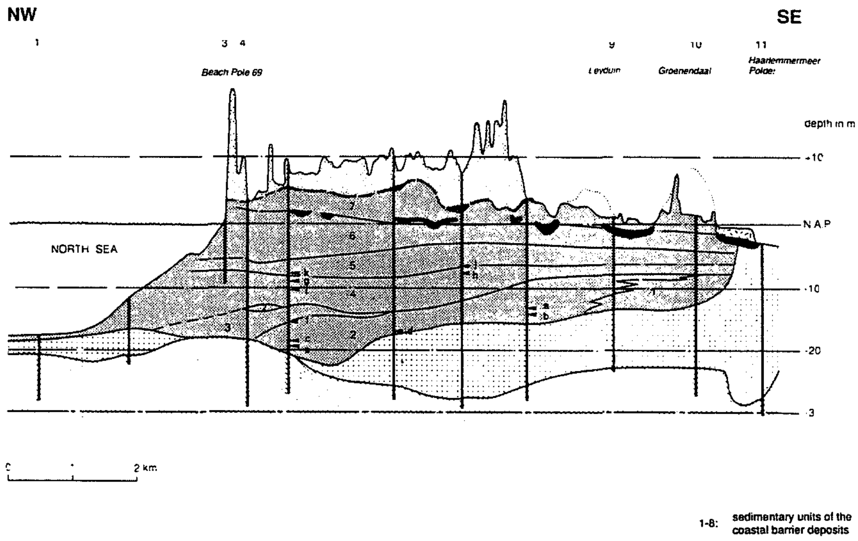


Fig. 10. Sedimentary units 1-8 of the barrier deposits of the Haarlem transect. For photographs of sedimentary units 2-5 and explanation of these photographs (marked a-k in the cross-section of Fig. 10), see Fig. 11. For a table of the characteristics of sedimentary units 1-8, see Fig. 12. For legend of background, see Fig. 3.

southern provenance. Selection according to grain size and, for the flat beach pebbles, shape has taken place in the marine environment (Zandstra, 1987). This RM.z type of gravel is known from a large area of beach barrier deposits, from the south side of the Old Rhine to some 20 km north of the cross-section (Fig. 1; Van der Valk, 1991 and unpublished data). The most probable source of the gravel is the immediate subsoil of the Old Rhine estuary, in which this type of gravel occurs in Pleistocene deposits. However, the possibility that a small portion of these gravels has been supplied by the Subboreal River Rhine cannot be ruled out.

The generalized mud content (all particles smaller than 50 μm) of the barrier sediments is depicted in Fig. 9. The frequency of mud laminae and layers preserved in these sediments is higher in the barrier sediments than in the underlying tidal channel deposits (which are not treated in this paper). Most clay layers and laminae have been preserved in the finer-grained sandy deposits (compare Figs. 8 and 9), which was to be expected. In the barrier sediments, mud has been deposited in several forms. In most cases, only thin (0.5 cm) layers occur. In the lowermost part of the barrier sediments below -10 m NAP, many mud laminae and layers of this type occur. In the east, also peat detritus is found at the same levels. Above this level, the number of clay laminae decreases. Clay deposition above the -10 m level is often accompanied by the deposition of peat detritus (Fig. 9). Another point is that the clay laminae bioturbated. Finally, a third form can be distinguished: the deposition of thick (*c* 10 to 30 cm) clay layers, presumably in the shelter of longshore bars in the 'breaker bar' facies (see below). The origin of the clay laminae and clay layers is discussed in more detail in section 3.3.4.1.

3.2.3. Sedimentary units

In interpreting the cross-section, restrictions are created by the diameter of the cores, the largest diameter being *c* 10 cm. This is certainly a point below the general depth to which construction pits are lowered in the western Netherlands: some -6 to -7 m NAP. Above this level, core data were matched with excavation data (Roep, 1984 and Roep *et al.*, 1983), but below this level interpretations were based exclusively on core data, which should be kept in mind.

On the basis of bedding structures and other criteria *e.g.* lithology and fossil content, the following eight sedimentary environmental units are defined (Fig. 10). From top to bottom:

8. Beach plain deposits (in core 9 only)
7. Dune sands with soils, gyttja and peat beds (*cf.* Jelgersma *et al.*, 1970)
6. Berm, beachface and upper shoreface breaker bar sands
5. Upper shoreface slightly bioturbated graded sands
4. Middle or transitional shoreface bioturbated graded sands
3. Lower shoreface outer sands
2. Lower shoreface and channel abandonment fine sands, silts and clays
1. Lower shoreface inner sands with some clay layers

Units 6, 5 and 4 are mainly wave-influenced, while units 3, 2 and 1 very probably are mixed wave and tidally influenced to varying degrees.

Of each unit a comprehensive description is given below (Fig. 12). Comments on the relations between these units are presented here. The sediments in the transect can be divided into two major units. The upper unit shows relatively coarse grain sizes and almost no bioturbation, while the lower unit contains varying amounts of clay and shows a variable degree of bioturbation. Generally, these two major units together form a coarsening-up sequence. The boundary between these two major units is placed at the contact between units 6 and 5. On the basis of the total aspect of these units (see below), the differences between them are attributed to differences in wave energy at the sediment surface: higher and more intense above the contact between units 6 and 5 than below it. The contact between units 6 and 5 may be regarded as the so-called daily wave base.

The contact between units 7 and 6 rises steadily towards the west, to a total of 4.5 m. This boundary is placed at the highest occurrence of shells in unit 6. It is interpreted as the upper swash limit and as such it is a sea-level marker (*sensu* Roep, 1984). The lowest levels of peat growth can be seen to follow this boundary.

The contact between units 6 and 5 first rises from -5.5 to -3.3 m to the west (cores 10 to 7) and then drops again from -3.3 to -6 m at the deepest point (cores 7 to 4). When these data are compared with lithological data, it follows that this zone is the coarsest. It contains the largest mean grain sizes and large amounts of shell material and most of the gravel occurrences. It is interpreted as the zone of breaker bars, intertidal beaches and berms. The rise and fall of this contact between units 6 and 5, needs some explanation, considering the sea level rise that has taken place during progradation of the beach barriers (see 4.1). From core 10 to core 7 the contact between units 6 and 5 follows a rising sea level in an upward direction. West of core 7, the boundary shows a drop of its level, in spite of continued sea level rise. This suggests a change in the circumstances that determine the level of the contact between units 6 and 5. This could be due to two factors: a larger tidal range or a higher-energy wave climate (or a combination of these). As Roep & Beets (1988) suggested, it is not very likely that a larger tidal range occurred during the younger third of the Holocene period, so this possibility can be ruled out, which leaves us with a change in wave climate. Although less strongly, the unit 5/4 more or less follows the same trend. The distinction between 4 and 5 is not very clear in the east, but from core 8 onwards, it can be made with confidence. Other arguments in favour of a possibly fiercer wave climate in the coastal area of the southern North Sea during the more recent Holocene will be discussed in the next section.

The relations between the lower units are more complex. The coarse-grained unit 3 only occurs in the west; the fine-grained unit 2 in the middle and eastern parts, it interfingers with unit 1. These relations will be discussed in the next section.

As may be deduced from Figs. 5 (units based on CPT data) and 10 (sedimentary units), these two diagrams are very closely related. A distinction between barrier deposits and under- and overlying deposits is easily made (see also Fig. 6). Also, the barrier sands can be divided into several units. Sedimentary unit 2 accords with unit 3 of the CPT derived data in Fig. 5. Sedimentary unit 2 with the lower part of 4a and sedimentary unit 4 (largest part) can be compared with unit 4b. Especially the upper boundary of unit 4a (Fig. 5) can be related to the upper boundary of sedimentary unit 5 (Fig. 10). This common boundary is associated with the transition between the bioturbated upper shoreface storm deposits and the generally non-bioturbated shallow truncated storm deposits (see below). Hence, it can be deduced that the bioturbation factor is an important element in determining CPT values. This has not previously been realized to this extent, as generally only pure grain-size factors are considered responsible for these values. Finally, the boundary between sedimentary units 6 and 7 (beach sands and dune sands) is not well reflected in the CPT data: the boundary between the two uppermost CPT data units is situated 1 to 2 m below this boundary. It is assumed that the abundance of shell layers in the beach sands is more decisive for the difference in CPT values than is the difference in packing of the sand grains in the high beach environment (firm) as compared to the packing in the aeolian environment (less firm).

3.2.4. Discussion

As indicated in Fig. 3, all deposits containing a open North Sea molluscan fauna are grouped as Older Dune- and Beach Sands. For the interpretation of units 4 to 7, the assignment to these deposits is no problem, as mentioned above. Units 4 to 7 belong to the same generally coarsening-up series, eventually giving rise to the prograding barrier sequence mostly under the influence of shoaling waves and intervening beach plains and/or dune slacks.

Units 1,2 and 3 require a different approach, because the status of these units is much less clear. A comparison with recent sediments at the same depth is difficult because these are poorly known. A more elaborate description of these units than that shown in Fig. 12 is required.

* Unit 3 consists of moderately coarse clean sands with few shells. The unit is found in boreholes 4 and 5 only. The general bedding type is mega-crossbedding directed towards land (Fig. 34). Figure 10 shows that the deposit thins landwards and covers the western part of unit 2, its base slowly rising in the same direction. The unit is dated at its base (Figs. 28 & 29) about 5,150 y BP. Presumably, it occurs up to 1 km further east of core 2 (CPT data: see Fig. 5).

* Unit 2 generally is a fine-grained Linsen & Flaser unit occurring in cores 5 to 9 (Fig. 11d). The lower boundary of the unit is usually well marked by a molluscan faunal change from a tidal to an open North Sea fauna (see section 3.3.5). The upper boundary is well marked lithologically, but only in the west. Here it is covered by unit 3 (core 5) or by a pronounced shell lag (cores 6 and 7). From core 7 towards the east, the upper boundary is less clear: the transition to unit 4 overlying it is gradual. In the area of core 9, units 2 and 1 interfinger. Three trends may be distinguished:

1. The sand of the Linsen is fining towards the east, possibly indicating a

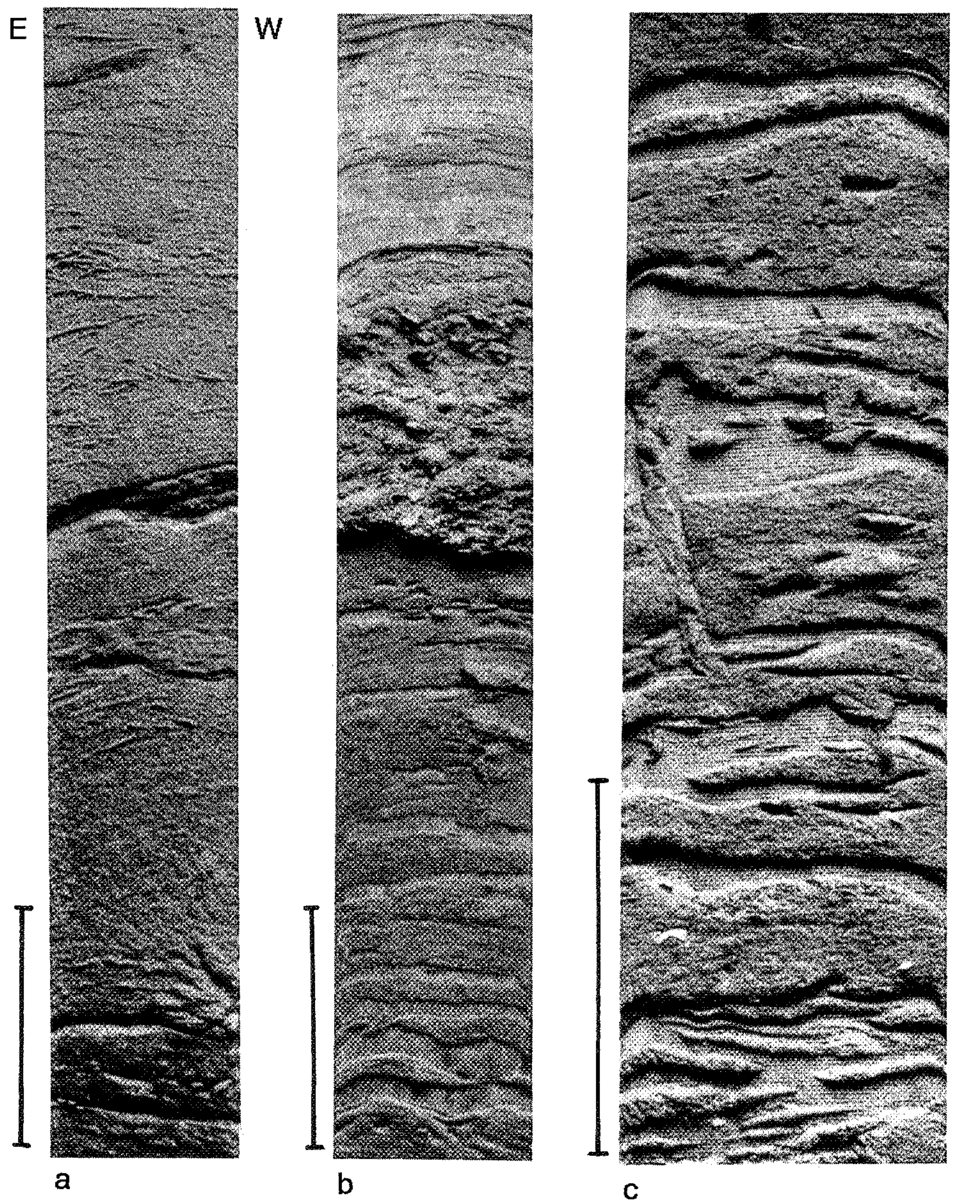
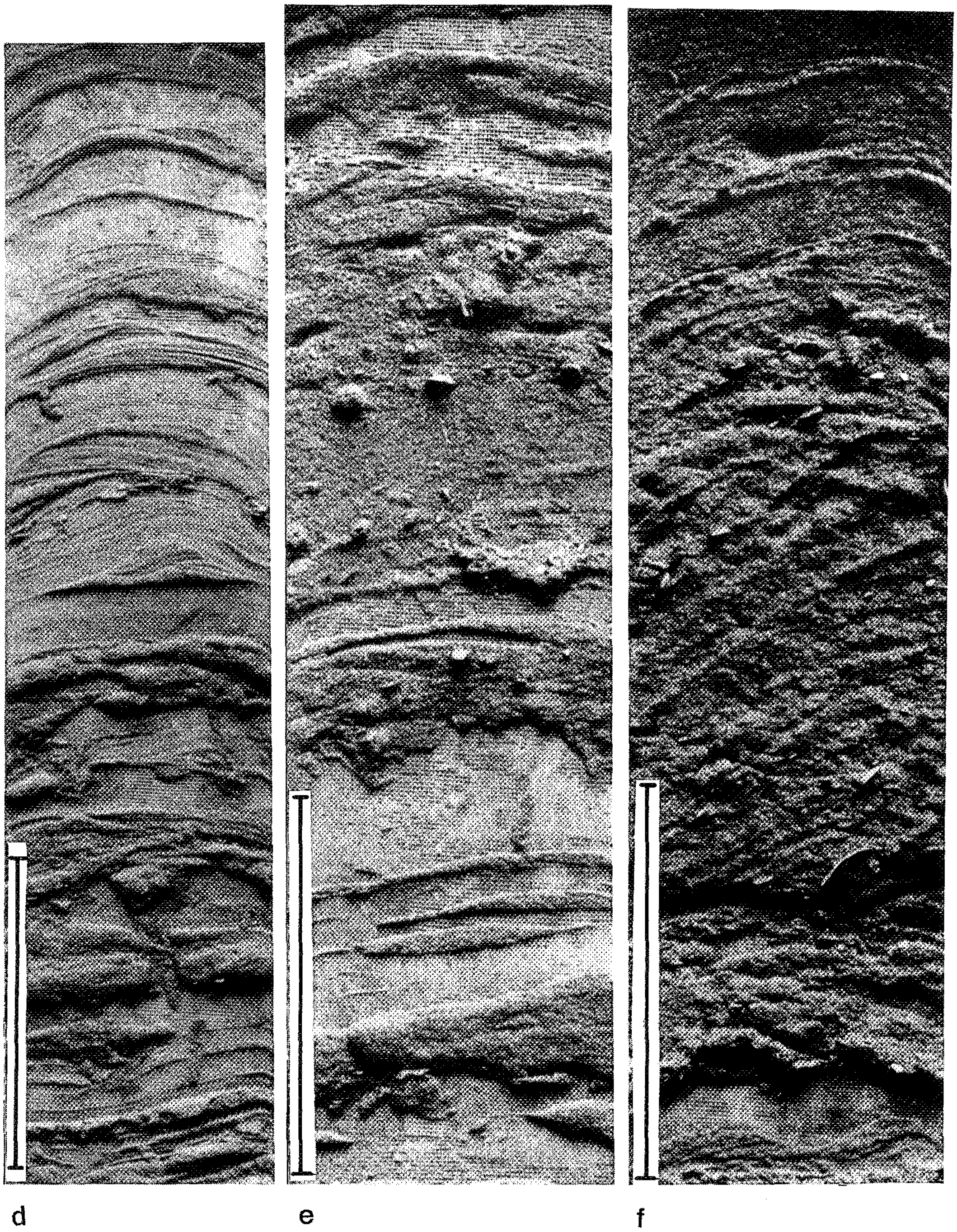


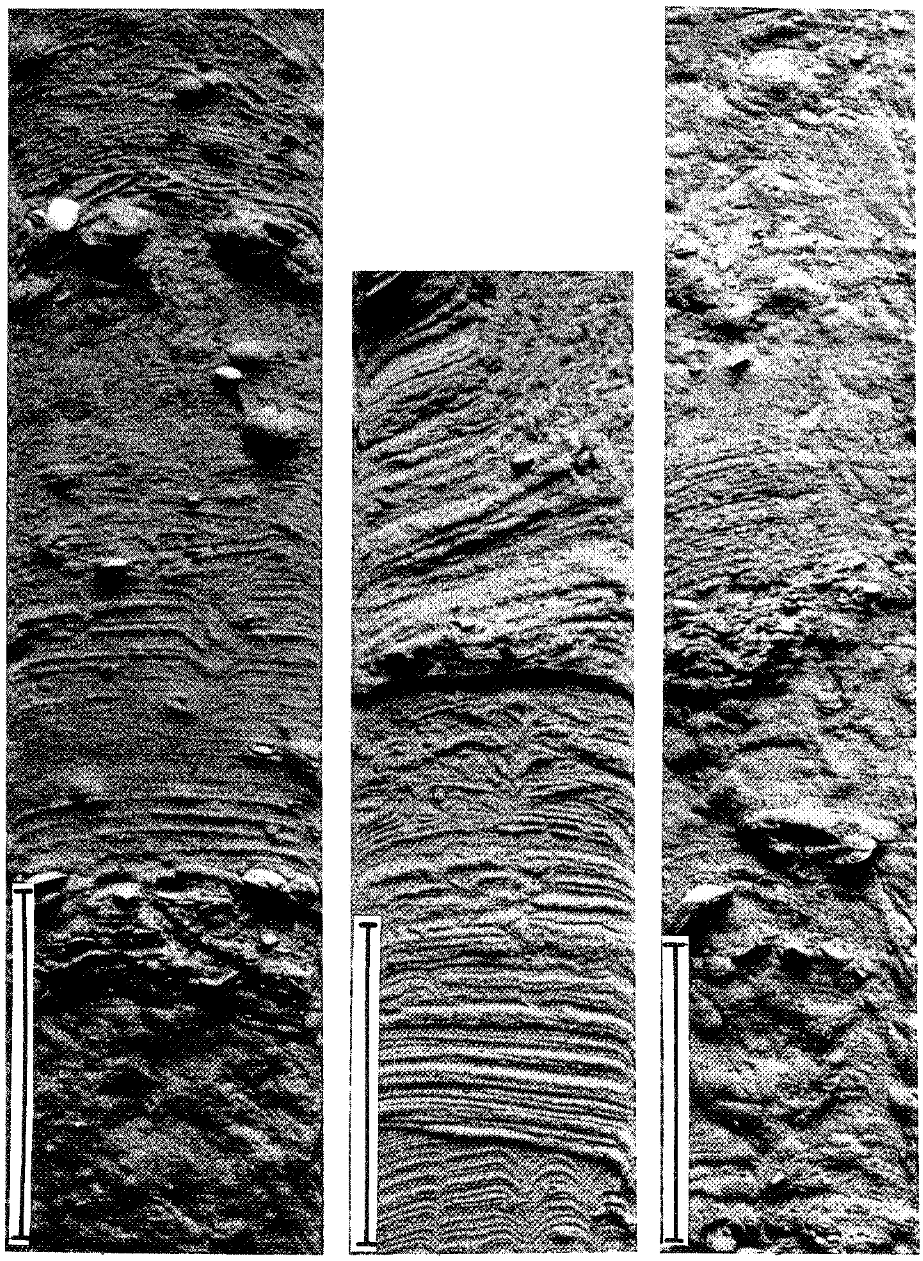
Fig. 11. Details of sedimentairy units 2 to 5 (see Fig. 10) of the barrier cross-section. RGD Photographs of lacquer peels, core width *c* 10 cm. The west is always on the right. The scale bar equals 10 cm.

Explanation of the photographs
Sedimentary unit 2 (Fig. 11a to 11e): lower shoreface and channel abandonment.
Bedding in this unit is generally small-scale (11 b-e), but occasionally composite large-scale cross-bedding is found (11a). Clay layers and laminae are sharply bounded above and below. Bioturbation is limited (11 c-e). Occasional shelly beds (11b) indicate influence of storm-wave derived winnowing. These beds occur predominantly in the eastern part of this unit. Note wave-ripple stacking in 11d (upper part).



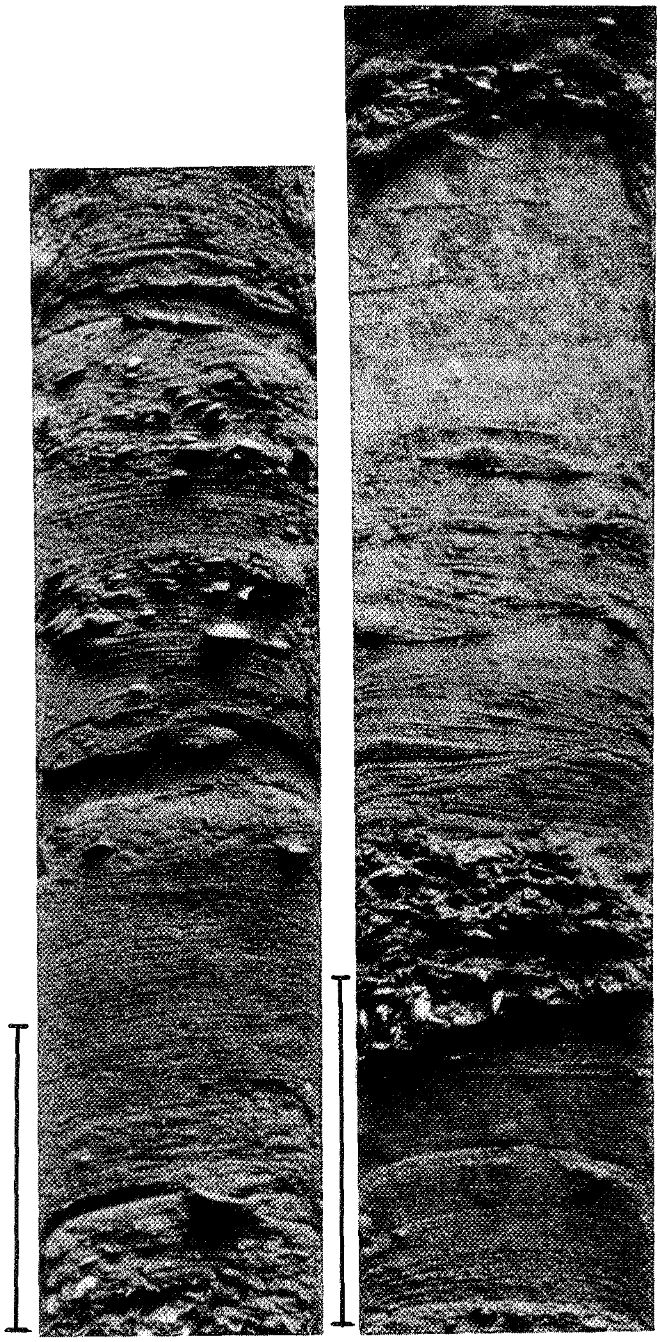
d e f

Sedimentary unit 3 (Fig. 11f): lower shoreface outer sands.
Probably mega cross-bedded sands, the base of which with a few shells is shown in 11f.



g h i

Sedimentary unit 4 (Fig. 11g to 11i): lower transitional shoreface.
This unit mostly consists of fine sandy, graded beds with a concentration of shells and shell fragments at the bases (11g and i). These graded beds are usually covered by thin, bioturbated clay layers (11g, lower part; 11i). Sometimes, low-angle cross-bedding occurs, interpreted as Hummocky Cross Stratification (11h).



j k

Sedimentary unit 5 (Fig. 11j and k): upper transitional shoreface.
This unit also comprises graded sandy beds, but of a slightly different nature. The beds in this unit show strong shell lags and a lesser degree of bioturbation in the top levels of the beds (11 j and k). In fact, the beds very often seem to be truncated by the base of the next higher-graded bed. Clay layers are also present (11k).

Unit	Description	Median sand grain size	Unit	Fig. 11
8	Plane bedded sands and clays interbedded.	180	beach plain	
7	Low angle cross bedded sands scoop shaped sets; root beds, decalcified and structureless horizons; thin gyttja and peat beds.	180	eolian sands	
6	Low angle cross bedded sands; plane bedded sets, occasional clay layers and peat detritus in lower part. Layers of shells and shellgrit; some micro cross lamination.	top: 235 basis: 180	berm intertidal beach/breaker bars	
5	Plane bedded fine sands; graded from shell beds to silts and thin clays; slightly bioturbated.	180	transitional shoreface	11 g-k
4	Plane bedded fine sands and silts; graded from shell lags to moderately to highly biotrubated silts and thin clays horizons.	120	transitional shoreface	11 g-i
3	Moderately coarse clean sands high angle cross bedded.	280	lower shoreface outer sands	11 f
2	Thin clays and wave-rippled thin sands, interbedded; extensively burrowed; in the east: sand beds interspersed.	(180)	lower shoreface and channel abandonment	11 c-d-e
1	Cross bedded sands with thin clays; thin shell beds; slightly bioturbated.	210	lower shoreface inner sands	11a-b

Fig. 12. Table of characteristics of sedimentary units 1-8 (Fig. 10) of the Haarlem cross-section barrier deposits. For the indications in the right-hand column, see Fig. 11.

North Sea provenance of the coarser sand in the west.
2. From core 7 to the east, some much coarser-grained deposits were found intercalated into this unit. Several of these deposits were recognized as storm deposits (in case they were graded). Other deposits are ungraded clean sands, the depositional setting of which is not clear. Some could be of tidal origin on the basis of the sedimentary structures.
3. There appears to be a change in the degree of wave influence from west to east. Cores 5 and 6 probably show wave-rippled sand layers. Wave-ripples are found in core 7, while further east micro-crossbedding is found, which was probably brought about by tidal action.
* Unit 1 shows micro-crossbedding with some clay Flasers, changing into a sandier facies towards the top, *i.e.* the unit shows a slight coarsening-up trend. This unit is generally sandier than unit 2. There may be a gradual change from unit 2 to 3. A basal lag is found in core 10.

It is very difficult to interpret satisfactorily the facies relationships of units 1-3. Van Straaten faced the same problem in the cross-section near The Hague. The western part of his section contained two coarsening-up sequences: an upper sequence comparable to our units 4-7 (8) and similarly interpreted as a prograding coastal barrier and a lower one. The lower coarsening-up sequence was tentatively interpreted by Van Straaten as a landward moving subtidal bar as part of a system of shoreface connected ridges.

Unfortunately, the nature of such ridges (of which there is a large field in the present-day shoreface) is poorly understood and even the internal sedimentary structures are poorly known. Currently, these ridges are being studied in detail by Van de Meene (Utrecht).

Returning to the problem of interpreting units 1-3 of the Haarlem section, the following summary may be presented:
1. The units were deposited in a North Sea setting (presence of *Spisula subtruncata*) and not in a back-barrier or (active) inlet setting;
2. The units were deposited in water deeper than the shoreface, which was situated further east at the time of deposition (see chapter 4). Correcting for sea level rise, the palaeodepth of the top of the sand of unit 3 must have been at about 9 to 12 below MSL of that time;
3. In units 3 and 2 wave activity must have played an important role (presence of wave-rippled Linsen & Flaserbedding in core 7); landward fining of sand in the Linsen & Flaser bedding; landward shift of sand of unit 3 over unit 2 and the landward mega cross-bedding of unit 3. Towards the east (cores 8, 9 and 10) the situation is further complicated by sandy influxes derived from more nearshore positions.
4. The evolution of the Dutch coastal barriers from more open tidal inlets between barrier islands (pre 5,500 to 4,500 y BP, depending on site from south to north) towards more closed barriers afterwards also implies a change in the major processes affecting the coastal sands from more tidal towards more wave activity. (N.B. an interesting parallel is at present developing in the present-day area of Zeeland !).

Units 1-3 therefore may be interpreted not only as shoreface connected ridges (Van Straaten's interpretation), but also as the seaward parts of tidal systems. Indeed, during most of the time it took to deposit this unit, the Haarlem tidal inlet was situated only *c* 10 km to the north.

For the moment there are two options to adequately describe units 3 and 2: either as shoreface connected ridge deposits or as (partly) wave reworked ebb tidal delta deposits. Preliminary data by Van de Meene (pers. comm.) do not show a landward movement of the ridges. Furthermore, ridge sands and trough sands are similar in present-day settings, except for bioturbation and a degree of sorting. These characteristics seem to be absent in our section. Here, the contrasting facies of units 3 (clean sands) and 2 (Linsen & Flaser bedding) interfinger (Fig. 10). Limited bioturbation in both units suggests rapid deposition.

These units are here interpreted to have resulted from rapid reworking by waves of ebb tidal sands. The rarity of bioturbation traces and also dead shells is in support of this interpretation (for the present-day situation in the transitional area between tidal inlets and the North Sea in Zeeland, see Craeymeersch *et al.*, 1989).

Few sequences of this type are well cored (*cf.* Elliott, 1986), which means that the sedimentology of this type of deposits is poorly known. This obviously hampers the construction of a sedimentary model. A recent analogue of the Holland shoreface should be constructed, preferably in a similar environmental setting. Fortunately, there is the 'graded shelf' model of the German Bight (Aigner & Reineck, 1982; Aigner, 1985). A major difference exists, however: the tidal amplitude in the German Bight is larger than that off the Holland coast (Hayes, 1979). In addition, the coastal morphology in the German Bight is slightly different. The German Bight is an essentially open coast consisting of a row of short and stunted barrier islands with intervening deep tidal channels. To a certain extent, a scale difference also exists. The German Bight area from barrier beach line to mainland has a width of 45 km, while the area of a Holland coast model comprises approximately only half this width. The graded shelf model of the German Bight is found in the same climatic zone, even in the same sea. This could indicate that a model, derived from this graded shelf concept with some modifications for the Holland barrier coast, would seem suitable. These modifications are:

1. the incorporation of dominance of storm influence into the genesis of the barrier deposits below the level of the breaker bars, and
2. the importance of the extremely shallow bathymetry of the southern North Sea.

Other features that should be incorporated into the sedimentary model are wave climate and position of cross-sections, as discussed below.

The wave climate (determined by the pattern of wave height and wave period) should be regarded in connection with the shallow bathymetry in the coastal area of the southern North Sea. This wave climate is generally thought to have shown only moderate changes during the Holocene. (Recent) study has revealed that subordinate changes in general wind directions and in wind strength have taken place during the last few centuries *c.q.* tens of years (Van Straaten, 1961; Hoozemans, 1990). However, long-term trends affecting coastal morphology cannot be extracted from these data. During the Subboreal, when the sea level rose from about -4 m NAP to about -1 m NAP, and the North Sea bottom was rose along, wave influence was strong. Should the same significant wave height pattern as found today have been present, this would have influenced the sea bottom much further from the coast than it does in the present-day situation (*cf.* Ribberink & Al-Salem, 1991). This could mean a significant transport of sand to the coast.

As far as the positions of both cross-sections in the barrier sequence cored so far are concerned(the cross-section studied by Van Straaten (1965) south of the River Rhine and the one studied in this paper), these are located in interfluvial position, or rather, half-way between two river outlets (and/or tidal inlets) (Fig. 1). These sections can be expected to show the strongest wave influence opposed to tidal influence. Other parts of the barrier complex, near the outlets and mostly to the south, show barrier-inlet sequences (Roep *et al.*, 1991). These sequences show a much larger influence of tidal currents (megaripple cross bedding for the bottom part).

Comprehensive descriptions of facies models of prograding barrier deposits may be found in McCubbin (1981), Reineck & Singh (1980) and Elliott (1986). All barrier sequences, whether from areas with a moderate or a strong wave climate, described in the literature have a single coarsening-up sequence in common. However, a closer look at the Mexican Nayarit sections described by Curray *et al.* (1969) reveals features resembling the sequence seen in the western Netherlands.

All barrier facies models described in the literature mentioned above emphasize the importance of storm sedimentation. For recent discussions on the origin of the so-called 'Hummocky Cross Stratified' (HCS) beds, reference is made to Leckie & Krystinik (1989), Duke (1990), Arnott & Southard (1990) and Myrow & Southard (1991). These discussions focus on the question of how ancient storms have influenced shallow marine deposits, and whether they originated under flows such as the ones observed in modern settings, or were laid down under storm-generated turbidity current conditions as suggested by geological evidence (Duke, 1990). The most recent approach by Duke *et al.* (1991) advocates that shore-normal transport of coarse bedload (*e.g.* shells) on the inner shelf and shoreface is caused by the interaction of oscillatory bottom currents and a shore-oblique bottom current driven by coastal downwelling, which is geostrophically balanced. Turbidity currents are not required to form HCS beds; waning-storm or swell waves could be responsible for much of the HCS in the stratigraphic record (Duke *et al.*, 1991). Because of the overall graded nature of individual beds of sedimentary units 2, 4 and 5 and the respective positions of these units in the barrier sediment body (Fig. 10), the Holland coast is regarded by the present author as a storm-depositional system below daily wave-base (Van der Valk, 1992).

Before the Holland coast facies model is presented in more detail (section 3.5), (bio)stratigraphical tools will be discussed.

3.3 BIOSTRATIGRAPHY

3.3.1 Introduction

Several cored boreholes were analyzed for diatom (4 cores), foram (2 cores) and molluscan contents (3 cores) for palaeoecological and biostratigraphical purposes and/or correlation. The diatom analysis was performed by De Wolf (1986, 1988). The foram content was studied by Neele (1988, 1989), while the molluscan content of three boreholes was investigated qualitatively and quantitatively by Meijer (pers. comm.), and the remainder of the bailer samples (sieved at 2 mm) of all boreholes was analyzed qualitatively by the author. Pollen analysis was also performed on all land-based boreholes. All boreholes containing barrier deposits (8 in all, of which one was not incorporated into the section because of its position several kilometres to the north at Spaarnwoude (Fig. 4) were sampled. Four boreholes were analyzed by the author and four by the palynological section of the laboratory of the Geological Survey at Haarlem.

3.3.2 Diatom analysis

As shown in Fig. 13, diatom analysis was not restricted to the barrier deposits. The underlying Calais Deposits were also included. Clays as well as sands were sampled. For methods used reference is made to De Wolf (1982) and Vos & De Wolf (1988). The results are summarized below.

Two assemblages of diatoms are distinguished, the first of which is divided into two sub-assemblages: A and B (Figs. 13 and 14) as subdivisions of the *Cymatosira belgica* Assemblage (Vos & De Wolf, 1988) and a barren assemblage C.

Sub-assemblage A is characterized by *Cymatosira belgica* (35-50 %) and the occurrence of the fragile species, *Sceletonema costatum*. Sub-assemblage B is characterized by a much lower percentage of *Cymatosira belgica* and the disappearance of the fragile species. It is remarkable that the distribution of sub-assemblage A is not restricted to the channel facies of the Calais Deposits, but occurs also in the generally, but not exclusively, fine-grained lower barrier deposits (Fig. 13).

Sub-assemblage B occurs only in less deep water in the east, but its top shows a distinct drop towards the west. Estimates of water depth at the time of formation are (in m respective to MSL at the time of deposition in Fig. 13): 0 to max. -7 m for core 9; ? to -7 m for core 7; ? to -11 m for core 5 and; ? to -18 m for core 2.

In cores 5 and 7 the barren assemblage C was found in parts. This may be explained as follows: At first, this lack of fossil diatoms did not seem to be in accordance with the expectations as all investigated strata are marine, subtidal deposits. Several factors may have contributed to this non-preservation of diatoms. Firstly, Recent North Sea bottom sediments are often devoid of diatoms. This could be due to the fact that during the growth season of the diatoms, several successive algal blooms take place which make use of the same volume of dissoluted biogenic silica. The amount of this type of silica is limited and, hence, it is re-used over and over. Deposition and preservation of diatom skeletons may become a rare event in this way in the present-day North Sea (Leewis, 1985; De Wolf, pers. comm.). Secondly, the effect could be post-depositional in the sense that diatoms may have been present at first, but have since disappeared. Rain immediately infiltrates a barrier sand body once it is deposited,

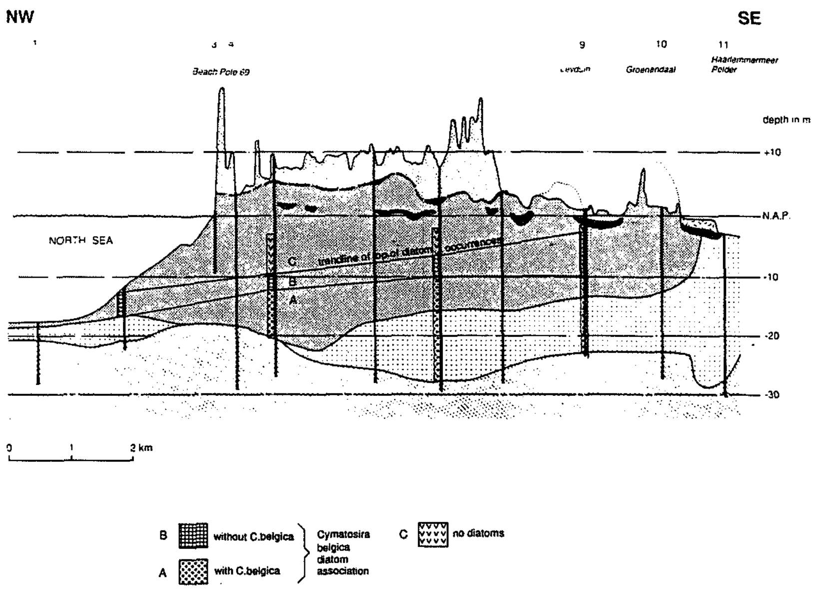


Fig. 13. Diatom zones of Mid and Late Holocene coastal deposits of the Haarlem transect. After unpublished data H. de Wolf, RGD. For legend of background, see Fig. 3.

	Zones	Main species	Accessory species	Sedimentary environment	Litho-strati-graphy
	C	(Barren)		beach barrier sands	Older Dune and Beach Sands
Cyma-tosira belgi-ca assem-blage	B	Cymatorsira belgica low or absent	Rhaphoneis aphiceras R. surirella		
	A	Cymatosira belgica 35 to 50%	Sceletonema costatum Thalassiosira decipiens	Tidal chan-nel sands	Calais De-posits

Fig. 14. Diatom zonation of Mid and Late Holocene coastal deposits in the Haarlem transect. After unpublished data H. de Wolf, RGD.

especially when coastal progradation occurs. Biogenic silica tends to dissolve rapidly in infiltrating fresh water (Zuurdeeg, 1979). This may apply more specifically to an area in which artificial replenishment of ground water takes place to compensate extraction of ground water for drinking water, as is the case in the study area. In fact, Zuurdeeg (1979), mentioned a remarkably high content of dissolved silica in ground water underneath dune areas due to 'dissolution of biogenic silica' or 'reactions of groundwater with clay minerals'. In this respect, Stuyfzand (1987) described the water type which naturally occurs in the barrier deposits of the western Netherlands. This water type contains a high amount of dissolved SiO_2. A possible source for this SiO_2 could be the biogenic silica of the diatoms in the predominantly sandy sediments.

That barrier sediments are partially barren of diatoms is thought to be due to both recycling of the biogenic silica and post-depositional dissolution by rain water, the main argument being the fact that diatoms are found in all samples of borehole 9. This borehole is situated in an area which formed part of the rapidly prograding Early Subboreal coast. A high depositional rate (with many clay layers and laminae) caused rapid burial of diatoms. This borehole is also situated beyond the infiltration area, which makes the sediments in the borehole less prone to dissolution.

This indicates that the different assemblages represent respectively :

A: deeper water, with moderate wave influence. The characteristic diatom *Cymatosira belgica* indicates the presence of considerable shallow North Sea areas (estimated depth averages 8 m below MSL because of light requirements of this species) in which the species could survive, somewhat sheltered from direct wave action as indicated by the presence of *Sceletonema costatum*. Seeing that modern percentages are much lower (H. de Wolf, Geological Survey pers. comm.), this suggests that during early progradation a much larger area of the North Sea coast was not deeper than 8 m. In view of a 4 m lower sea-level and less steep shoreface gradients (*cf.* Fig. 30) this assumption seems reasonable. It is remarkable that this sub-assemblage occurs both in tidally influenced sediments of the Calais Deposits and in the lower and older, more wave-dominated barrier sediments, which suggests few changes in living conditions for diatoms. High depositional rates can be inferred for both these types of sediment (limited bioturbation and very few infauna; see also section 3.2.

B: less deep water at first, but deeper during the later phase of coastal progradation with a stronger wave influence.

C: the result of the diffuse intermingling of two separate processes (primary non-deposition and dissolution), leading to the same result: the disappearance of biogene silica, *i.e.* diatom tests.

It follows that diatom assemblages in the barrier deposits may be better used to interpret sedimentary facies rather than provide a biostratigraphical zonation. Sub-assemblage A fossilized only when the sedimentation rate was high, as was the case during the depositional phase of the Calais Deposits and of the early barrier sands. Apparently, conditions for deposition and preservation of the diatoms did not change considerably, although the environment changed from a tide-dominated coastal inlet in a wave-dominated shallow North Sea. When the rate of coastal progradation slowed down during the Subboreal, wave action increased, which led to fossilization of sub-assemblage B. During the last phase of coastal evolution, progradation slowed down to such an extent (or even turned into erosion), that syn- or early post-sedimentary dissolution could occur. Recent silica leaching by artificial infiltration waters may have caused further dissolution of diatom tests.

3.3.3 Foraminifera analysis

Cores 5 and 7 were analyzed for Foraminifera (Neele, 1988; 1989). Core 5 penetrated only barrier deposits, while core 7 contained barrier deposits as well as older tidal deposits. These tidal deposits could be distinguished from the barrier deposits on the basis of a low degree of faunal spreading (as defined by Walton, 1952) and by a very low Percentage of Selected Sessile Species (PSSS) for the tidal deposits in comparison with the barrier deposits.

No biostratigraphical zonation could be established within the barrier deposits. This was to be expected, as barrier formation is rapid, which is why it was not to be expected that during this short period biostratigraphically important changes in the fauna would occur. However, some minor changes were visible which are as follows:

Faunal dominance (Walton, 1952) and PSSS do not show any systematic change from core 7 to core 5, nor within each core. Faunal spreading only shows a decline towards the top of both cores, but no changes occur from one core to the other. The reported changes, together with the species composition of some samples, *i.e.* 'high tidal flat/ tidal marsh' (Neele, 1988) in a subtidal position definitely point to reworking of foram tests on a large scale. These changes should therefore be interpreted as variation according to depth (or to energy level, obviously related to depth) of the individual deposits. When foram analysis results are interpreted in this way, it is obvious that there is a much more diffuse relationship between foram occurrences and depositional environment at this time scale of a mere 3,500 years. Hence, no biostratigraphical conclusions can be drawn. The number of data is considered to be insufficient. If sufficient data had been available, numerical techniques could have been applied to investigate the fossil-sediment relationships. This approach is discussed in the next paragraph.

3.3.4. Pollen analysis

3.3.4.1. *General*

The period during which the Older Dune- and Beachbarrier Sands were deposited, *i.e.* the end of the Atlantic, the Subboreal and the Subatlantic, is not characterized by significant vegetational changes in the Western Netherlands. A slightly warmer period is assumed to have occurred during the Atlantic and the Subboreal (Zagwijn, 1986). Observed changes are mainly related to human activities, but it is not very likely that these activities were reflected in the pollen deposition in the shallow North Sea at that time, which the diagrams presented here show. As a reference for the pollen zonation in the Western Netherlands, usually Zagwijn's (1986) zonation is used (Fig. 15). It will be shown that the applicability of this zonation for the diagrams presented here is limited. For instance, there is the very early occurrence of substantial percentages of *Fagus* pollen in the Early Subboreal, due to fluviatile transport from the present-day southern German area. In the classic scheme, based on aeolian transport only, *Fagus* pollen first appears in high frequencies not earlier than 3,000 BP. A slightly different approach is used at first to analyze our pollen analytical data. This analysis will then be compared with the results from the more usual approach.

3.3.4.2. *Aims*

The main reason for analysing the pollen content of the sediments was the wish to be able to establish a high-resolution (chrono)stratigraphic framework, and to compare the palynological data with other (chrono)-stratigraphic methods, especially ^{14}C analysis.

At this point it is necessary to recall Zagwijn's (1965) findings, he used changes in pollen composition of spectra from clayey beds within barrier deposits (which were related to changes in sea-currents, wave action and riverine influence) for chronological correlation within the beach barrier complex. On this he concluded that very flat gradients had existed in barrier deposits during progradation of the Dutch coast.

In order to compare ^{14}C-based gradients with pollen-based gradients, two ^{14}C samples were obtained from the western part of the cross-section at The Hague studied by Van Straaten (1965) and Zagwijn (1965) at an early stage during the present investigation . Predicted ^{14}C values were based on the flat coastal gradients, as assumed by Zagwijn (1965) and Van Straaten (1965). The results of the two samples, however, were not in agreement with the predictions. A difference of some 600 ^{14}C years emerged, the result being younger than the predicted ^{14}C age. For full results reference is made to De Gans *et al.* (in prep.). This result indicated that the concept of reconstructing coastal gradients on the basis of pollen analytic correlations on the scale previously employed (the *Ulmus* decline is not incorporated into this issue), is open to discussion.

3.3.4.3. *Methods*

Of every clay layer or lamina selected for analysis, a volume of 2 cc (in exceptional cases 4 cc) was extracted from the cores. Pollen samples were treated as follows: After coarse sieving and rinsing, acetolysis was performed along the lines described by Erdtman (1954). Clay was removed with HF 40 % . The pollen samples were studied at the Free University (4 boreholes) and at the Geological Survey (4 boreholes) by means of light microscopy techniques. In the diagrams all Cainozoic pollen types are represented by a single curve. The pollen sum is composed of 200 tree pollen (Arboreal Pollen or AP) grains, but occasionaly, when pollen contents was very low, a sum of only 150 or 100 AP grains was counted.

14C y BP (Ka)	cal AD/BC	geological subdivision		pollen zonation	pollenanalytic features	
1	8th century A.D	Late Holocene	Subatlantic	Vb2	Fagus >5%	* Mais Fagopyrum Centaura Secale
2				Vb1		Carpinus >1%
				Va		Carpinus <1%
3, 4	1100 BC, 2100 BC	Middle Holocene	Subboreal	IVb / IVa	Fagus >1% Ulmus <5% * Cerealea	
5, 6, 7	3850 BC		Atlantic	III	Alnus,Quercus dominating Ulmus >5% Pinus declining	
8	(not well known)	Early Holocene	Boreal	II	Pinus dominant Quercus,Ulmus, Corylus	
9			Praeboreal	I	Betula,Pinus	

Fig. 15. Pollen analytic zonation of the Holocene of the Netherlands (after Zagwijn, 1986).

The composite data set of relative pollen and palynomorph counts was stored in the RGD data base to facilitate uniform handling. In view of the unpredictable time resolution, no concentration counts were performed. Diagrams were plotted using RGD facilities (appendices 1-8). The species were plotted on the format of the so-called 'Holocene diagram of coastal dunes', meaning that species were grouped ecologically. In the diagrams monoletes psilate type spores values were added to the *Dryopteris-Thelipteris* type spore values, represented by a single curve. For PCA (see below) analysis, however, both spore types were kept apart.

3.3.4.4. *Results*

The results of the pollen analysis are given in diagrams (appendices 1-8). From these diagrams a zonation was not immediately apparent. As a consequence, an attempt at zonation was made using the computer program CONSLINK (Gordon & Birks, 1972, 1974) to see whether it was possible to detect any zonation by means of computer analysis. This zonation program is based on the distribution and changing frequencies of pollen. The resultant zonation (local zones per diagram) and some of the characteristics of the local zones distinguished are given in Fig. 16, while in Fig. 17 these local zones are indicated on the transect, with the exclusion of borehole 12. This borehole in the oldest barrier ridge was analyzed palynologically, but is situated *c* 9 km north of the transect, and is therefore not incorporated into the section.

From Fig. 16 it is apparent that the four easternmost boreholes may be divided into three zones, while the four westernmost boreholes show two zones each. A comparison between the zones of adjacent boreholes offers no correlations. Only sporadically do individual taxa show systematic trends in development. No further attempts at zonation were made.

In spite of these difficulties, attempts were made to establish isochrons with palynological means (*cf.* Zagwijn, 1965) in the beach barrier sands. Before discussing the results of this method, it may be useful to consider the mode of origin of the deposits from which the pollen samples were taken. All samples consisted of clay (usually sandy and occasionally slightly humic or clay with fine peat detritus). Peat detritus mainly occurs in the more easterly barriers and in the west in the barrier deposits above -10 m (Fig. 9).

In the present-day shallow North Sea there are several possibilities for deposition of clay laminae (< 5 mm) or clay layers (> 5 mm). According to Eisma (1968, fig. 54), a continuous band of some 10 km width is present in the recent North Sea, in which at least 1 % of the bottom material consists of particles smaller than 50 µm: silt-clay. This fine-grained material originates from various sources (Eisma, 1990): from the rivers debouching into the North Sea, from reworking of older Holocene fine-grained deposits along the coast or from the Atlantic Ocean and the Channel area. The total influx amounts to some 50 x 10^6 tonnes per annum. As the major topographic features of the southern North Sea Bight have not changed to a large extent since the formation of the beach barrier belt, there seems to be no reason to assume the existence of another North Sea hydrographic regime on that scale, or of a different input of fine-grained sediment. Nevertheless, some restrictions should be kept in mind when accepting the present-day situation to be the analogue of the former situation. A major factor would be a utterly different position of river outlets, but this has not been the case. The pollen contents of the samples reported upon here indicate a strong dominance of the River Rhine as a major source of fine-grained material and a very restricted influence of other sources. This is not in accord with present-day mud sources along the Belgian-Dutch coast, which are supplied primarily through Dover Strait. The proportion of River Rhine mud is estimated at 14-30 % (Van Alphen, 1990). Probably, the bay-like palaeogeography at about 5,000 y BP of the area between the present-day locations of Hoek van Holland and Alkmaar (Beets *et al.*, 1992) has caused preferential deposition of Rhine-derived mud in this area. Also, the mud supply from Dover Strait may have been much less during the Subboreal. The developments in this area during the Subboreal/ Subatlantic are poorly known.

At present, the fine-grained material is carried in suspension towards the shore and tends to stay there (Eisma, 1968). There are several explanations for the fact why this material is liable to stay in this shore zone (Eisma, 1968, 1990):

1. The residual bottom current is directed mainly to the shore;
2. The direction of the tidal current is directed mainly parallel to the shore, implying a longshore instead of offshore movement of the fine-grained material;
3. Frequently, fronts come into existence due to outflowing river waters. The lighter fresh river water is pushed over the heavier salt water of the North Sea. In the front zone between the two a concentration of suspended and floating particles is present and forms a zone of flocculation. This leads to increased settling of fine-grained sediment. River plume fronts have been observed parallel to the Dutch shore several tens of kilometres out (Otto *et al.*, 1990), and are likely to play a role in the sedimentation of fine-grained material to the east of the front;
4. A scour lag effect is operational and
5. Waves cause the fine-grained material to move shoreward (except for the upper foreshore, where daily wave activity removes any fines).

These effects are counteracted by rip currents and diffusion. Net effect of all mentioned processes is a concentration of fine-grained material near the shore in the -5 to -15 m depth zone (Eisma, 1968).

Judging from the amount of clay layers preserved in the barrier deposits, the preservation potential of these clay layers must have been high. On the other hand it is clear that certainly not every clay layer or lamina deposited, has been preserved. In that case, many more fine-grained layers should have been encountered.

Clay deposits in the beach barrier sediments are estimated to take a maximum of 10 % of the total volume of sediments. They are encountered as:

1. clay lamina, generally 2 to 5 mm thick;
2. clay layers, thicker than 5 mm and occasionaly up to 10 cm thick, and
3. bioturbated clay worked into the underlying deposits.

The description already suggests that not all clay deposits have a similar

boring no's	4	5	6	7	local zones
Alnus	high	high	incr 15-47	incr 20-30	
Fagus	5-15	incr to 10	decr 26-5	incr to 10	
Picea	0-1	0-2	absent	0-2	
Abies	0-1	incr 0-1	decr 1-0	0-2	
Tilia	very low	very low	0-1	0-1	
Ulmus	0-4	0-5	low	1-4	
Pinus	12-5	2-10	decr 7-1	3-12	2
Gramineae	high	2-13	1-10	peak 20	
Chenopod.	high	0-3	1-6	1-10-5	
Ericaceae	high	0-2	1-8	low	
Sphagnum	high	0-3	low	very low	
Polypodium	low	absent	1	decr 4-0	
Pteridium	low	5-10	0-5	2-4	
Drypt./Thel.	high	8-20	0-16	decr 27-8	
Pediastrum	high	peak 25	low	low	
Alnus	low	low	low	20, peak 37	
Fagus	incr 35	0-1	1-10	0-2	
Picea	0-1	0-1	absent/vl	0-2	
Abies	0-2	0-2	absent/vl	0-2	
Tilia	very low	absent/vl	0-2	absent/vl	
Ulmus	decr 7-3	2-5, peak 15	8-0	undul 10	
Pinus	0-6	2-10	1-12	2-9	
Gramineae	low	low	low	9-2	
Chenopod.	low	0-5	0-5	decr 16-2	
Ericaceae	low	0-2	0-4	absent/low	
Sphagnum	low	0-2	low	absent/low	
Polypodium	low	0-2	0-7	0-2	
Pteridium	low	low	low, p.7	0-2	
Drypt./Thel.	low	undul 18	undul 27	30-5-24	
Pediastrum	low	low	undul 57	0-5	

Fig. 16. Zonal characteristics of barrier deposits pollen diagrams in the Haarlem cross-section (local zones; see Fig. 17). Nos 4 - 12 at the top of the diagram refer to cores (see Fig. 17). Indicated in figures are percentages; relative criteria otherwise.

boring no's	8	9	10	12	lo-cal zo-nes
Alnus	decr 20-12	low	31		
Fagus	2-8	low	absent		
Picea	0-4	3-5	absent		
Abies	0-2	2	absent		
Tilia	very low	very low	very low		
Ulmus	3, peak 6	0-2	3		
Pinus	5-10	incr 40-50	18	poor	3
Gramineae	low	incr to 37	11		
Chenopod.	low	low	absent	in	
Ericaceae	low	very low	absent		
Sphagnum	very low	0-1	absent	pollen	
Polypodium	peak 10	0-1	absent		
Pteridium	0-2	3-5	1		
Drypt./Thel.	undul 12	incr 93	91		
Pediastrum	0-2	3-8	absent		
Alnus	11-28-20	high	decr 35-18	20-10	
Fagus	<5	<5, peak 20	0-3	absent	
Picea	0-2	undul 6	0-1	top low	
Abies	0-1	0-1	1	absent	
Tilia	peak 2	very low	very low	very low	
Ulmus	incr 0-5	0-5	decr 8-2	5	
Pinus	5	decr 11-5	4-9	6-16	
Gramineae	low	1-8	5-13	22-3-21	2
Chenopod.	low	low	decr 6-1	5	
Ericaceae	low	very low	0-1	2-3	
Sphagnum	absent	0-1	0-1	low	
Polypodium	<1	0-2	0-1	peak 5	
Pteridium	<1	incr to 5	0-1	low	
Drypt./Thel.	low	10	decr 23-10	15-30	
Pediastrum	peak 12	0-2	0-3	peak 5	
Alnus	decr 28-15	peak 70	33-13	15-32	
Fagus	8, tops abs	peaks to 15	absent	absent	
Picea	top 1	0-2	2	absent	
Abies	top 1	0-1	1	absent	
Tilia	very low	peak 3	very low	very low	
Ulmus	incr 5-13	decr 9-1	5-0	3	
Pinus	10	8-18-2-13	2-10	15-0-24	1
Gramineae	decr 15-2	2-13	2-27	incr to 15	
Chenopod.	high	1-6	5-7	3-5	
Ericaceae	low	low	0-1	<1	
Sphagnum	1	0-1	0-1	very low	
Polypodium	0-1	0-1	0-1	very low	
Pteridium	0-1	0-1	0-1	very low	
Drypt./Thel.	peak 60	decr 40-8	10-30	25-7-60	
Pediastrum	0-6	0-2	1-17	low	

origin. Of the formation of such layers little is known. Thin clay lamina may form in very short periods, a turn of the tide may suffice. For thicker clay layers other sea states, *e.g.* more prolonged quiet conditions or shelter from the waves by longshore bars, would be responsible. A period of several days or even weeks of fair weather with easterly winds could lead to thicker clay deposits in the shallow North Sea without intervening sand deposition. At present, for instance, such conditions prevail during spring and early summer. Bioturbated clays require at least one season to form (settlement and growth of invertebrates and relatively high temperatures). Wave-reworking during the story counteracts bioturbation (Aigner & Reineck, 1983).

Sampling strategy was directed at full coverage of the entire barrier belt at the 0.5 m interval in each borehole. For this reason, it was impossible to sample only one type of clay layer. All three types had to be sampled.

3.3.4.5. *Provenance of pollen*

All pollen and palynomorphs in the boreholes are of secondary origin. Zagwijn (1965) distinguished three categories:

1. pollen reworked from older deposits;
2. pollen from the mid-European continent transported by the large rivers;
3. pollen from the coastal fluviatile and perimarine plain of the central Netherlands and pollen of the coastal area occupied by beach barriers and tidal deposits.

In discussing these pollen groups, it should be borne in mind that the field of clastic palynology is a rapidly evolving science (*e.g.* Traverse, 1988). The fact that the pollen samples originate from clastic sediments, indicates that great care should be taken in interpreting them. Diagrams for the back-barrier (peat) area from the same time period as during which the formation of the barrier deposits took place, are extremely scarce (*e.g.* Witte & Van Geel, 1985). Moreover, they cannot be compared easily with the coastal dune diagrams because of different vegetational development (Jelgersma *et al.*, 1970) and the short distance over which pollen of the dune area vegetation spreads into surrounding areas (Van der Valk, 1979).

1. Pollen reworked from older deposits

Definitely Mesozoic, Cainozoic and Early/Middle Pleistocene pollen is frequently observed in the samples, but values never reach more than a few percent. Their presence is assumed to be due to reworking from older deposits outcropping at the North Sea seafloor, and to transport by the large rivers from the mid-European continent, where deposits of the appropriate age are being eroded. Another source of reworked pollen may be Eemian (last Interglacial) deposits. One of the few pollen types which was probably reworked from deposits of that age is *Carpinus*. From the diagrams it appears that *Carpinus* pollen were encountered only rarely, less than 2 %, in the samples of the older beach barrier deposits. These results are in agreement with those obtained by Zagwijn (1965).

2. Pollen from the mid-European continent

As indicated on the maps of Holocene vegetational changes in Europe published in recent years (*e.g.* Huntley & Birks, 1988) a number of tree species has experienced a marked development during the period in which the beach barriers of the western Netherlands formed. Based on pollen representation in diagrams, some tree species show rapid spreading (*Fagus, Carpinus*), other species remain in a status quo (*Abies, Picea*) and still others show a decline (*Ulmus, Tilia*). Pollen of these (and other species) have been found in coastal barrier deposits, so it can be expected that some of the developments in the hinterland are reflected in the pollen content of the coastal deposits, predating the immigration of these species to the coastal zone of the western Netherlands.

During the period of formation of the deposits from which the samples were taken, the main outlet of the River Rhine was situated some 20 km to the south. This implies that the larger part of the fine-grained deposits with its pollen content would have originated from this river, as explained above. Hence, any development in the composition of the pollen content of the River Rhine may be expected to be reflected in the barrier deposits.

Taking *Fagus* as an example, some of the problems in interpreting the pollen diagrams become obvious immediately. It is generally accepted that *Fagus sylvatica* has grown in the Netherlands since 3,800/3,500 BP (*e.g.* Janssen & Ten Hove, 1971). In the diagrams here presented, however, *Fagus* already shows continuous curves prior to 5,000 BP and between 5,000 BP and 4,200 BP at least one peak value of 20 % occurs (enclosures 1-8). Another example, again *Fagus*, may be presented for the westerly barrier sediments. In two boreholes (Flesseveld, enclosure 1; Strandweg, enclosure 3) in the post-3,000 BP part of the barrier complex, a peculiar trident saw-tooth pattern of the *Fagus* curve appears. A correlation appears self-explanatory. In between these two boreholes, however, borehole Duizendmeterweg (enclosure 2) does not show this trident pattern. Since the same sampling strategy was followed for all three boreholes, it is unlikely that the trident pattern was missed in the central borehole. This indicates that this trident should not be used for correlation purposes. A similar development is noted for *Carpinus* pollen. From 3,000 BP onwards *Carpinus* pollen is continuously present in the samples, which cannot have originated from *Carpinus* trees in the Netherlands (Janssen & Ten Hove, 1971), because this genus first appeared *c* 1,800 BP.

The conclusion may be that correlations on the basis of palynological analyses cannot be made in a direct way, even in the case of species that are known to have had an immigrational history in NW Europe in the time interval studied, and of which pollen encountered in the shallow North Sea deposits may have been originated.

3. Pollen of the mid-Netherlands coastal plain and the coastal barrier area

In the period concerned (the second half of the Holocene), an extensive marsh was present in the western Netherlands. Brackish at first, soon a freshwater marsh and after that in the areas in between the river branches, extensive 'Hochmoor' development took place. For details, reference is made to Zagwijn (1986). The vegetation bordering the main course of the River Rhine and other river branches will undoubtedly have contributed to the pollen content of the river water. Forest communities of the *Alnus* swamp forest and the *Ulmus-Fraxinus-Corylus* levee forest would mainly have been present.

A distinction should be made between pollen of the barrier area itself, involving dune-sand based floral communities and pollen from estuarine halophytic environments. Indeed, of both environments distinct elements are present.

3.3.4.6. *Numerical analysis*

General

As mentioned above, no clear pollen analytic relationships can be found between the studied boreholes on the basis of the 15 commonest species. Numerical methods may be employed to compare pollen sequences and find major patterns of stratigraphical change within and between pollen sequences from specific geographical or ecological areas (*i.a.* Birks & Gordon, 1985). Recently, Ran (1990) has shown that these techniques can also be used for palaeoecological reconstructions in clastic environments. A good reason for applying ordination techniques is to find out whether or not any important ecological variable has been overlooked (Jongman *et al.*, 1987). Even if these methods cannot be a substitute for ecological data (Birks, 1986), they can provide an insight into the causes of Quaternary biotic and environmental changes.

Therefore, it appeared promising to apply numerical techniques to try to find relations (time or origin) between the various boreholes based on palynological evidence. In view of the more or less homogeneous character of the data set, Principal Component Analysis (PCA) was applied. Use was made of the PAIS program in the MacIntosh environment, operational in the Department of Palynology and Paleo-actuoecology of the Hugo de Vries Laboratory of the University of Amsterdam. The aim of this operation was to detect whether or not similarities in species composition existed.

Results

At first sight the results were somewhat disappointing. The two principal axes only account for less than 40 % of the total variance. This low figure should be kept in mind, as it influences expressiveness of the conclusions. Nevertheless, some remarks can be made as to the distribution of the species within the three-dimensional space, the relative position of the spectra and the distibution of the spectra over the sedimentary units that were distinguished (Fig. 10).

The distribution of the species

In Fig. 18 the ordination patterns of all species used in the PCA are shown. Two imaginary axes (A and B) are drawn, based on the appearance of species points. Three genera, *Corylus*, *Tilia* and *Ulmus*, (CTU) form a cluster at the left-hand side of axis A. This axis is almost perpendicular to axis B. Along axis B the remainder of the species can be found. At the bottom part of axis B, a cluster of *Fagus*, *Picea*, *Abies* and *Potamogeton*

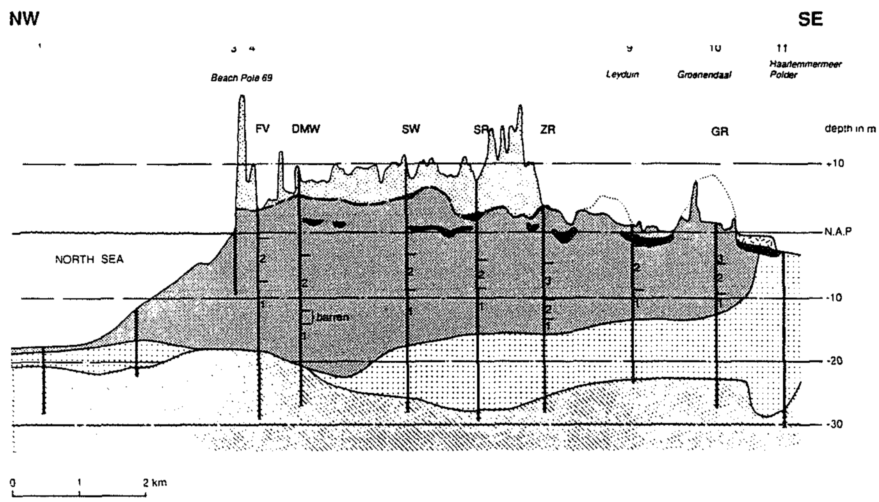


Fig. 17. Local pollen zonation (per core) of the barrier deposits in the Haarlem transect according to CONSLINK (explanation see text). Core 12 (SP = Spaarnwoude) is beyond the location of this cross-section: see Fig. 4. For legend of background, see Fig. 3.

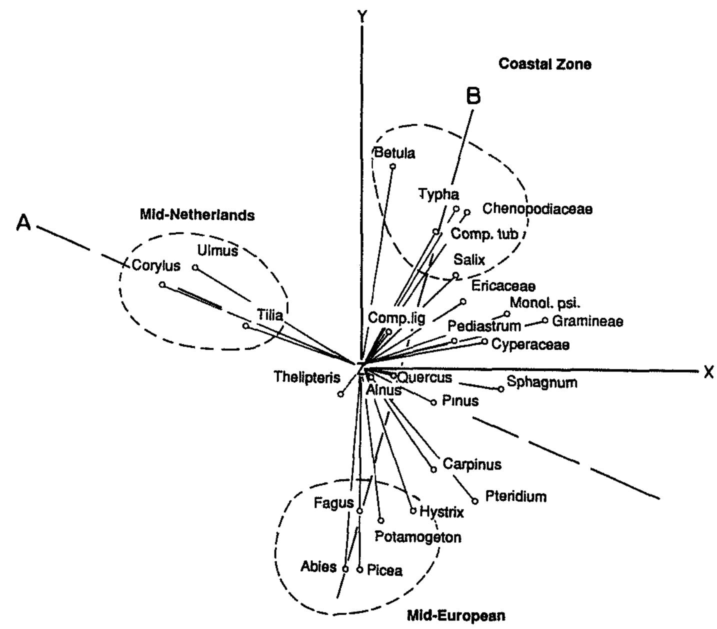


Fig. 18. Ordination pattern of pollen species involved in PCA. Z axis perpendicular to the flat geometry of the X and Y axes. See text for explanation.

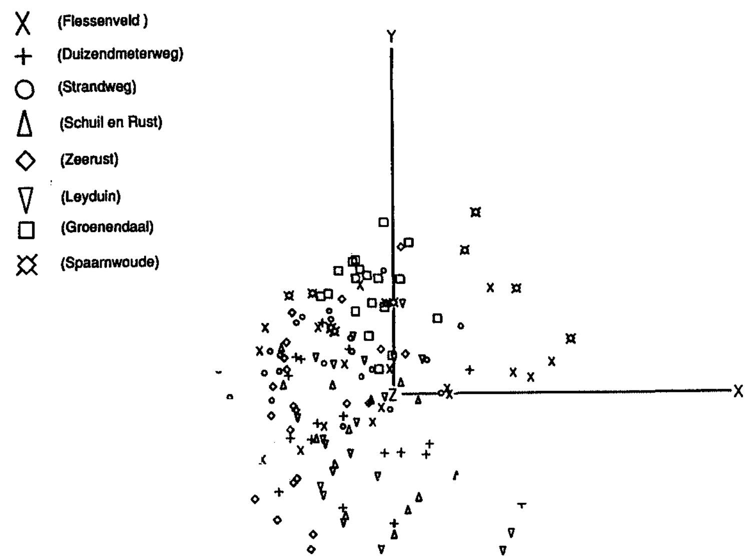


Fig. 20. Ordination pattern of spectra per core involved in PCA. Each point represents one spectrum. Z axis perpendicular to the flat geometry of the X and Y axes. Axis units spectra : axis units species of Fig. 18 = 1:4.

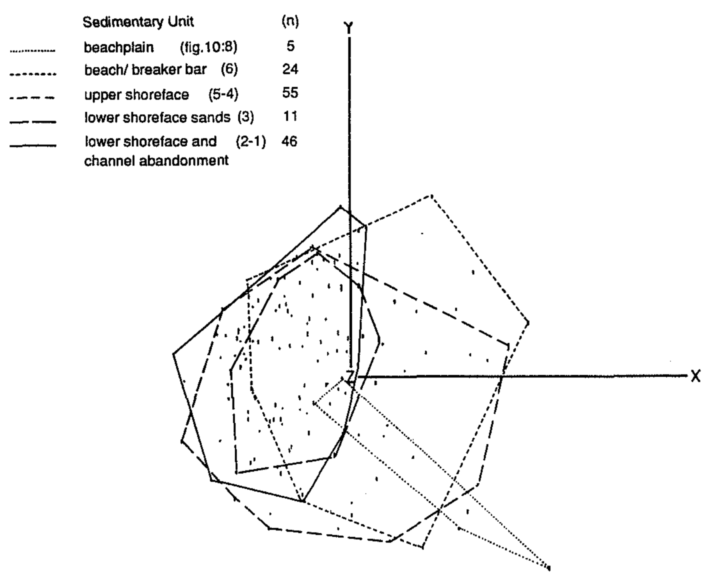


Fig. 21. Ordination pattern of spectra per sedimentary unit involved in PCA. Z axis perpendicular to the flat geometry of the X and Y axes. See text for explanation.

(FPAP) is found. On the other end of this axis a cluster is found of the herbal genera *Typha*, Chenopodiaceae and Compositae Tububuliflorae (Comp. Tub). The tree genus *Betula* and, to a lesser extent, *Salix* are thought to belong to this cluster (TCSB) as well.

On the basis of species composition per group and the configuration of the groups relative to each other, this distribution is tentatively linked to the provenance areas of the pollen of these species (Fig. 19). The CTU group of species is linked to the mid-Netherlands area. The FPAP group is linked to far-away sources, the mid-European continent. The predominantly herbal group is linked to the coastal area itself. Species present in more than one area can be seen grouped around the origin of the axes (*Alnus, Quercus*).

In view of the fact that the clusters representing the mid-European area and the coastal area are found on opposite ends of axis B they may be considered to be negatively correlated. When species of one cluster are represented by high values, the species of the other show low values and vice versa.

When axes A and B are turned slightly counter-clockwise axis A more or less parallels the first diverting axis and B parallels the second axis along which the species are diverted. Therefore, it can be concluded that the presence/absence of mid-European species is the most discriminating factor which is not influenced by other groups.

The configuration of the spectra

The ordination pattern of all spectra is shown in Fig. 20. The clustering of the spectra is conspicuous. Virtually no outlying points are present. Even when the spectra are grouped per borehole, almost no difference between boreholes is noted. Spectra of every borehole are located throughout the data point cloud in Fig. 20, the sole exception being borehole Groenendaal: spectra of this borehole are located in a restricted sector of the tree dimensional space. Within the restrictions brought about by the low percentage indicated by the first two axes, all spectra can be considered to form a more or less homogeneous cloud of data points. This explains why differences between separate spectra are so slight.

Most spectra positively correlate with the CTU cluster. In this way the species of the mid-Netherlands area are the ever-present species which have had a more or less constant input in the shallow marine depositional system. Depending on local or time-related circumstances (actual residual currents, season) pollen of one or the other group may co-occur.

The distinction of spectra according to sedimentary unit

Figure 21 represents the division of the spectra between the 5 sedimentary units distinguished in section 3.2.3. Several remarks as to this figure can be made. The beach plain facies unit is not incorporated into this discussion, because of the very few (5) spectra that lie within this group.

The outline (actually the projection of the cloud of data points on the XY plane geometry) is not influenced by the number of data points per

Local coastal area	Mid Netherlands area	Mid European area
Betula, Typha, Chenopodiaceae, Compositae tub., Salix	Corylus, Ulmus, Tilia	Fagus, Picea, Abies, Potamogeton

Fig. 19. PCA derived division of species over the three source areas.

sedimentary unit	AP mean percentage	-/+ (relative to mean percentage)	number of spectra (n = 138)
beach plain 8	70	17/10	5
beach + breaker bars 6	74	18/16	24
transitional shoreface 4-5	88	20/9	53
lower shoreface outer sands 3	84	8/9	11
lower shoreface 1-2	86	13/8	45

Fig. 22. Pollen samples from the coastal barrier deposits of the western Netherlands: Arboreal Pollen (AP) percentages vs. sedimentary units 1-8 (see Fig. 10).

sedimentary unit. There is distinct overlap of outlines per sedimentary unit in the central area (see 3.2.3). A distinction can be made between two groups of sedimentary units: one group of the two upper ones (beach and breaker bar sedimentary unit and the shoreface unit) and another group of the two lower ones ('shoreface connected ridge' sedimentary unit and the channel abandonment/upper shelf sedimentary unit). The upper group shows a far more extensive areal coverage than the lower one. The larger areal coverage is located preferentially in the sector where local, coastal species and the mid-European species are present. From Fig. 22 it is clear that the AP/NAP ratio of the beach and breaker bar sedimentary unit differs from the AP/NAP ratio of the other units. As most species of the local, coastal group are herbal species, in the beach and breaker bar unit a proportionally larger influence of local, coastal vegetation is suggested. This approach is not valid for the shoreface unit. For this sedimentary unit it is suggested that a compensation for the loss of coastal species is made by the gain of mid-Netherlands species.

3.3.4.7. *Discussion and conclusions*

No direct pollen analytic correlations between the boreholes in the coastal profile south of Haarlem could be found. Only through numerical analysis did some effects observed in the diagrams become clearer. Still, because of the low value of the percentage of variance explained by the first two axes, caution is called for. Another factor which seriously hampers the interpretation of the results, is that no actuo-palynological research has been done on the provenance and transport of pollen in the middle and lower Rhine areas (*cf.* Zagwijn, 1965).

Pollen deposition in the shallow North Sea is influenced by various factors. Observed patterns of deposition are linked to hydrodynamic circumstances, of which water depth in combination with sea state seem to be the most important. These variables are well reflected in the composition of the spectra.

This type of data, pollen samples from clastic deposits in a strongly wave-influenced environment of this period (the end of the Atlantic to the Subatlantic), is of limited value for the reconstruction of coastal gradients. However, the data do offer valuable information as to the effect of coastal dynamics on pollen deposition. For instance, it appears that not all clay laminae were rich in pollen: this could indicate deposition during the winter season, when only a limited amount of pollen is transported by the River Rhine.

A clear indication of a major change in coastal configuration viz. the shortcut of the River Rhine towards Katwijk (probably occurring shortly before 5,000 BP, *cf.* Pruissers & De Gans, 1988), is presented by the very early presence of substantial amounts of *Fagus* in the pollen curves of barrier sediments. This event has to be dated as preceding the Atlantic-Subboreal transition. The *Fagus* pollen was furnished by mid-European areas and transported by the River Rhine. The pollen was carried in suspension in the shallow North Sea and was deposited during slack waters. Preservation is due to the high preservation potential in that area. The pollen content of the samples shows that reworking from older deposits was of minor influence on its composition and that the River Rhine influence is pre-eminent.

No direct pollenanalytical correlations were observed between the cores in the coastal profile south of Haarlem. However, in the light of the discussion of pollen provenance (3.3.4.5.), a closer look at some of the curves was taken. Especially the curves of pollen types provisionally related to the mid-European continent could be of importance in this respect. The *Ulmus* curves of the diagrams of cores 8-5 show a marked decrease to below 8 % (Enclosures 5-2). The line which connects points of equal development dips in cores 9-5 from east (at about -12 m NAP) to west (at about -17 m NAP) (Enclosures 6-2). Another important genus in this respect might be *Pteridium*. The line which connects points showing the first substantial increase in values of curves of this genus, equally shows a dip from east (core 9 at - 4 m NAP) to west (core 5 at - 14 m NAP). The increase of the *Pteridium* curve can be compared with the radiocarbon isochrones of Fig. 30. It appears that this increase occurs around 4,200 BP. Tentatively, the presence of *Pteridium* spores in general may be related to human activity in the Rhine basin, more precisely to a possible change in the rural economy related to the grazing of cattle in the woods, in combination with a more mature soil development phase at that time. Unfortunately, no literature references to this subject were found, but already prior to 5,000 BP spores of *Pteridium* are found in environments influenced by man (C.C. Bakels, pers. comm.; P. Cleveringa, pers. comm.). Both factors just mentioned would have promoted a wide dispersal of spores of *Pteridium* in the soil material and subsequently in run-off and suspended matter in the rivers.

Summarizing, pollen curves of some mid-European plant genera may yield some clues as to (parts of) former coastal gradients. From the depths just mentioned it is obvious that only parts of these gradients could be found. The data from the section near The Hague (Van Straaten, 1965; Zagwijn, 1965) probably did not yield any data, comparable to the results of the present paper (apart from *Ulmus*), because barrier deposits younger than 3,000 BP do not seem to be present there.

3.3.5. Molluscan analysis

3.3.5.1. *General*

Very few authors have studied the molluscan contents of the Holocene deposits in the coastal barrier area of the western Netherlands since Van Straaten's (1965) work. Serious doubts existed about whether further research could at all contribute to a more detailed insight into molluscan faunal changes during the Holocene (Sliggers, pers. comm.). On the one hand it was thought less plausible that during the short period concerned any faunal changes could have taken place, although some molluscan species (*e.g. Chamelea striatula*) were considered recent additions to the Dutch coastal fauna. On the other hand, scepticism prevailed because of high grades of reworking of barrier shell material.

However, a renewed study of the barrier shell material was thought advisable on the following grounds. First of all, it had become clear during

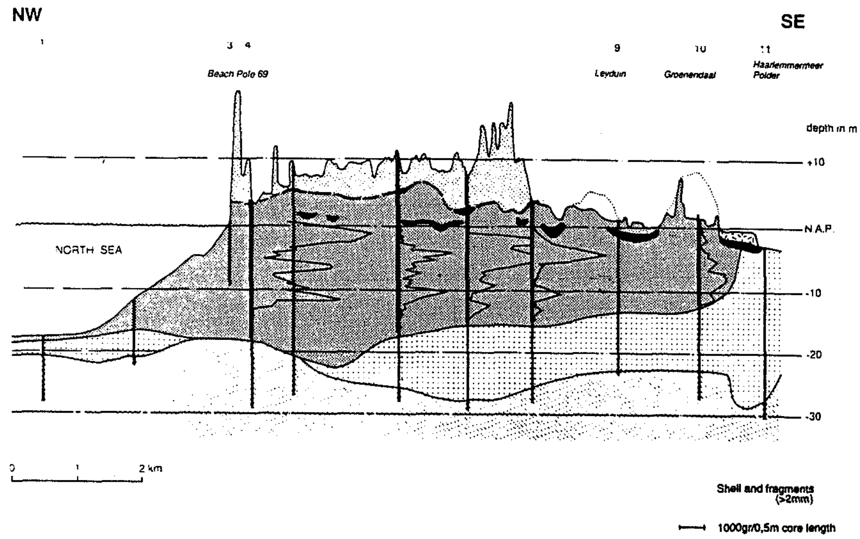


Fig. 23. Quantity of shell material (> 2 mm) per 0.5 m core length of the Haarlem transect cores. Core 5 data are not indicated on this cross-section; of core 1-3 and 9 no comparable data are available. For legend of background, see Fig. 3.

	sedimentary unit (see fig. 10)	type of shell material
7	eolian	no shells
6	berm and breaker bars	large shell concentrations especially at the base (not in the east of the barrier complex)
4-5	transitional shoreface	few to moderatelty large shell concentrations highly variable amount of material
3	lower shoreface outer sands	low shell content, few concentrations
1-2	lower shoreface: channel abandonment lower shoreface inner sands	low to moderate shell content, few concentrations

Fig. 24. Content and concentration of shell material per sedimentary unit in the barrier deposits of the Haarlem cross-section.

the preparation of this study, that faunal changes could have taken place, and in fact did so, during the Holocene, including the period of barrier progradation.

Secondly, dating of the predominantly sandy barrier deposits by means of ^{14}C analysis of molluscan shells is another important reason for studying these molluscs. Only shell material is available for dating purposes in this type of deposits. In order to provide representative dates, this shell material must have experienced the shortest reworking time possible. For this reason it was necessary to study the (variations in the) occurrence of the various species present in the boreholes and to examine the habit of several common species. In the bailer samples available, sufficient shell material for conventional ^{14}C dating (preferably more than 10 grams) was present only in the desired fresh habit of the common species (*e.g. Spisula subtruncata, Macoma balthica* and *Cerastoderma edule*). Only recently, data on the distribution of recent shell material along the Dutch coast have become available (Van der Valk & De Bruyne, 1990; De Bruyne & Van der Valk, 1991; Van der Valk, 1991). In the last named paper a comparison is made between a small-scale survey of the present-day coast and geological sections of *c* 2,000 y old deposits. The results will be used in this study.

Data were collected in various ways.

1. All 0.5 m bailer samples (about 400) were analyzed qualitatively on molluscan species composition (and other constituents);
2. During core description all identifiable molluscan species present were noted;
3. During the selection of shell material to be used for ^{14}C dating, the sieved (at 2 mm) bailer samples (which provided the shell material for the ^{14}C analysis) were checked once more for species composition (some 70 samples); and
4. The barrier deposits of three cores (5, 7 and 9) were analyzed by the macropalaeontology department of the Geological Survey (Meijer, pers. comm.).

3.3.5.2. *Absolute quantity of shell material*

As mentioned above, the total amount of material (shell, peat lumps and occasional gravel, over 2 mm) of all land-based boreholes was weighed per 0.5 m length of casing (diameter 22 cm) bailer sample. For the barrier sands of cores 4, 6, 7, 8 and 10, this total amount is indicated in Fig. 23. Some observations on the systematic distribution of this coarse material in the barrier sands will be found below:

- Based on the drilling technique applied there is no reason to assume that bailer samples are contaminated by material from above sampling depth. This is confirmed by the observation that considerable differences occur between successive samples, both in weight/volume and in species composition.
- The absolute amount of shell material generally increases from east to west, especially in the upper half of the cores (until the supratidal beach deposits are reached, which virtually yield no shells (Fig. 23). A major boundary seems to be present west of core 9; while core 6 presents a

somewhat different picture: generally there is less shell material in this core than in the cores to the east and the west;
- Largest concentrations of shell material occur above the -8 m NAP level (with a major exception in core 10).

Most specimens are not found in life position. Species found (in life position as well as in reworked state), are present-day shallow-based species of the North Sea foreshore (see De Bruyne (1990) for a recent survey). This indicates that the shell material found in the boreholes very probably represents the parautochthonous product of shell species of this foreshore. It might therefore be expected that a large number of molluscs would be present *in situ* in the cores. However, only a few levels with molluscs in life position were found in the cores, a feature also known from cores studied by Van Straaten (1965, fig. 8), and to be considered a general phenomenon. An explanation may be found in the overall character of storm-related sedimentation on the shoreface (see chapter 4).

When the distribution of the shell material is compared with the distribution of the sedimentary units (Fig. 24), it becomes clear that the major amount of the shell material is found in sedimentary unit 6 (the 'breaker bar' facies). In units 5/4, the 'upper/middle transitional shoreface', a extremely varying amount of shell material is present, the maxima of which only reach relatively high values in the most easterly core 10. These maximum values are very probably due to the erosion depth of the regressive coastline immediately to the east, causing a shelly lag deposit. When data on the distribution of Recent *Spisula subtruncata* are considered, it is not unlikely that units 4/5 present the optimum habitat of this species. Mohlenberg & Kiorboe (1981) reported that the largest specimens of this species are found only on sea floors with great water movement at 8-12 m depth, which coincides with a maximum in phytoplankton biomass. Doerjes (1979) mentioned that another typical species of the shoreface, *Donax vittatus*, has an optimum population between 7 and 14 m depth. In spite of the near-absence of molluscs *in situ* in the cross-section sediments, it can be concluded that units 5/4 are likely to represent the zone which supports many of the living molluscs, not only in the present-day shoreface, but also in ancient shoreface profiles. This unit shows the characteristics favourable for molluscan growth much more clearly than other environmental units: a fine sandy bottom, a high rate of food supply of suspended organic material of the River Rhine and propitious energy conditions.

The content and type of shell material found seems to be typical of each sedimentary unit (Fig. 24). Unfortunately, a comparison with the Recent North Sea shoreface cannot be made to a full extent as sedimentary units have not yet been defined. Only recently, has a pilot survey of the upper 12 m of the upper units been published (Van der Valk, 1991), but those data are insufficient, as the shoreface reaches down to at least -18 m NAP (De Bruyne & Van der Valk, 1991; at this depth, the break between the slope of the shoreface and the flat modern North Sea bottom is found). The pilot survey showed that live molluscs occur in a unit comparable to sedimentary unit 5/4, below the 'breaker bar' unit comparable to unit 6. Most importantly, this survey showed that the 'breaker bar' unit of the recent coast does not support molluscan life at all.

Another point need of further clarification, is the degree to which the autochthonous shell material is dispersed over the shoreface. Research into this subject is in progress (see also Van der Valk & De Bruyne, 1990; De Bruyne & Van der Valk, 1991). Available data show that the bulk of the recent shell material on the beach in the study area originates from two shoreface depth zones: roughly between 5-20 m. Only exceptionally, depending on rare high-energy conditions, does shell material found on the beach originate from greater depths (over 20 m). This general conclusion refers to the bulk of the shell material. For individual species refinements have to be made.

3.3.5.3. *Composition of shell material*

As mentioned above, all bailer samples were analyzed qualitatively. The composition of every sample was plotted on the cross-section (Fig. 26). In the barrier sediments, characterized by the presence of *Spisula subtruncata*, a total of 13 thanatocoenoses could be recognized. The composition of every thanatocoenosis is presented in Fig. 26. Considerable differences can be noted between separate thanatocoenoses. Partly these differences are due to the autochthonous production of the site, as suggested in the previous section. For another part, also mentioned above, transport processes during the formation of the barrier complex probably led to the re-distribution of dead shell material along the palaeoshoreface. Hence, the species composition of a bailer sample must be considered to represent a mixture of local and transported shells. Since the successive occurrence of especially thanatocoenoses 6 to 12 may be well correlated in individual boreholes (Fig. 26), it appears that the sample composition of each individual thanatocoenosis was determined by a common set of factors. These factors need to be reviewed, before further conclusions can be drawn. For this review, all data on the composition of shell samples of the barrier section were used (see paragraph 3.3.5.1). As a whole, the described faunas are considered part of the low-Boreal fauna, as defined by Teyling-Hanssen (1955). According to Coomans (1962), the Holland region is part of the North Sea area of the Celtic Province.

Firstly, it is noted that there is from east to west a marked change of composition of thanatocoenoses west of core 9. East of this core a mixed tidal-North Sea composition shows a distinct mixture of the shells of faunas of both tidal and North Sea environments. This mixed fauna is characterized by the presence of *Cerastoderma edule, Macoma balthica, Hydrobia ulvae* and *Spisula subtruncata*, together with a large proportion of reworked shell material from the underlying Calais Deposits. The same feature was noted by Van Straaten (1965, fig. 8). The top of core 9 carries a distinct beach plain fauna (many articulated *Cerastoderma edule*).

To the west of core 9, the general species composition more closely resembles a recent North Sea fauna. *Spisula subtruncata* is dominant and is accompanied by *Macoma balthica, Angulus tenuis, Angulus fabula* and *Lunatia* sp. Also west of core 9, a distinct increase in species richness is noted during barrier progradation. This increase occurs not only vertically towards the upper shoreface of the barrier deposits (just underneath the

No's	Species
13	S,C,M,At,Aa,D,L,(Sc),(Myt), Cham, Litt. sax
12	C(worn), S(coarse), M(coarse)
11	S,C,M,D, Mactra, L, (Cham), Bal, (Litt),(Nass),(Myt)
10	S,Aa,At,M,D,C,L,Af,Bal,Ech,(Litt), (Cg)
9	S,C,M,D,L,At
8	S,M,C,D,L,Aa,At,Bal,Ech,(Myt),(H), (Vener)
7	S,C,M(coarse),At,Mac-tra,Bal,Ech,(Litt),(Cg),(Myt),(Bar (H),(Sc)
6	S,M,C,Myt
5	M,S
4	C(juv),H,Myt
3	C,M,S,(H),(Sc),(Litt),(Bar),(Myt)
2	C,M,(S),(various reworked species) or M,C
1	(various reworked species) (+ S)

S - Spisula subtruncata
M - Macoma balthica
C - Cerastoderma edule
Cg - Cerastoderma glaucum
D - Donax vittatus
Aa - Abra alba
Af - Angulus fabulus
At - Angulus tenuis
L - Lunatia catena/alderi
Cham - Chamelea striatula
Mactra - Mactra corallina cinerea
Bal - Balanus sp.
Ech - Echinocardium sp.
Litt - Littorina littorea
Nass - Nassarius reticulatus
Myt - Mytilus edulis
Zirf - Zirfaea crispata
Bar - Barnea candida
H - Hydrobia ulvae
Sc - Scrobicularia plana
Ven - Venerupis sp.

Fig. 25. Table of molluscan assemblages 1-13 of the coastal barrier deposits of the Haarlem cross-section. For the position of these assemblages in the cross-section: see Fig. 26.

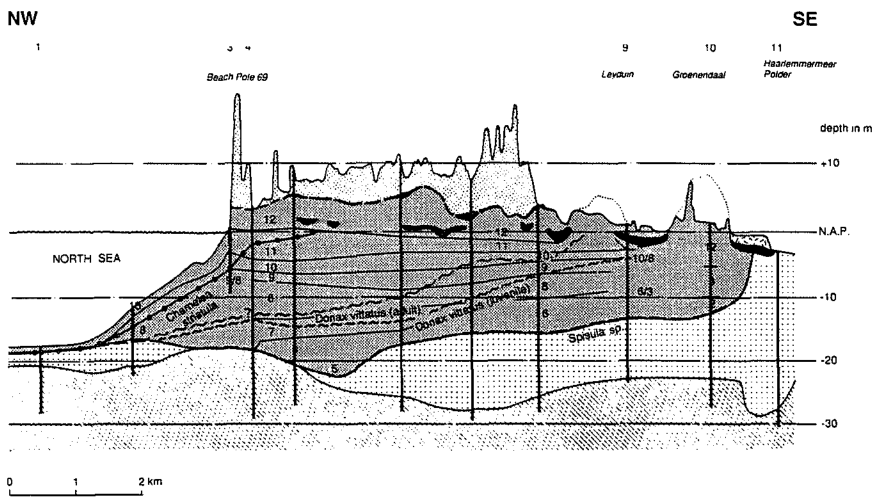


Fig. 26. The situation of the molluscan thanatocoenoses in the Haarlem cross-section and first appearances of shells of some molluscan species (lower boundaries of occurrence drawn above the species' name in the diagram) in the barrier deposits of the Haarlem transect. For an explanation of nos 1-13: see Fig. 25. For legend of the background, see Fig. 3.

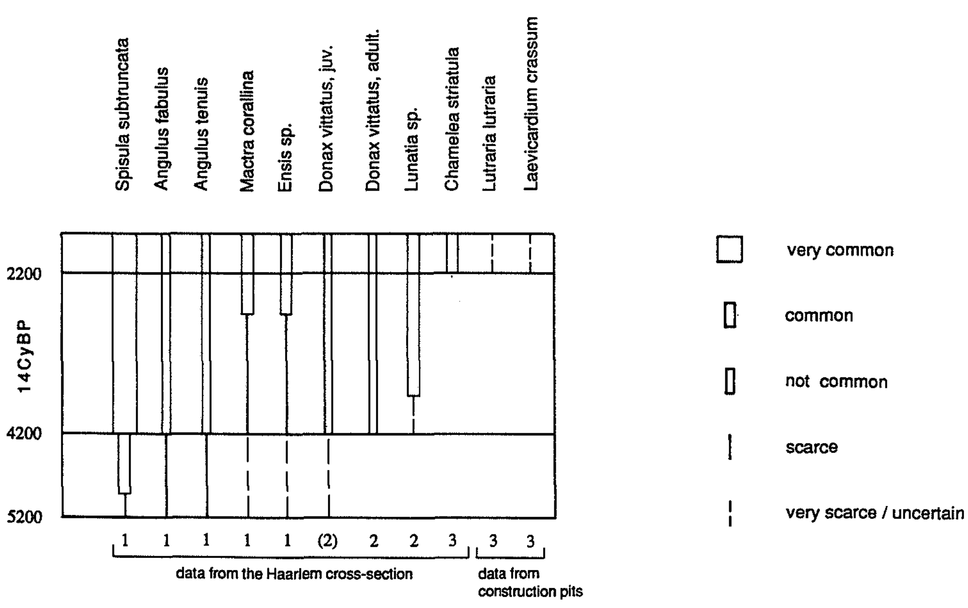


Fig. 27. Table of first appearences of molluscan species during the Subboreal and Subatlantic (Holocene) progradation of the barrier coastline in the Haarlem area. 1-3: "invasions" in order of appearance.

boundary between sedimentary units 5/4 and 6), but also laterally towards the west. Above the upper shoreface, a general decrease in species richness is observed. These trends certainly need further comment.

The barrier complex prograded from east to west during the period 5,300 y BP to at least 2,200 y BP, *i.e.* during 3,100 ^{14}C years (Fig. 30). The pattern of the ^{14}C isochrones intersects almost all facies boundaries, which means that every facies migrates to the west during barrier progradation. When the pattern of thanatocoenoses (Fig. 26) is compared with the pattern of sedimentary units (Fig. 10), it appears that boundaries of the sedimentary units and some of the boundaries between the thanatocoenoses are roughly parallel. Indeed, the thanatocoenoses boundaries are also intersected by ^{14}C isochrones (compare Figs. 26 and 30). This implies that the increase in species richness towards the top of sedimentary unit 5, which coincides with the boundary between thanatocoenoses 9 and 10, is a environment-related phenomenon. This pattern is clearer for the barrier deposits younger than 4,000 ^{14}C years than for the older barrier deposits (between 5,150 and 4,000 ^{14}C years). Obviously, this is related to the fact that the ^{14}C isochrones of the older lower shoreface deposits in the west dip less steeply and even show a slight upward shift in the west.

The increase in species richness during barrier progradation is interpreted as the effect of the changes the shoreface experienced. During the first 1,200 ^{14}C years of progradation, a transitional situation existed between the major transgressional phase of the Holocene, represented by the predominantly sandy tidal Calais Deposits, and the progradational coastal sequence of the Older Dune- and Beach Sands. A morphological change of the shoreface took place. The next 2,000 ^{14}C years the coast no longer experienced such large morphological changes at the site of the section, but it is suggested here that the system as a whole was better adapted to the wave climate of the North Sea. Arguments in favour of this suggestion are provided by combined sedimentological-malacological evidence. This will be explained in detail below.

As mentioned before, the species richness declines again above the thanatocoenosis 9-10 boundary. This phenomenon occurs from east to west, all over the prograded barrier system. This decrease in species richness is attributed to sedimentary selection processes in the 'breaker bar' and berm sedimentary unit 6 (Van der Valk, 1991). Frequent reworking by North Sea waves, even during the early progradational phase, is held responsible for these selection processes.

A confirmation of this adaptation of the North Sea shoreface can be found in the establishment of species that are well adapted to a wave-dominated environment. In fact, species common at present, show first appearances in the prograded barrier sediments. Of course, first appearances of 'North Sea' species may be earlier or later in other areas. Indications exist for an earlier appearance of 'North Sea' species for the area of Rijswijk (Van der Valk, in press), and perhaps later dates apply for the more northerly area (unpublished information Geological Survey). It follows that this type of data, essentially environmental, cannot be extrapolated along the full length of the Dutch barrier coast, but can be used in a restricted area such as the Haarlem section. A summary of the shell data from the barrier system in the Haarlem area is presented below. The dating of the first appearances is given in conventional ^{14}C years. For basal data see Figs. 28 & 29 (section 3.4).

3.3.5.4. *Conclusions*

When progradation started, the bivalve *Spisula subtruncata* first appeared in small numbers. This number grew rapidly subsequent to 5,000 BP. Shortly before 4,200 BP, juvenile *Donax vittatus* appeared for the first time, followed shortly by adult specimens of this species. A search for the first appearance of this species in the area of The Hague showed that in sediments younger than 4,000 years *Donax vittatus* is indeed present (author's data, unpublished). Another species appearing during the progradational phase is *Chamelea striatula,* at 2,200 BP. A number of other species show a certain affiliation to the three afore mentioned species. These data are summarized in Fig. 27. It follows that together with the species just mentioned, a limited number of additional species show more or less the same pattern of appearance. The overall pattern is interpreted as follows:

From 5,200 BP (the start of barrier progradation) to 4,200 BP, the palaeogeographic setting of the area changed rapidly to such an extend (the rate of sea level rise declines but still amounts to about 10-20 cm per century: Roep & Beets, 1988) that although a North Sea molluscan fauna (indicated by the presence of *Spisula subtruncata*) was already present in the area, depositional rates surpassed the adaptational possibilities of most species of that fauna, probably concommitant with a frequent change in salinity of the sea water. Only species that could survive these rapid changes did occur (*e.g. Macoma balthica* and to a lesser degree *Spisula subtruncata*). The environment was simply not stable enough to support the North Sea fauna in total. This is suggested by the analysis of the 5,100-4,250 BP spatfall fauna of core 9, in which almost all species which would appear later on the shoreface, are present (Meijer, pers. comm.). This means that settlement success was restricted to a very limited number of species. Another argument supporting this conclusion is that in the easternmost cores only a limited number of specimens of the commoner species reach maturity (Meijer, pers. comm.).

From 4,200 BP to about 2,200 BP, the North Sea fauna was able to manifest itself better. Species augmenting the fauna include *Donax vittatus*, juvenile at first, and *Mactra corallina, Angulus tenuis, A. fabulus* and most probably *Ensis* spp. Progradation was still moderately rapid. Apparently, the environment allowed settlement success: lower sedimentation rates and probably a more constant salinity. A larger number of molluscan species survived (or recolonized) on the upper shoreface.

Subsequent to 2,200 BP, still other species invaded the Dutch shoreface. In this respect, *Chamelea striatula* should be mentioned first. The settlement of this species is probably accompanied by that of *Lutraria lutraria* and *Laevicardium crassum* (unpublished data from excavations). As both last-named species are very rare, it is not clear wether these species really have the same significance as does the presence of *Chamelea striatula*. Progradation slows down around 2,300-2,200 BP (Roep, 1984), which is thought to be the main reason for the introduction of notably *Chamelea striatula*. Apparently, this species was not able to survive in the environment of a rapidly or even moderately rapid prograding coastline. The dating of this event by ^{14}C analysis corroborates the above view that the introduction of *Chamelea striatula* into the coastal environment of the southern North Sea occurred late during the Holocene.

The value of Fig. 27 might only be of local importance. This is contradicted by a the first appearance of *Donax vittatus* at *c* 4,000 BP in the area of The Hague. As these are the first data of this kind to be published, caution is due as to their interpretative value.

The significance of the faunal data presented here for the general stratigraphic framework will be discussed in section 3.5, with a comparison of the gradients established on the basis of molluscan analysis and gradients based on other evidence.

3.4. CHRONOSTRATIGRAPHY

3.4.1 Introduction

As noted in section 2.2.3, a total of 24 marine shell samples from the transect discussed in the present paper were dated by means of ^{14}C analysis. Some additional samples (including a sample of land molluscs) were taken from construction pits in an area (*c* 20 x 10 km) surrounding the transect. Details of these construction pits are not supplied here; they may be obtained from the author. The dates of these pits were used only indirectly for the construction of the palaeogeographical maps of section 4.

3.4.2. Results

The results of the ^{14}C datings are given in Fig. 28. They are grouped according to the deposit from which they originate. Dating results are given in the manner of the Groningen University Centre for Isotope Research. As the so-called reservoir effect (of *c* 400 years) about equals the isotopic fractionation that takes place in the North Atlantic (of *c* 410 years), both corrections are omitted here (Olssen,1986; Mook & Van de Plassche, 1986). Corrections for (delta) ^{13}Cwill be discussed in a separate paper (Van der Valk & Mook, in prep.).

All dating results from samples taken from the transect are shown in Fig. 29. Three additional results for organic deposits in the Older Dunes (Jelgersma *et al.*, 1970) resting on the marine deposits, were added. The results are briefly discussed below.

A comparison of dates shown in Fig. 29 indicates that all shell datings in the barrier deposits show a consistency. All samples are arranged from old to young both from east to west and from bottom to top. This is in agreement with previous general views on the origin of the barrier deposits (Van Straaten, 1965; Jelgersma *et al.*, 1970). The three added dating results (2,750, 2,510 and 2,970 y BP in Fig. 29) between dune deposits on top of the barrier sediments are in accord with the barrier dating results.

On the reliability of the shell dating results the following should be noted. Marine shell are not the most suitable material for dating purposes: various corrections are (or: should be) applied before the results can be

	Location	Borehole	Local no.	Sample no.	Coordinates	Surface (mNAP)	Depth of sample (mNAP)
	BARRIER SANDS						
1	(North Sea)	87MK290	1	-	52 24'27"N 4 30'10"E	-11.35	-12.35/-13.35
2			2				-15.35/-16.35
3	Flessenveld	24H599	1	5A	95.450 484.850	+3.64	-0.34/-0.84
4			2	7B			-2.84/-3.34
5			3	14B			-9.09/-9.59
6			4	18B			-12.99/-13.45
7			5	23B			-17.64/-18.19
8	Duizendmeterweg	24H594	1	8B	96.080 484.710	+5.68	+0.03/-0.22
9			2	14C			-5.52/-5.75
10			3	30			-18.22/-19.12
11	Strandweg	24H598	1	18B	97.640 483.990	+7.92	-9.03/-9.48
12			2	21A			-11.33/-11.83
13			3	21A			"
14			4	21A			"
15	Schuil en Rust	24H595	1	13	98.800 484.225	+8.60	-1.70/-2.50
16			2	19			-6.40/-7.40
17	Zeerust	24H596	1	12B	99.910 484.300	+3.79	-6.86/-7.26
18			2	20A			-13.81/-14.31
19	Leyduin	25C343	1	I/4		+0.95	-2.55/-2.85
20			2	II III/3	101.120 484.340		-11.05/-11.55
21	Groenendaal	25C347	1	15A	102.280 483.820	+1.40	-12.60/-13.10
	OLDER TIDAL DEPOSITS						
22	Strandweg	24H598	5	31A			-20.68/-21.08
23	Cruquius	25C346	1	11A	103.220 483.090	-2.95	-13.25/-13.75
24	Hoofddorp Overbos		1		105.650 481.650	-4.0	-5.15
25	Spaarnwoude	25C1213	3	18B	107.810 490.860	-0.37	-18.17/-18.67
26			4	27B			-27.17/-27.67
27	De Liede	25A1215	1	4B	107.740 488.075	-4.05	-7.35/-7.85
	BARRIER SANDS (OUTSIDE TRANSECT)						
28	Hillegom Oosteinde				100.570 480.960	-1	-1.96
29	Haarlem Houtplein				103.530 487.730	+1.4	-4.3
30	(Zuiderpolder) Haarlemmerliede				106.170 487.640	-0.8	-4.9
31	Spaarnwoude	25C1213	1	8B	107.810 490.860	-0.37	-8.17/-8.67
32			2	8A			-7.67/-8.17

Fig. 28. Table of ^{14}C datings in the Haarlem area, grouped according to geological unit (barrier sands etc.) and provenance sub-area. Co-ordinates of the Dutch topographical map; in the North Sea, the position is given according to the Greenwich meridian.

Species column:
1 = *Spisula subtruncata*
2 = *Mactra corallina*
3 = *Macoma balthica*
4 = *Cerastoderma edule*
5 = *Scrobicularia plana*
6 = *Cerastoderma glaucum*
7 = *Cepaea nemoralis*

Habit column:
1 = very fresh, with periostracum
2 = fresh, periostracum partially preserved
3 = fresh, neither worn, nor periostracum preserved
4 = slightly worn
5 = worn, chemically leached

Species	Habit	Grams	Sed. unit	δ 13C/14C	Age (y BP)	GrN
1	2	26	4	-0.72	1960 ±60	14222
1	2	62	4	-0.68	2210 ±50	14223
1	3-4	45	6	-0.42	2230 ±80	14196
1	3-4	33	6	-0.45	2410 ±50	14197
1	2-3	40	5	-0.87	2810 ±50	14198
1	2-3	35	2	-1.39	3750 ±60	14199
1,2,3	1-2	8	3	-1.9	5150 ±90	14224
2	4	11	6	-1.12	2320 ±80	14225
1,2	2-3	18	5	-1.07	2540 ±60	14226
1	1-2	15	2	-2.36	4910 ±100	14195
1	1-2	48,7	5	-1.88	3740 ±60	15125
1	1	38	4	-3.20	4210 ±60	14202
1	3	23	4	-1.93	4250 ±60	14201
1	5	17	4	-1.66	4260 ±60	14200
3	1-2	15	6	-2.58	3620 ±60	14193
1	2-3	40	5	-1.77	3780 ±50	14194
1	1-2	24	5	-2.83	4070 ±70	14227
1	1-2	11	2	-3.76	4820 ±90	14228
4	1	30	8	-1.93	4270 ±60	14203
1	1-2	20	1	-3.44	5080 ±50	14204
3	1-2	2	1	-5.11	5330 ±280	14231
4	2-3	38		-4.40	7010 ±120	14206
3	2	31		-4.42	5620 ±60	14209
5	1, in viva	55		-5.88	5220 ±60	14211
4	3	17		-2.73	6160 ±70	14207
4/6	2-3	70		-4.60	7050 ±70	14208
4	2-3	46		-2.47	5750 ±70	14210
1	4	40	6	-2.72	4640 ±70	14229
3	1	31	6	-5.11	4960 ±70	14230
3	1	26	6	-4.95	4780 ±70	14232
3,4,1	2-3	20	6	-3.63	5820 ±90	14205
1	1,2	0.58	6	-3.69	5295 ±105	Ua1259

(to be continued on the next pages)

(continued from the last page)

	Location	local no.	Coordinates	Surface (M NAP)	Depth (m NAP)
33	Castricum		102.960/506.040		-1.55
34	Velsen Pen Noorderweg		103.830/498.450	+5	+0.57/-0.18
35	Velsen Noordzeekanaal		104.260/497.490		-0.5 /-0.6
36	IJmuiden Haringhaven	1	100.120/497.540	+3.5	+2
37		2			+2
38	IJmuiden Spuisluis		101.810/498.500		
39	Velserbroek "boring 3"	VIII	105.870/493.440	-0.5	-3.47/-3.53
40	Velsen Huis ter Spijk		105.800/495.280		-2.3/-3.0
41	Velserbroek "boring 2"	1	106.950/494.970	-0.3	-6.54/-6.53
42	Overveen Dompvloedslaan		102.450/490.050	-0.3	-2.7
43	Haarlem Burgwal		104.225/488.025		-3.3 /-3.32
44	Haarlem Schalkwijk (FIOD)	1B	104.950/486.250	-2	-3.01/-3.03
45	Heemstede Station		101 /486	0,5	(not recorded)
46	Amsterdamse Waterleiding Duinen SXIV		96 /482	ca. +5	4-4.3 m below surface
47	Lisse boring 13				-1.64/-1.67
48	Ruigenhoek		95.050/478.600		-0.68/-0.7
49	Vogelenzang (arch. excavation)		98.800/481.440	+2	c.+0,5
50	AWD section X (AX1)	4	95 /482		-0.65/-0.72
51	AWD Droge Kom	6			+0,15/+0,16

Spec. Material	Habit	Age (Y BP)	GrN	Reference
4	1	2180 ± 35	8661	Westerhoff et al., 1987
1	2	3400 ± 55	4566	Jelgersma et al., 1970
4	1	3845 ± 45	5853	Jelgersma et al., 1970
2	3	2295 ± 40	15157	Van der Valk, 1991
7	4	2170 ± 110	16185	Van der Valk, 1991
1	1	2310 ± 35	6445	Roep et al. 1975
sandy peat		4250 ± 60	5916	Zagwijn, 1986
5	1	4190 ± 35	9041	(RGD not published)
(base of peat) slightly clayey		4735 ± 55	5664	Zagwijn, 1986
(peat)		3680 ± 40	4935	Jelgersma et al., 1970
base Phr. peat		4075 ± 35	9402	De Jong, 1984
Base of sandy peat		4200 ± 60	10921	De Jong, 1987
1 4		4125 ± 90 4040 ± 90	778 779	Van Straaten, 1965 Jelgersma et al., 1970
charcoal base soil horizon B2		2510 ± 55	4665	Jelgersma et al., 1970
Base of Phr. peat		3470 ± 60	1569	Jelgersma, 1961
Base of peat		3000 ± 65	1150	Jelgersma, 1961; Jelgersma et al., 1970
charcoal		3470 ± 60	14692	Ten Anscher, 1990
sandy gyttja		2750 ± 55	4565	Jelgersma et al., 1970
Base of peat bed		2970 ± 60	4772	Jelgersma et al., 1970

used. On the other hand, the material as such is generally available in sufficient quantities (preferably 30 g of dry weight). The availability of material was restricted, because of the fact that bailer samples (dimensions generally 0,5 m x 22 cm diameter, equalling *c* 1,700 cm^3 volume of bailed-out sediment) had to be used for the recovery of shell material for dating purposes. Each sample thus collected is a mixture of fresh shell material, possibly still articulated in the sediment, and reworked shell material representing several geological events that led to the deposition of every half m core. The amount of fresh material is generally very low. Therefore, some 70 samples were thoroughly analyzed for fresh valves of the commonest molluscan species of the barrier sands, *Spisula subtruncata*. Whenever this species was not available in the desired quantity or quality, a suitable other species was selected for ^{14}C dating. This was not preferred, however, because it was the intention to rule out any interspecific differences in metabolism between molluscan species. In Fig. 29 is also indicated which molluscan species was used for dating.

Two additional considerations in favour of the reasonable reliability of the ^{14}C data set presented here may be added.

The first consideration is the result of a test at an intra-sample level. Of five habits distinguished in the total *Spisula subtruncata* sample three (worn, slightly worn and intact) were selected and dated separately (see also 2.2.4.). The results are shown in Fig. 28 (table) and Fig. 29 (in the cross-section core 6: Strandweg). It shows that the freshest habit yielded the youngest dating result and the worn the oldest. In view of the sigma value of 60 years this result is not significant. What is significant, however, is the fact that the three samples show very small differences in dating results. This is a strong point in favour of the representativeness of the outcome, considering the potential influence of ageing through reworking of this kind of samples taken for ^{14}C analysis.

The second consideration draws on the (delta) ^{13}C measurements (Fig. 28). Large quantities of fresh water are discharged by the River Rhine along the coast of the western Netherlands. It is not unreasonable to assume that this quantity was different during the Subboreal and Subatlantic. This fresh water is likely to be of influence on the isotopic fractionation, incorporated into their shells by the molluscs through metabolic processes (*e.g.* Mook, 1971). Low values of (delta) ^{13}C , *i.e.* less than -8 ‰, could then be expected (Mook, 1971). From the table in Fig. 2, it is obvious that this is not the case. It shows that the measured values of the stable isotopic carbonate from molluscan shells in the barrier sediments barely drop below the -5 ‰ value and fall in 50 % of the cases within the limits of the range of (delta) ^{13}C marine carbonates of - 2 ‰ to + 2 ‰, as indicated by Mook & Waterbolk (1985). This again indicates that the shell carbonate was deposited more or less in equilibrium with the environmental indicators of the mollusc (Van der Valk & Mook, in prep.). Thus, the fresh water from the River Rhine had but a minor influence on the isotopic composition of the molluscan shells used for dating in this study. The shell material yields reasonable dating results which do not need substantial correction (*cf.* Mook & Van de Plassche, 1986). For further analysis reference is made to Van der Valk & Mook (in prep.).

The results of the shell datings in this study compare reasonably well with the datings on the organic levels in the Older Dune Sands (Jelgersma *et al.*, 1970). The former are ≤ 500 ^{14}C years older than the latter (Fig. 29), which is in agreement with the general views held on the formation of the Older Dunes. Datings on dune peat (2, 970 +- 60; GrN 4 772; 2750 +- 55; GrN 4565) and charcoal from an Iron Age settlement (2,510 +- 55; GrN 4665) (Jelgersma *et al.*, 1970) can be seen to post-date underlying barrier shell datings by several centuries. This is understandable, because of the history of the broadening of the dune system and the associated rise in ground water level (Bakker, 1979; Zagwijn, 1984). These datings were not used in the construction of the gradients in Fig. 30.

Finally, a remark on the density of the dated samples in the transect is called for. Care has been taken to 'cover' the transect as fully as possible. Yet, the density is not of the level that all possible dune-to-upper shelf gradients are documented by the required minimum of two dated levels. Nevertheless, it is suggested that the density is sufficient to document the geological processes behind the formation of this barrier belt. This aspect of density (equalling the resolving power of the geological model) is further elaborated upon in Van der Valk & Pool (in prep.).

3.4.3. **Coastal gradients**

The purpose of the radiocarbon analysis was to find out whether any isochrons could be drawn between the dated levels. As a first step to enable the reconstruction of former coastal gradients, simple lines were drawn between the limited number of datings that showed more or less similar results. This yielded 5 parts of beach-to-upper shelf gradients. A full set of dune-to-upper shelf radiocarbon time gradients was constructed, using these mathematical gradients and all other available datings, and interpolating between the dated levels. The section constructed in this way is shown in Fig. 30. The interval between the isochrones is 200 ^{14}C years. As may be seen, this spacing offers maximum resolving power, consistent with the +/- 1 sigma range of 180 years for most of the barrier datings.

The diagram of Fig. 30 is also briefly commented upon. Almost all isochrones could be drawn from the top of the barrier sands down into the upper shelf deposits. Most importantly, the isochrones can be seen to rise considerably towards the west, *i.e.* during progradation. Several periods of equal development can also be distinguished. The periods 5,300 to 4, 800 BP and 4,400 to 4,000 BP show wide spacing between the isochrons, indicating rapid progradation of the coastline. Contrary to this, the periods 4,800 to 4,400 BP and 4,000 to 3,600 BP show very narrowly spaced isochrones indicating slow progradation (or the sum of short phases of progradation and erosion). The period younger than 3,600 BP shows more or less regular progradation. Two periods of truncation of isochrones are observed. The first period occurred between 3,800 and 3,600 BP, and the second between 2,800 to 2,600 BP. From 2,600 BP onwards, the dip of the gradients shows a remarkable similarity to the gradient of the modern shoreface profile.

To find out whether calibration would have any influence on the ^{14}C

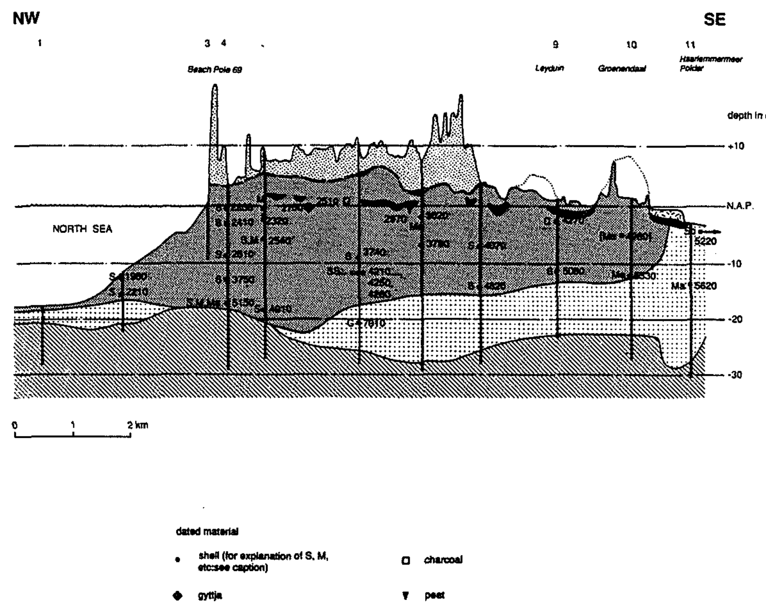


Fig. 29. Plot of ^{14}C samples of the Haarlem cross-section (material and results). For legend of background, see Fig. 3. ^{14}C data points between brackets are projected into the section laterally.
Shell material dated: S = *Spisula subtruncata,* M = *Mactra corallina,* Ma = *Macoma balthica,* Sc = *Scrobicularia plana,* C = *Cerastodera edule*

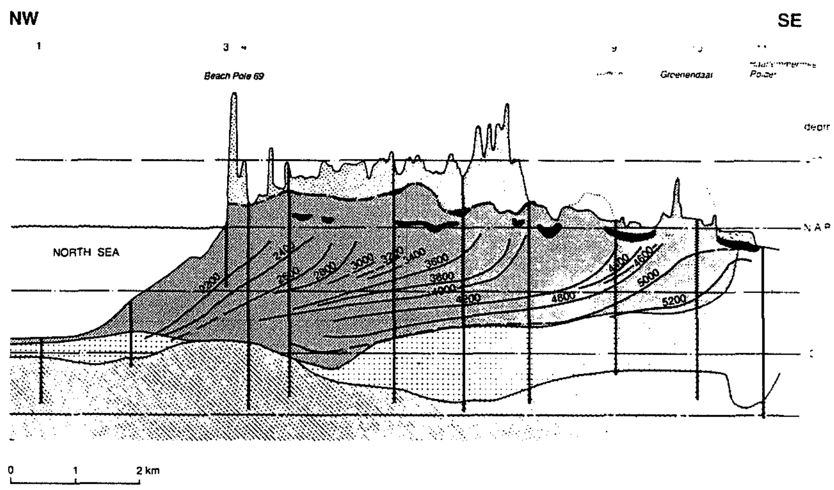


Fig. 30. Inferred ^{14}C time gradients (200 ^{14}C years interval, not calibrated) in the Subboreal and Subatlantic (Holocene) beach barrier deposits of the mid-Holland area. For legend of background, see Fig. 3

gradients, all datings of the Haarlem transect were calibrated, using the Pearson & Stuiver (1986) calibration set, as implemented for computer calibration by Van der Plicht and Mook (1988). After plotting the values provided by the computer program, it appeared that no effect (steepening or flattening) whatsoever was visible in the gradients, that could be plotted between the calibrated values. Therefore, gradients based on the conventional ^{14}C ages (as described above) are illustrated here.

3.5. THE STRATIGRAPHIC FRAMEWORK

When Figs. 8 (average grain sizes), 11 (sedimentary units), 13 (diatom zones), 25 (molluscan assemblages/first appearances) and 30 (inferred coastal gradients) are compared, it appears that these diagrams can be divided into two categories.

The first category is characterized by generally flat, undulating or slightly sloping boundaries between the distinctive units, with reference to:

1. average grain size (Fig. 8)
2. sedimentary units (Fig. 11)
3. diatom zones (Fig. 13) and
4. molluscan assemblages (Fig. 25).

The second category shows surfaces that are inclined towards the present-day coastline, with reference to:

1. first appearances of molluscan species (Fig. 25) and
2. ^{14}C isochrones (Fig. 30)

Since the latter category refers to the time aspect in the Haarlem transect, a few remarks are here added. To start with, the first appearance of molluscan species is a matter of suitability of the environment rather than time during the Holocene. Nevertheless, because of the restricted area dealt with herein, it may in this particular case be considered a time-related aspect. Consequently, lines drawn under these first appearances, can be compared directly with the ^{14}C isochrones, which are considered to be of prime importance in the establishment of phasing of the coastal barrier progradation. The two sets of gradients show a comparable development. The oldest gradients are both relatively flat, while younger gradients show progressive steepening.

Second category gradients cut first category boundaries. This is, generally speaking, an indication of a time-transgression of first category items (average grain size, sedimentary units, diatom zones and molluscan assemblages), *i.e.* they are environment-related. Because of the general steepening of the gradients of category 2 to the younger side, it can also be concluded that the depositional environment of the coastal zone of the southern North Sea occurs, between 5,300 BP up to at least 2,600 BP. Subsequently, coastal gradient presumably did not change considerably (see 3.4), although progradation continued at least up to 2,200 BP (Fig. 30).

4. RECONSTRUCTION OF THE MID-HOLLAND COASTAL EVOLUTION DURING THE LATE ATLANTIC, SUBBOREAL AND EARLY SUB-ATLANTIC.

4.1 THE RECONSTRUCTION

The reconstruction of large-scale coastal development of the Dutch coast is not just a matter of a single-section approach. Recent papers on this subject matter have focussed on the interference of progradation of the beach barrier complex with the development of tidal inlets (Beets *et al.*, 1992; Roep *et al.*, 1991). In these papers the Holocene coastal evolution is discussed in a more general way. From such an approach it is clear that the Haarlem section is situated in an area with several tidal inlets (Fig.1), which, in due course, will all be closed as a result of filling-in of the tidal areas behind the barriers (Beets *et al.*, 1992). These processes of shifting and closing of inlets started *c* 5,300 BP (Hoofddorp inlet) and continued up to *c* 2,000 BP (Haarlem inlet; Oer-IJ inlet) in this area. Hereafter, this part of the Holland coast was no longer interrupted by inlets, and prograded only slightly, presumably until Roman times (Zagwijn, 1986; Westerhoff *et al.*, 1987). This more general line is supplemented with detailed palaeo-geographical maps (Fig.32a-g) representing the period during which the most important changes in the coastal area were related to tidal inlet activity, from *c* 5,600 BP 'open channel' to *c* 4,250 BP. Around the latter date the influence of tidal inlet activity on the cross-section studied here had virtually ceased, since the inlet was situated some 20 km to the north. The maps focus on shorelines and shoreline changes, but a variety of other data were also taken into account, mainly taken from the literature, but also from unpublished sources (author's data and Geological Survey data). The reconstructions given here are tentative, and sometimes somewhat speculative, but the sources justify in our opinion the chosen time interval of 200 radiocarbon years. This interval was chosen because a) it is the time-span recorded in radiocarbon datings and b) the presumed changes occur so rapidly that another larger time interval would not be helpful in understanding of what might have happened during the period 5,600 BP-4,250 BP.

Around 6,000 BP a large tidal inlet with a channel depth of 20 m existed in the Zandvoort-Heemstede-Hoofddorp area (the Hoofddorp inlet). Fig. 32a shows the presumable 5,600 BP situation: the Hoofddorp inlet is about to be closed. Adjacent coastal inlets are situated some 20 km to the south (Pruissers & De Gans, 1988: Warmond), as well as to the north (Westerhoff *et al.*, 1987: Uitgeest). The situation of the Hoofddorp inlet changes rapidly. Most importantly, the rate of sea-level rise declined rapidly (Jelgersma, 1961; Van de Plassche 1982). Subsequently, the southern transgressive chenier-type barrier coastline is forced inland, and rapidly grows to the northeast as well, presumably due to a strongly developing longshore drift, following the northward displacement of the southern shore of the Haarlem tidal inlet. This inlet then probably took over part of the tidal area from the Hoofddorp inlet about to be closed. Simultaneously, the northern shore is forced backwards. The eroded sediment is carried inland.

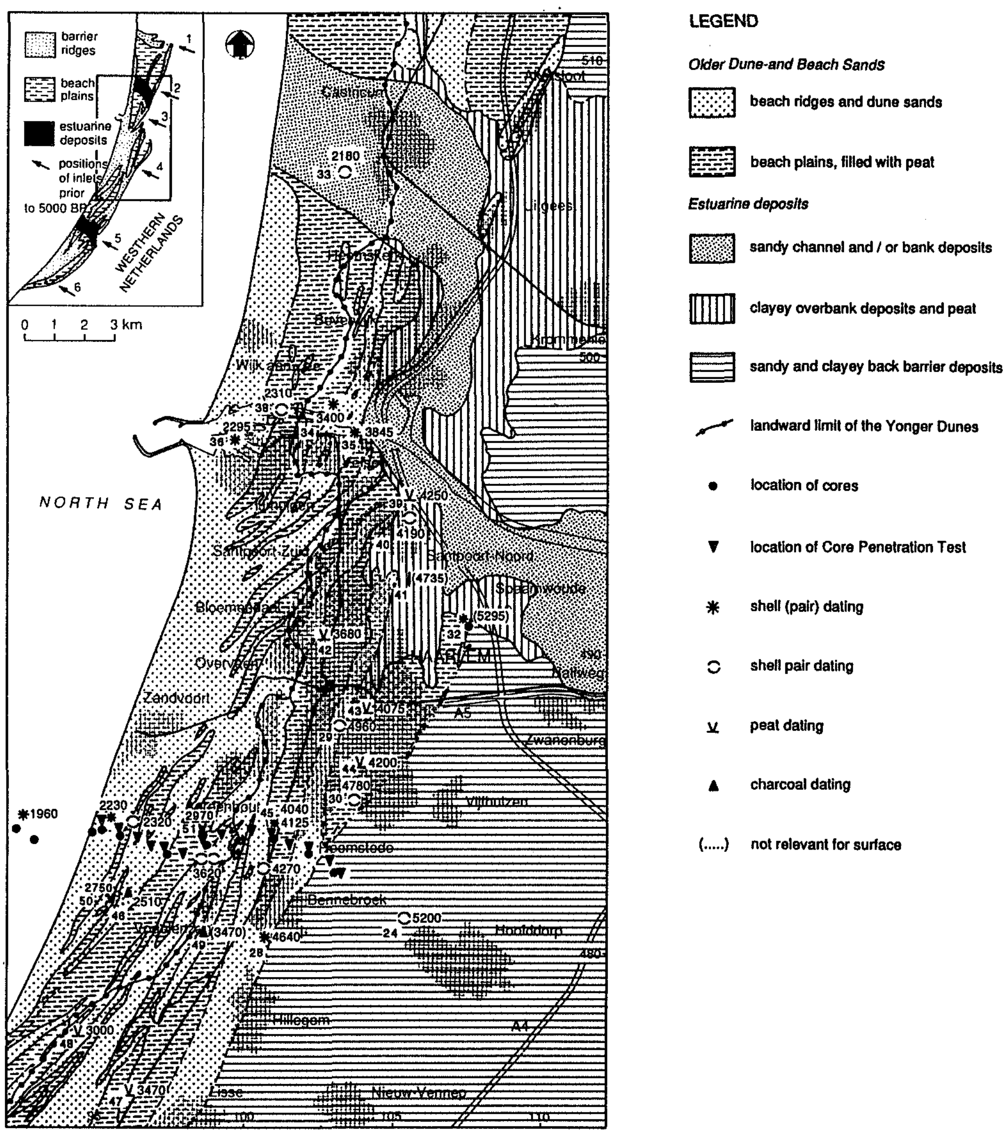
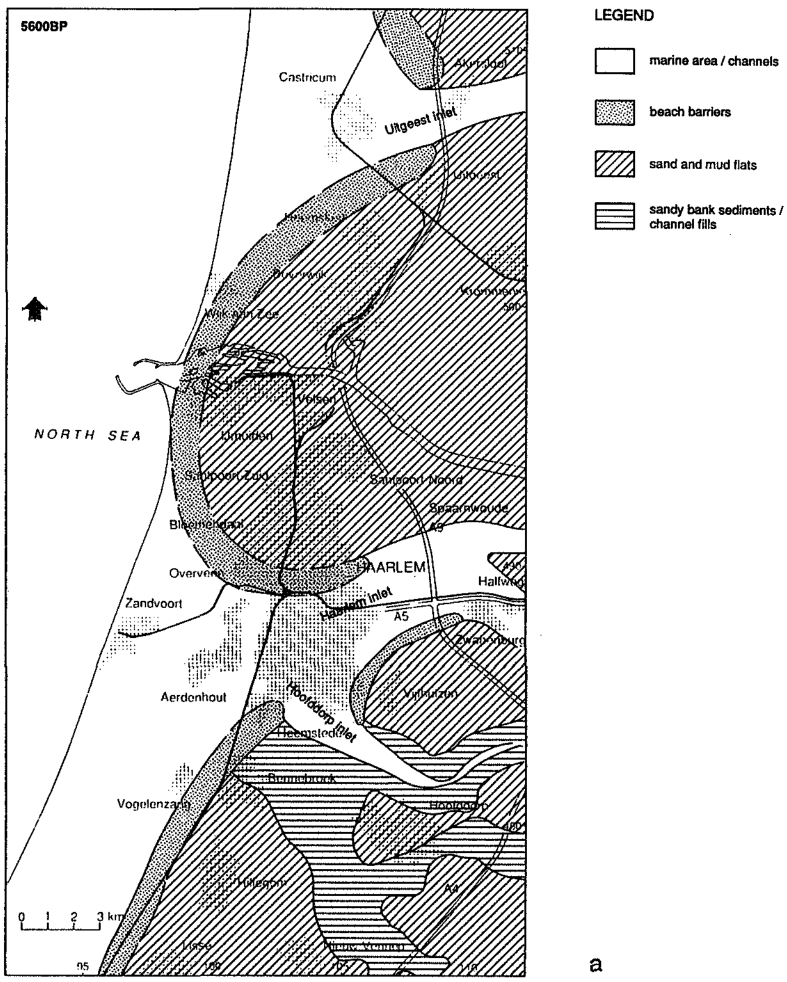


Fig. 31. Map of the study area with near-surface ^{14}C data.
^{14}C ages are indicated. Ages in brackets refer to datings with are occasionally older (4,750) or younger (3,470 and 2,510) than the presumed time of formation of the barrier sediments.

Combined effects of 1. increased longshore drift, 2. landward motion of the low southern barrier and 3. decline of tidal volume, force the meandering inlet to re-orientate itself, its in- and out-flowing axes becoming more southwesterly-northeasterly than the previous WSW-ENE direction, as deduced from the orientation of the sand bodies in the Haarlemermeer area (Fig. 32a). Possibly around 5,350 BP, channels reached their maximum depth (palaeo-depth 22 m; locally deeper spots occur up to 27 m), as a result of the re-orientation of the channel and the movements of the barrier coastlines north (landward) and south (almost stable by that time) of the inlet. We think this occurred around 5,350 BP, based on pollen analysis because by that time clay deposition had started, indicating the start of the abandonment of the deep channels. Shortly after, *c* 5,200 BP, the earliest signs of progradation of chenier type barriers start east of Spaarnwoude to the south of the major (flood?) channel. Progradation could start as early as this because a large volume of ebb-tidal delta sands were available from the Hoofddorp tidal inlet. The palaeo-tidal current pattern of the North Sea is assumed to have resembled the present-day pattern. The present tidal wave progresses towards the southern North Sea along the English coast and partly arrives through the Channel. These two waves join before the Belgian coast and then turn north. This means that the tidal flood-wave along the Holland coast comes from the south, which determines the SW-NE orientation of the tidal inlets (van den Berg, 1986; Sha, 1990).

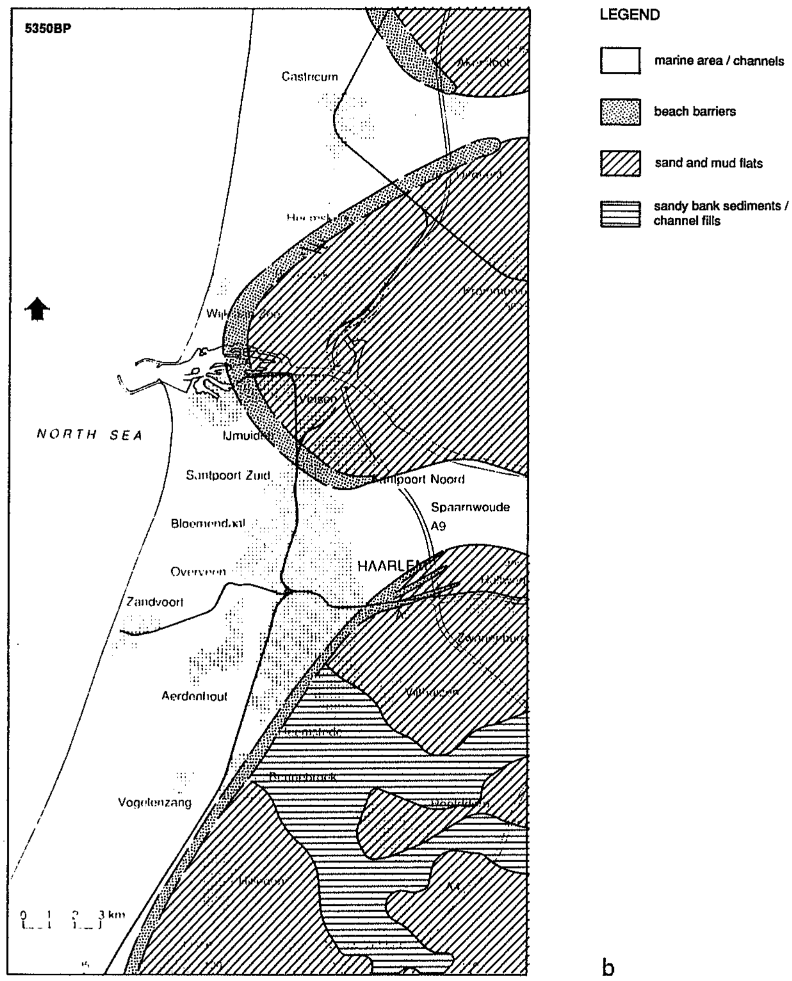
Inshore movement of the presumed northern barrier island continued. In the meantime, the tidally influenced area in the back barrier area diminished rapidly in size which meant a decline of the tidal volume to be transported through the inlet. In its turn this triggered an adjustment of the so-called wet cross-section of the channel by sediment infill (see for an example in the Zeeland area: Kuijpers *et al.*, 1990). The deep incisions of the then overfit channel underneath the present-day villages of Zandvoort and Santpoort were rapidly filled in with mainly fine-grained sediments, showing rhythmic storm-depositional features (*cf.* the 'Bergen Clay' in the Bergen inlet further north: Westerhoff *et al.*, 1987 and Fig. 11). Around 5,000 BP the southern barrier island more or less reached its easternmost position. Further recession of the coastline may be ruled out in view of the decline in sea-level rise and the rapid silting up of the area behind the barrier. Thick consolidated clays in the shallow subsoil west of Lisse (unpublished data, RGD) may also have contributed to calling a halt to the landward movement of the barrier. Longshore transport caused a *c* 7 km long sandy spit to form, in front of the Spaarnwoude chenier,separated by a wide beach plain. This started actual progradation in the area. Changes are rapid, as indicated by slightly contradictory ^{14}C dating results (compare the 4,780 +- 70 (GrN 14232) and 4,960 +- 70 (GrN 14230) results in Fig. 31 in the Haarlem area).

The northern barrier island still moved inland by wash-over processes and breakdown of the shoreface by means of longshore drift. Of the eroded material presumably the major part was directed north and the minor part south into the tidal inlet (because the barrier islands to the north continued their landward motion for several hundreds of years, and the inlets in between remained open since the tidal volume passing through

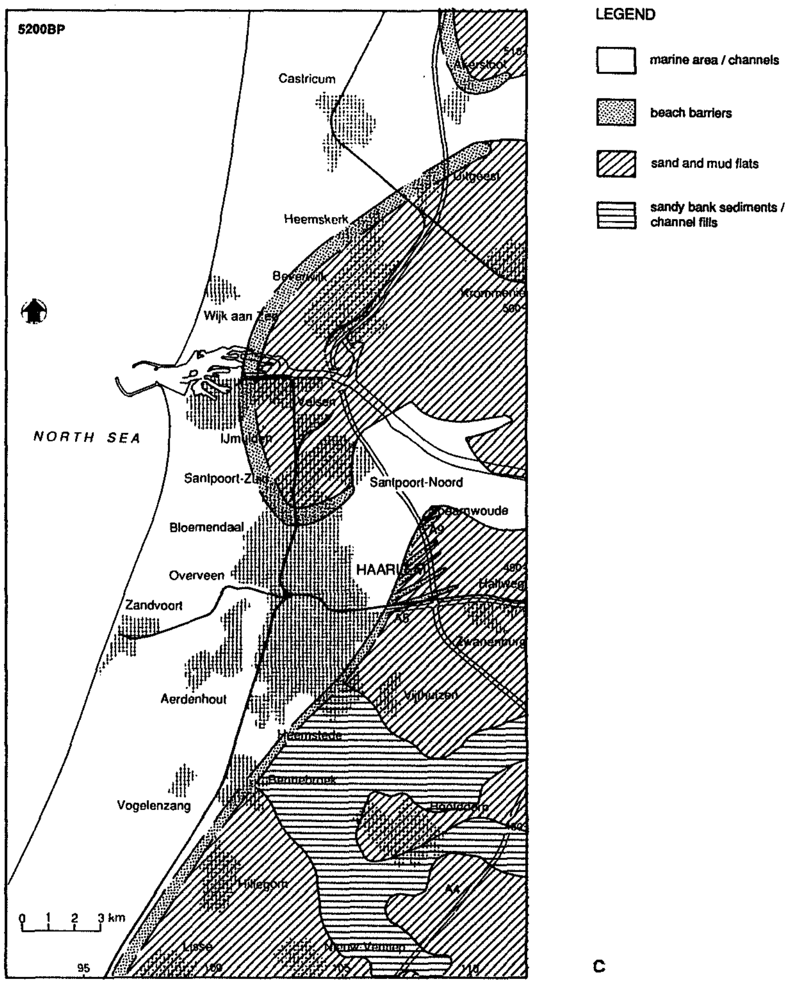


a

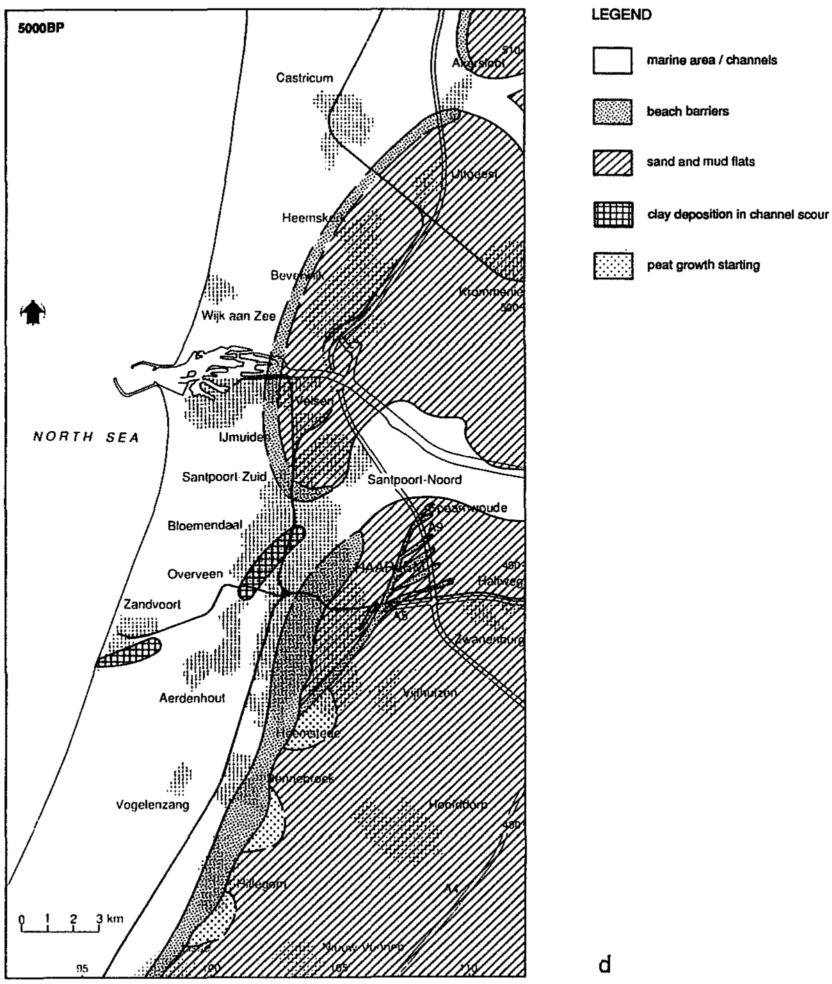
Fig. 32a-g. Palaeogeographical maps 5,600-4,250 BP for the Haarlem area.


5350BP
Castricum
NORTH SEA
IJmuiden
Santpoort Zuid
Santpoort Noord
Spaarnwoude
A9
Bloemendaal
Overveen
HAARLEM
Zandvoort
Aerdenhout
Vogelenzang
0 1 2 3 km
LEGEND
marine area / channels
beach barriers
sand and mud flats
sandy bank sediments / channel fills

b

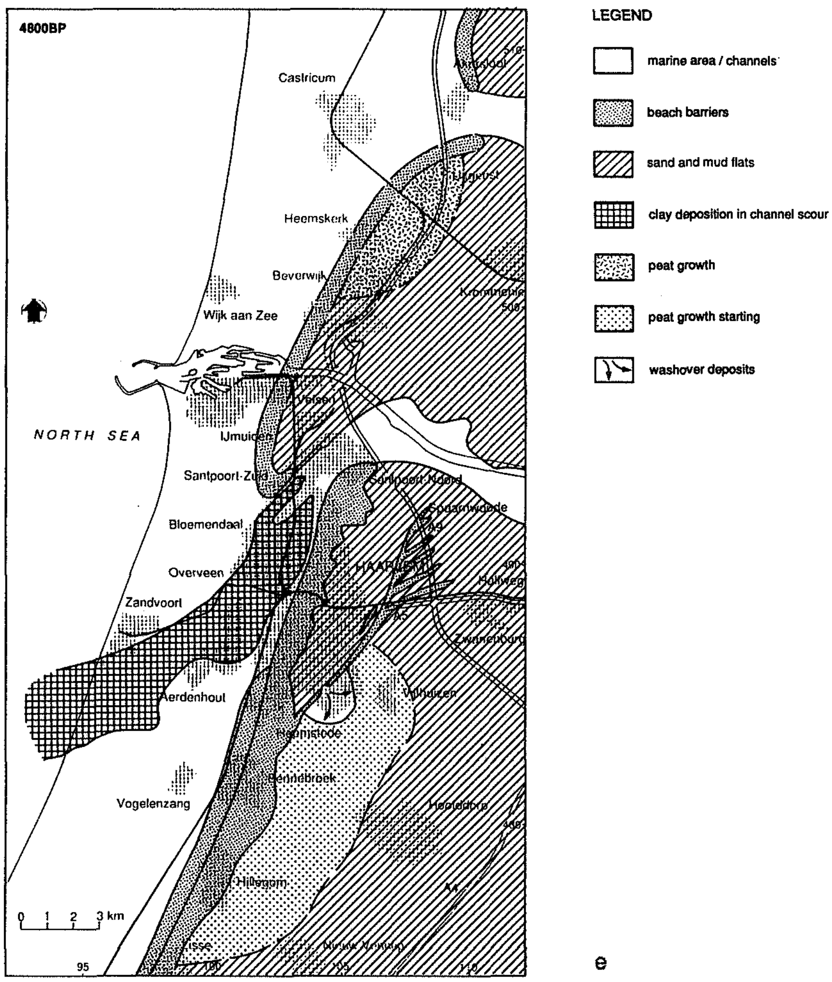

5200BP
Castricum
Akersloot
Uitgeest
Heemskerk
Beverwijk
Krommenie
Wijk aan Zee
NORTH SEA
Velsen
IJmuiden
Santpoort-Zuid
Santpoort-Noord
Bloemendaal
Overveen
HAARLEM
Halfweg
Zandvoort
Zwanenburg
Aerdenhout
Vijfhuizen
Heemstede
Bennebroek
Vogelenzang
Hoofddorp
Hillegom
Lisse
Nieuw-Vennep
0 1 2 3 km
95
100
105
110
LEGEND
marine area / channels
beach barriers
sand and mud flats
sandy bank sediments / channel fills

c

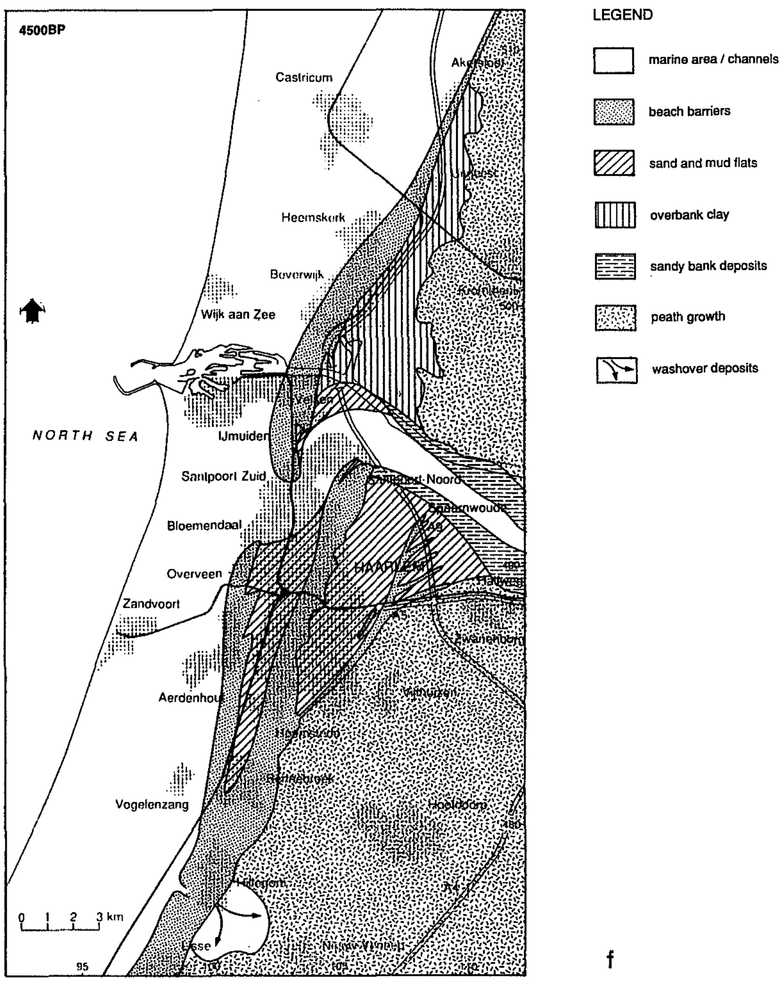


5000BP
Castricum
Heemskerk
Wijk aan Zee
NORTH SEA
IJmuiden
Santpoort Zuid
Santpoort-Noord
Bloemendaal
Overveen
Zandvoort
Aerdenhout
Vogelenzang
0 1 2 3 km
LEGEND
marine area / channels
beach barriers
sand and mud flats
clay deposition in channel scour
peat growth starting

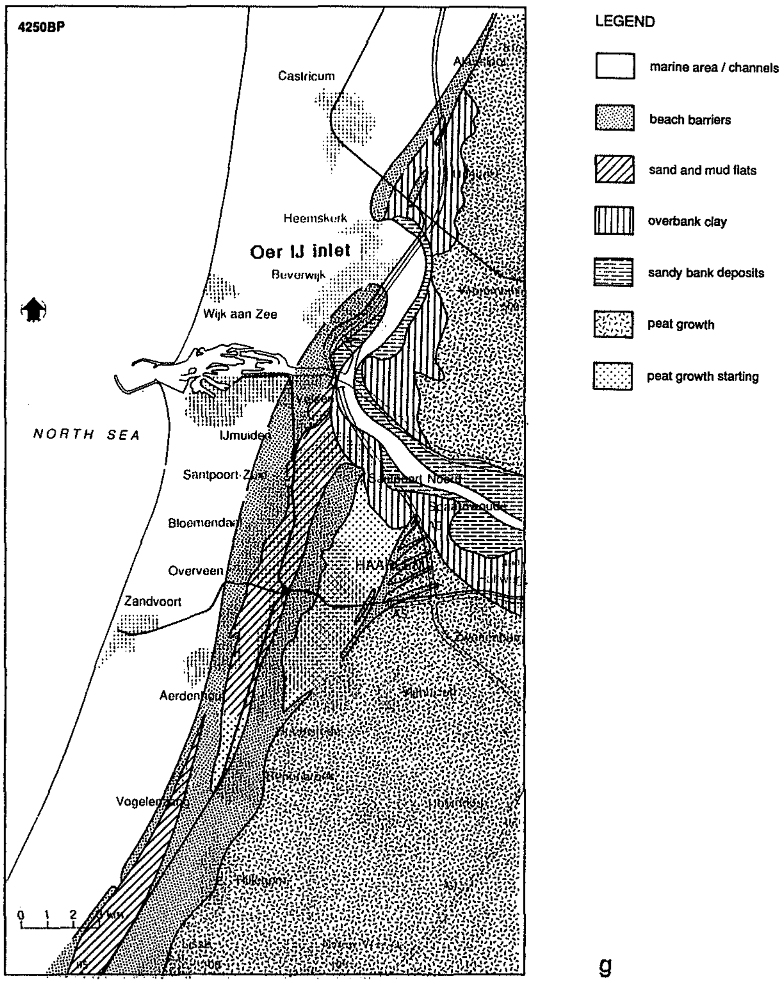
d


4800BP
Castricum
Heemskerk
Beverwijk
Wijk aan Zee
NORTH SEA
IJmuiden
Velsen
Santpoort-Zuid
Santpoort-Noord
Bloemendaal
Overveen
Zandvoort
Aerdenhout
Vogelenzang
Hillegom
Bennebroek
Heemstede
Vijfhuizen
Zwanenburg
Halfweg
HAARLEM
Spaarndam
Limmen
Uitgeest
Krommenie
0 1 2 3 km
95
100
105
110
LEGEND
marine area / channels
beach barriers
sand and mud flats
clay deposition in channel scour
peat growth
peat growth starting
washover deposits

e


4500BP
Castricum
Heemskerk
Beverwijk
Wijk aan Zee
NORTH SEA
IJmuiden
Velsen
Santpoort Zuid
Santpoort-Noord
Bloemendaal
Overveen
HAARLEM
Zandvoort
Vogelenzang
Hillegom
Lisse
Zwanenburg
Vijfhuizen
Heemstede
Hoofddorp
0 1 2 3 km
LEGEND
marine area / channels
beach barriers
sand and mud flats
overbank clay
sandy bank deposits
peath growth
washover deposits

f


4250BP
Castricum
Heemskerk
Oer IJ inlet
Beverwijk
Wijk aan Zee
NORTH SEA
Overveen
Zandvoort
0 1 2
LEGEND
marine area / channels
beach barriers
sand and mud flats
overbank clay
sandy bank deposits
peat growth
peat growth starting

g

these inlets was still too large). The largest amount of sand eroded from the foreshore of these landward moving barriers was transported into the inlets to the north due to the orientation of the barrier coast-line relative to the dominant direction of the flux of wave energy (pers. comm. J.H. van den Berg).

Just north of the former Hoofddorp inlet the barrier was firmly established (Fig. 30) in the period 5,300 to 4,800 BP. Continued decline of the tidal volume (and continued retreat of the barrier north of the inlet) led to a further decline and squeezing-in of the inlet around 4,800 BP. In the channel in process of abandonment a large volume of mainly fine-grained sediments was deposited starting around 5,000 BP (Fig. 32d-e). Longshore transport could probably bypass the inlet area by 4,500 BP, since progradation presumably started at that time at Uitgeest-Akersloot (Westerhoff *et al.*, 1987). South of the former Hoofddorp inlet the barrier still slightly moved inland, indicating a sand source area for the slight progradation near Heemstede. The tendency of substantial local progradation in the Haarlem area and local erosion further south continued during the next few hundred years at least up to 4,600 BP (see the close spacing of the inferred coastal gradients 4,800 to 4,400 BP in Fig. 30). A large spit formed in front of the Haarlem barrier (Fig. 32 f-g). It probably joined the southward outflowing ebb-tidal channel of the Haarlem inlet. All sand available by cross- and longshore transport was stored in this spit until 4,000 BP. The northern barrier reached its easternmost position by 4,600 BP (Westerhoff *et al.*, 1987). The whole process of channel reorientation may have been the result of the northward shift of the channel axes of the Haarlem inlet. Similar reorientation of channel axes have taken place in historic times in the Zeeland coastal area (Van den Berg, 1986).

By 4,250 BP, a major change occurred. Further recession of the barrier east of Beverwijk, together with the shift of a smaller channel at the rear of this barrier very probably caused a break-through at this spot. Consequently, the remainder of the Haarlem inlet silted up entirely very rapidly. The location of the inlet suddenly shifted some 6 km to the north. Spit growth north of Heemstede continued, directed landinwards towards the newly formed inlet (Fig. 32g). Reconstruction of this phase is in part hampered by later Oer-IJ erosion because of lateral channel shifts (Zagwijn, 1971; Vos, 1983). This 4,250 BP major change may also account for the sudden, but late start (compared with the rest of the area further east) of Holland Peat growth in the Haarlem area (De Jong, 1987). This late start is related to the marine influence that persisted until the break-through east of present-day Beverwijk occurred. Further mapping is needed.

More rapid barrier progradation at the location of the cross-section started shortly before this time as a consequence of this channel avulsion and continued at least up to 4,000 BP. Progradation now occurred from the north side of the River Rhine (unpublished data) up to the Santpoort area along the entire barrier line. During this time large amounts of sand were apparently available, probably originating from the shallow North Sea bottom and possibly from the Old Rhine river outlet, to be used for barrier progradation for that particular area. The relatively great height to which the so-called Older Dunes were blown up in the area may also indicate that this coast in between two inlets witnessed a rich sand supply.

The reconstruction of further developments after 4,250 BP is documented by the map of the coastal barriers on which ^{14}C datings are indicated (Fig. 31) and the cross-section showing barrier progradation (Fig. 30). The influence of the tidal inlets, now 30 km to the south (the Old Rhine) and 20 km to the north (the so-called Oer-IJ) is far less easily traced. Major changes such as more rapid or slower progradation or truncations cannot easily be related to the known younger geological history of the inlets. Nevertheless, for major truncations between 3,800 and 3,600 BP and between 2,800 and 2,600 BP (*cf.* 3.4.3) the following suggestions may be made.

-The 3,800/3,600 BP truncation.

For the inlet north of the transect it is known that the coastline was situated at Velsen *c* 3,850 BP (Jelgersma *et al.*, 1970). From 4,250 BP to 3,850 BP the pattern of Older Dune ridges arched in a southwesterly-northeasterly direction (Fig. 31). However, on the basis of the general chronology of the barrier deposits between Rhine and Oer-IJ, it is unlikely that this dune ridge pattern also indicates the beach barrier morphological pattern below the dunes. Instead, the pattern could indicate growth of the dune system by sand being blown inland during several phases. Just north of the Old Rhine estuary, extremely rapid progradation took place from 4,500 to at least 3,600 BP, but this can be considered to be a local phenomenon, as almost all beach plains in this area are no longer discernible south of the location of the Haarlem transect. This indicates that the 3,800/3,600 BP truncation in reality meant a period of several hundreds of years of non-deposition, or, more likely, a period of slow progradation, with periods of frequent erosion, as the transect is situated in the area halfway between the two outlets. Here the effects of slow general progradation of the coastline are clearest because of the lack of a major horizontal tidal component in the movement of the shallow coastal waters and related supply of sediment.

The arguments in favour of truncation are therefore not very strong. Another background cause of the 3,800/3,600 BP event could be the following. A major change occurred around 3,900 BP at the mouth of the Rhine outlet south of the transect. From that moment onwards, channel axes show a consistent shift to the northwest, while the channels were directed to the west before 3,900 BP (unpublished data). A period of a stronger effect of longshore drift could be the cause of this shift. Exactly how this effect is related (cause or consequence) to a strongly hampered outflow of river water is not well known. That this was a hampered outflow could be deducted from the fact that a large area in the River Rhine estuary was flooded and basin clays were deposited (Dunkirk 0 Deposits; Pruissers & De Gans, 1988).

- The 2,800/2,600 BP truncation.

In the Rhine outlet area all coastal deposits of this period were removed by subsequent erosion (except for coastal dune deposits blown inland far enough to escape this erosion). Consequently, no data are available for this area. North of the Haarlem transect, very few data are available, but Westerhoff *et al.* (1987) have shown that the Oer-IJ was active during this period. No barrier datings in the latter area are known, but it is likely that here, as in the Haarlem transect, a period of non-deposition or erosion occurred. Two barrier shell datings are close to each other (2 km), dated 3,400 +- 55 (GrN 4566; Jelgersma *et al.*, 1970) and 2,310 +- 35 (GrN 6445; Roep, 1986) (Fig. 31) indicating slow progradation.

Also, a peat layer was observed at Velsen (approximately near the location of older dating mentioned above) dating from the truncation period (pers. comm. J. de Jong) which was partly removed by aeolian erosion. This type of erosion can take place only when the peat has desiccated through a lowering of the groundwater table. In a dune system this can only be effected by a reduction of the width of the dune area (*cf.* Bakker, 1979). As a reduction of dune width in this period could be due either to coastal recession at the seaward side, or at the rear of the dune area by erosion because of the lateral shift of the Oer-IJ meanders, it cannot be determined wether or not coastal recession did occur. Supplementary evidence on the palaeogeographic evolution of the Velsen area is needed to permit final conclusions.

The history of the accumulation of Older Dune sand blown onshore might also provide some clues as to the coastal erosion associated with the truncation observed in the Haarlem transect. Older Dune phase IIa (Jelgersma *et al.*, 1970) can be dated in this period. This deposit has recently been mapped (Pruissers & Blokzijl, 1989). It has been found to cover a large area, and hence, it may be considered to represent a more general dune forming phase ending before Roman times, during which open dune shrubs flourished (Jelgersma *et al.*, 1970). This indicates landinward transport of dune sand. The availability of a large volume of dune sand along a long-stretched part of the coast between the Rhine outlet and the Oer-IJ inlet suggests coastal erosion at the sea-side of the dune system on a more than local scale.

Summarizing, it is likely that what appeared as the first truncation of 3,800/3,600 BP, might not be a truncation after all, while the second truncation of 2,800/2,600 BP appears acceptable in view of the regional geological development. On the other hand, the pattern of coastal gradient development of Fig. 30 is likely to be genuine, even if uncertainties of the method of age determination are taken into consideration.

4.2. COASTAL STORM SEDIMENTATION

With the help of Figs. 10 and 30, the outlines of the coastal depositional system responsible for the formation of the Subboreal and Subatlantic barrier sediments in the mid-Holland coastal area can be defined. As discussed above (3.2.4.), the Holland coast was influenced to a large extent by the North Sea wave climate. In the same section it has also been suggested that the Holland coast sedimentary system is essentially storm-dominated. Here this suggestion is elaborated upon and a model is presented and discussed.

The proposed storm-depositional mechanism of the Holland coast is illustrated in Fig. 33. For the construction of this model, the cores of the Haarlem transect were used, in combination with data from temporary exposures. The latter were added, in view of the limited core width of the boreholes in the cross-section. Unfortunately, these exposures (mostly shallow pits in construction works), seldom reached deeper than the Low Tide Level (LTL). In some deeper exposures, however, data could be collected which are of importance in this matter (*e.g.* Roep *et al.*,(1983) and unpublished data of the author). This means that sedimentary units 7, 6 and 5 (the last only partly) of Fig. 10 are known both from the cores and from exposure data. Units 5 (for the larger part) to 1 are known from cores only.

The storm-depositional character of this system is documented in several ways. For the sedimentary units: see Fig. 10.

- supratidal storm layers (sedimentary unit 6: top)

Above the general High Tide Level (HTL) frequently thin shell layers are found, which formed on a storm-eroded flat beach surface (Roep, 1986; Van der Valk, 1991). These layers are characterized by the presence of large shells of different species, but predominantly of worn shells of *Cerastoderma edule,* with holes in the umbones due to aeolian sand blasting (*cf.* Schermer, pers. comm). These layers are overlain, and sometimes also underlain by aeolian deposits.

- longshore breaker bars (sedimentary unit 6)

Strictly speaking, the mega-cross bedded deposits cannot be attributed to storm processes, since from actual observations it is known that breaker bars 'shape up' during more or less fair-weather conditions. A recent survey by Short (1990) indicates that morphodynamic changes are frequent in this zone, higher in frequency than and surpassing storm frequency (see for other beach surveys: Van den Berg, 1977 and Roep, 1986).

- upper shoreface (sedimentary units 5 and 4)

A distinctive feature indicating that the upper shoreface deposits originated predominantly as storm wave deposits, is the direction of foresetting, documented in the lacquer peels taken in a cross-palaeoshore direction (Fig. 34), in combination with the graded architecture of the individual event-type deposits (Figs. 10 & 11). Below -10 m NAP (but sometimes also two or three metres higher up), a proportionally larger part of the direction of foresetting of individual sets (when compared to the deposits above this depth) is directed towards the North Sea. This information is available as a result of the orientated way in which most of the cores (6 out of 10) were taken (Fig. 34). Of course, this is as far as the cores can be interpreted: the core splits were taken perpendicular to the coast. This indicates that a longshore component could not be measured. The boundary plane between sediments which indicate through their sedimentary structures a predominantly shoreward sediment movement, and sediments which show structures indicating a more or less off-shore transport is generally at level from E to W. Foresetting directions away from the coast may be associated with shoreface storm wave set-up, the water returning to sea by undercurrent. In conclusion, the intermittent depositional activity (event character) and the directions of foresetting in combination with depositional depth suggest storm-wave action as the

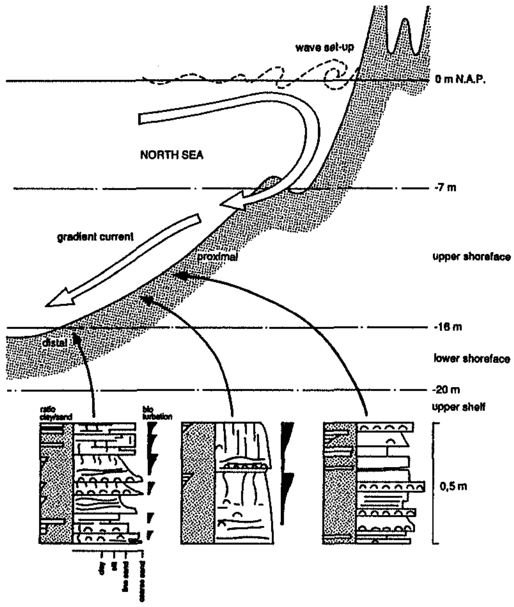


Fig. 33. Geological model of Holland coast storm deposits.

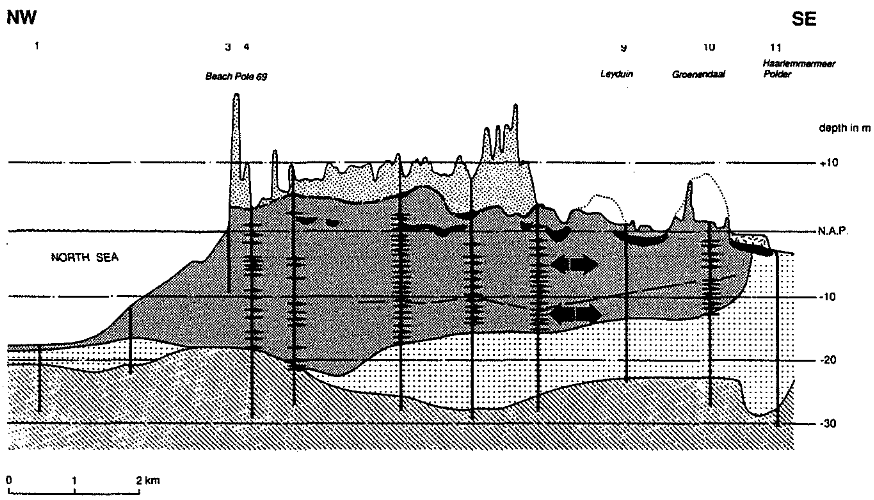


Fig. 34. Generalized direction of foresetting of micro- and megastructures of the orientated barrier cores (Haarlem area, western Netherlands). Note that general direction of foresetting in the breaker bar sedimentary unit is shoreward; general direction of foresetting in the sedimentary zones below the latter reflects varying influence of shoreward and offshore movement of bed forms.

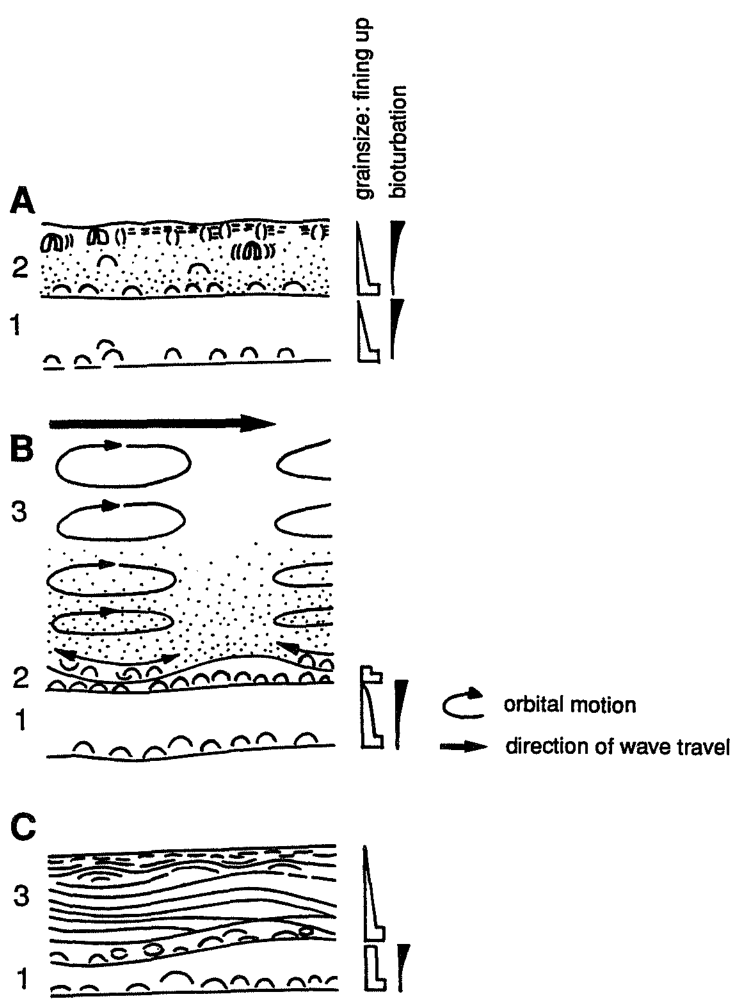


Fig. 35. Possible sequence of storm deposits on the shoreface of the western Netherlands coast.

A) Two former storm event deposits: both fining-up and bioturbated;

B) During the following storm event, particles smaller than 200 µm are taken into suspension by the oscillatory motion of the sea-water under the influence of storm waves at the surface. Molluscs (and other biota) are washed out of their live position and are in part washed away. An event-concentration is formed, incorporating an earlier event-concentration (2);

C) After the storm, the suspended material is rapidly deposited under waning storm conditions. A storm-sequence is formed, resembling a hummocky cross bedded unit. No survivors amongst molluscs or worms; the area needs to be re-colonized.

most probable agent.

The mechanism of storm-layer formation in unit 5 is illustrated in Fig. 35, but *mutatis mutandis* it may explain the mechanism of unit 4 as well. Before a storm, the sea-bed is in a quiet stage and thoroughly bioturbated (Fig. 35A). When the oscillatory motion of the water near the bottom starts during storm build-up, the sediment is stirred up and all material smaller in grain size than 200 µm is taken into suspension (Fig. 35B). Shell material (dead and alive) is washed out to form an event concentration (Kidwell, 1991)(Fig. 35B). Under waning storm conditions, the suspended material rapidly covers winnowed-out shell concentrations and coarser-grained HCS beds, producing a kind of graded unit (Fig. 35C). The nature of the event deposits depends on depth in the (palaeo-) North Sea. Distal storm event deposits are thin (a few centimetres at a depth of *c* 15 m) and show the complete sequence of winnowed shell lag below, overlain by graded sand, top clay bed and burrowing. Higher up, the event deposits gradually change into beds of several tens of centimetres of thickness, showing a thick shell lag, followed by HCS bedding. Often, the fine-grained top deposits and the burrowing are missing from the cores due to reworking by the wave action of a subsequent storm. As long as the progradation continued, the preservation potential of the storm deposits was high for the deeper lying deposits, and for higher deposits equal in the truncated fashion, as explained above. For recent storm deposits in the shallow southern North Sea, unfortunately, there are no data.

- lower shoreface (sedimentary units 3, 2 and 1)

Unit 1 is the predominantly sandy unit that occurs in the east. This unit is associated with the barrier coastline bordering the Haarlem inlet to the south (Fig. 32 d-e). Unit 2 is the very clay-rich unit that occurs seaward of unit 1, and interfingers with the latter. Unit 3 comprises bar-like sand features that lie still further out to sea (Fig. 10). Unit 1 shows scours at the base of shelly sands and often directions of foresetting towards the west, *i.e.* towards the North Sea. Again several beds show slight clay deposition, often worked into the sediment by bioturbation activity. These very probably event-related features point to storm deposition. The interfingering with unit 2, deposited simultaneously with unit 1 but more seawardly and under quieter conditions, shows a progressive fining-out into sea. The event character of unit 2 is demonstrated by the frequent lithological change from sand to pure clay and the occurrence of (mostly thin) shell lags. Between the separate thin beds frequently bioturbation took place. Still further out to sea, unit 3 was deposited in the form of moderately coarse sands with a very low clay content and very little shell material. This unit is supposedly contemporaneous with the units 2 and 1, but as the number of ^{14}C datings involved is very low, there remains some uncertainty over their time relationship. The overall sandiness of this unit indicates the work of tides rather than storm waves: the fines are permanently winnowed out. This sandy character conforms more or less with that of the present-day ebb-tidal delta front in the Zeeland area. This unit 3 does therefore not show the event character that was assumed for the other sedimentary units mentioned above.

4.3 PROGRADATIONAL SOURCES

Pre-progradational sand transport ways were normal to the present-day coastline, as indicated by the erosion pattern of the Early Holocene Basal Peat occurrences (Fig. 7) and reconstructed palaeogeography (Fig. 32) of channel pathways. Thus, it is acceptable to assume that a certain amount of cross-shore sand transport did take place in front of the pre-5,200 barrier. As the Old Rhine river outlet was not in operation before 5,000 BP (Pruissers & De Gans, 1988), all sand must have come from the shallow North Sea bottom directly offshore of the Haarlem area, probably supplemented by a more distant sand source, a Boreal/Early Atlantic delta of the Rhine/Meuse outlet west of Rotterdam (Beets *et al.*, 1992), which is only some 50 km to the south.

After 5,000 BP the Old Rhine outlet at Leiden may have acted as a sand source, contributing in this way to the progradational sources. Proof is difficult to find, as mineralogical features (Eisma, 1968) or other lithological parameters hardly permit to distinguish fluviatile sand from sand derived from either the shallow North Sea or the palaeo-delta west of Rotterdam. There is, however, some circumstantial evidence pointing to a post-5,000 BP contribution of the Rhine to the coastal sand budget. First, there is the rapid coastal progradation west of Leiden, which came into existence immediately after the connection of the Rhine to the North Sea (Beets *et al.*, 1990; Van der Valk & Pool, in prep.). The connection is formed by a purely sandy river meander belt, suggesting sand transport towards the coast at least during the period of barrier progradation. Secondly, after c 3,800 BP a strong shift occurs in the sedimentation pattern. The mouth of the River Rhine shifted to the north only from that time, and the old channels were filled with sand. Coastal drift supposedly was the cause of this shift (Roep *et al.*, 1991). Thirdly, gravel in the barrier sediments is found predominantly to the north of the River Rhine outlet, suggesting a relationship with the River Rhine (a Holocene source, however, cannot be proved however, since the gravel could easily have been reworked from the Pleistocene subsoil (Van Straaten, 1991)). Lastly, in the barrier sediments occasionally freshwater molluscs and terrestrial molluscs are found at locations north of the River Rhine outlet (Meijer, pers. comm. and author's unpublished data), suggesting a Rhine provenance.

The bulk of the sand used for progradation came from the shallow North Sea, however. This is documented by the molluscan fauna, found in the barrier sands. The presence of reworked Atlantic molluscs (species from a tidally dominated environment such as *Mytilus edulis, Cerastoderma edule, Scrobicularia plana* and *Littorina littorea*) in these barrier sands progressively declines from ea st to west, *i.e.* the direction of progradation. This indicates that the source (the western part of the so-called Calais Deposits, at the start of the progradation lying off-shore: Fig. 3) declined in volume. As soon as this source was depleted, sands for further progradation were picked up from the seafloor of the adjacent North Sea. Another argument for a shallow North Sea source is the erosion pattern of the Basal Peat (Fig. 7). The SW-NE trending erosion line below the present-day cities of Lisse and Haarlem suggests a truncation parallel to the ancient shore brought about by a certain mechanism. This mechanism can only have been wave action. The Basal Peat in the Velsen-IJuiden area escaped erosion because of its deeper occurrence and protection by the stiff clay of the Velsen Layer. A tidal current parallel to the coast is not a very likely mechanism for uprooting the Basal Peat, considering the shallower depth of the Early Subboreal North Sea, and hence weaker tidal currents (Franken, 1987). This leaves wave action as an agent. When the Basal Peat was eroded (as is still happening in the area off Bloemendaal: with every storm large lumps of Basal Peat reach the shore), sands overlying it would be a possible source for progradation. When the peat was removed, also the underlying Pleistocene sands were available. Recently, cores from the shallow North Sea area around the cores discussed in this paper have shown that indeed the Pleistocene deposits more or less lie at the top of the sea bottom covered only with a thin veneer of Holocene sand (Beets, pers. comm.; Van de Meene, pers. comm.).

5. CONCLUSIONS

1. Over the past 5,000 radiocarbon years relative sea level rise in the Netherlands has amounted to 4-5 m. Some 3-4 m of this rise occurred during the 3,300 radiocarbon years of coastal development documented in the sediments of the Haarlem cross-section. Despite this the coast showed strong stepwise progradation, with marked retardations (or slight erosion) around 3,700 and 2,700 BP.

2. In the course of the progradation of the barrier coast near Haarlem a general steepening of the shoreface gradient took place: from 1 : 540 at 5,000 BP through 1 : 450 at 3,800 BP to 1 : 145 at 2,200 BP. Gradients mentioned are based on the vertical distance from palaeo-MSL to the deepest point where the related shoreface was still observed (*cf.* Fig. 30: 12 m at 5,000 BP, 10 m at 3,800 BP and 14 m at 2,200 BP). When studied in detail, it appears, at least at the chronological resolution of *c* 200-300 ^{14}C years which could be achieved, that in the upper -10 m subsequent coastal gradients remained basically equally steep. The present study does not permit conclusions with regard to possible variations in the steepness of the upper 10 m of the coastal gradient from phases of barrier formation (presumably steeper) to phases of beach plain formation (presumably less steep). This can be ascribed to too few radiocarbon datings in the barrier section above -10 m.

The general trend of gradient evolution is not affected by calibration of the radiocarbon datings on which it is based, although minor effects occur (*e.g.* slightly less steep gradients pre-3,000 BP when calibrated ages are applied).

The general steepening and the occurrence of periods of marked slow progradation and/or truncation of the barrier foot deposits suggests that

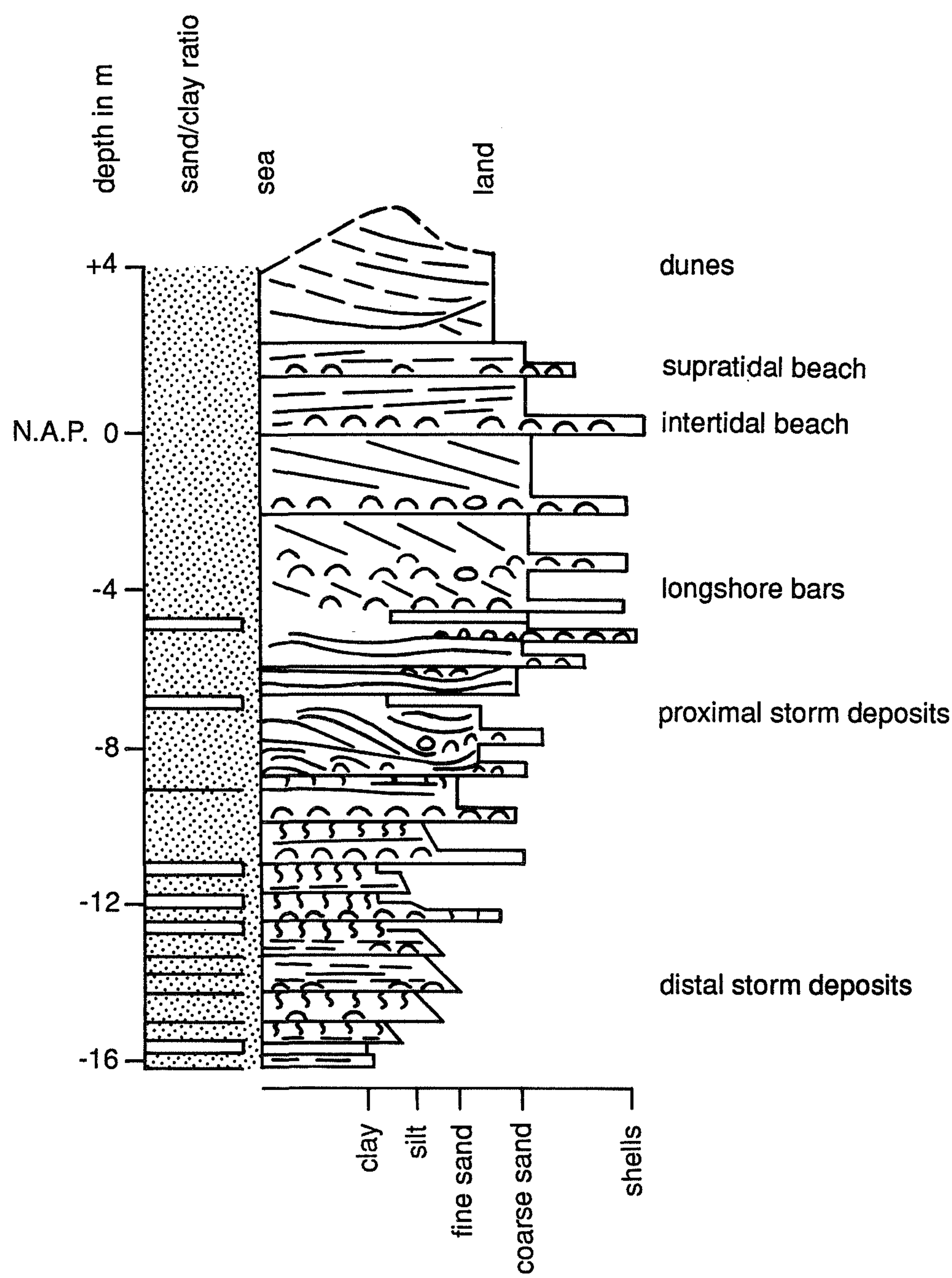


Fig. 36. Generalized Subatlantic/Subboreal beach ridge sequence of the western Netherlands.

the concept of the Bruun rule (Bruun, 1988) cannot be applied to the prograding barrier of the western Netherlands during the Subboreal and Subatlantic sea level rise as indicated above. A more extensive discussion on this subject is made by Van der Valk & Pool (in prep.), who will provide an account of the quantitative approach towards barrier formation by means of mathematical modelling.

3. So far as the genesis of the barrier sands of the western Netherlands is concerned the combined litho- and biostratigraphical evidence points to a sedimentary regime primarily related to storm-wave action. Minor tidal influence was mainly restricted to larger depths (over 16-18 m) where it prevented fine-grained sediment particles from becoming deposited in open-sea circumstances (Fig. 36).

4. Applying radiocarbon dating of carefully selected reworked, but fresh-looking molluscan material from the deposits studied resulted in a plausible, internally and externally (i.a. first appearance of certain molluscan species) consistent and apparently reliable chronology, with a 200-300 radiocarbon years resolution (*cf.* 3.4.2.). Provided that the same precautions are herded, this dating technique may be applied generally to establish the chronology of barrier (or other sandy coastal) systems.

5. Facies evolution, including both lithogical (*cf.* 3.2.3) and palaeontological (*cf.* especially 3.5.3 (molluscs)) aspects, of the Haarlem barrier deposits shows that per time unit the amount of wave energy on the coastal profile must have increased during the *c* 3,300 years of progradation. Several causes may be considered:
1. the sand sources from which the barrier sand wedge was constructed during progradation reached depletion, which meant changing morphology of the shallow North Sea coastal area ;
2. a climatic change in the southern North Sea area resulted in increased windiness. Indeed, Van Straaten (1961) showed that such could have been the case, but up to now no unambiguous data for the Subboreal and Subatlantic have been published with regard to the western Netherlands in this respect; 3. an intermingling of the effects mentioned under 1. and 2.

Should the energy increase on the coastal profile be due exclusively to depletion of the sand sources, then the total of the progradation of the Subboreal/Subatlantic coast must be considered to represent the result of the slowing down of the rate of sea level rise in the southern North Sea subsequent to *c* 5,500 BP. As far as a climatic cause for the end of the progradation is concerned, Van Straaten (1965) remarked that the shore-parallel orientation of the Older Dune ridges might point to a more southerly wind climate than the present-day westerly wind climate. The present author does not consider this a sound argument, since the orientation of the Older Dunes on top of the pre-3,500 BP barrier ridges (to which Van Straaten referred) is primarily related to the rate of progradation of the total barrier. This implies that rather too little time was available for aeolian transportation away from the shore than that the

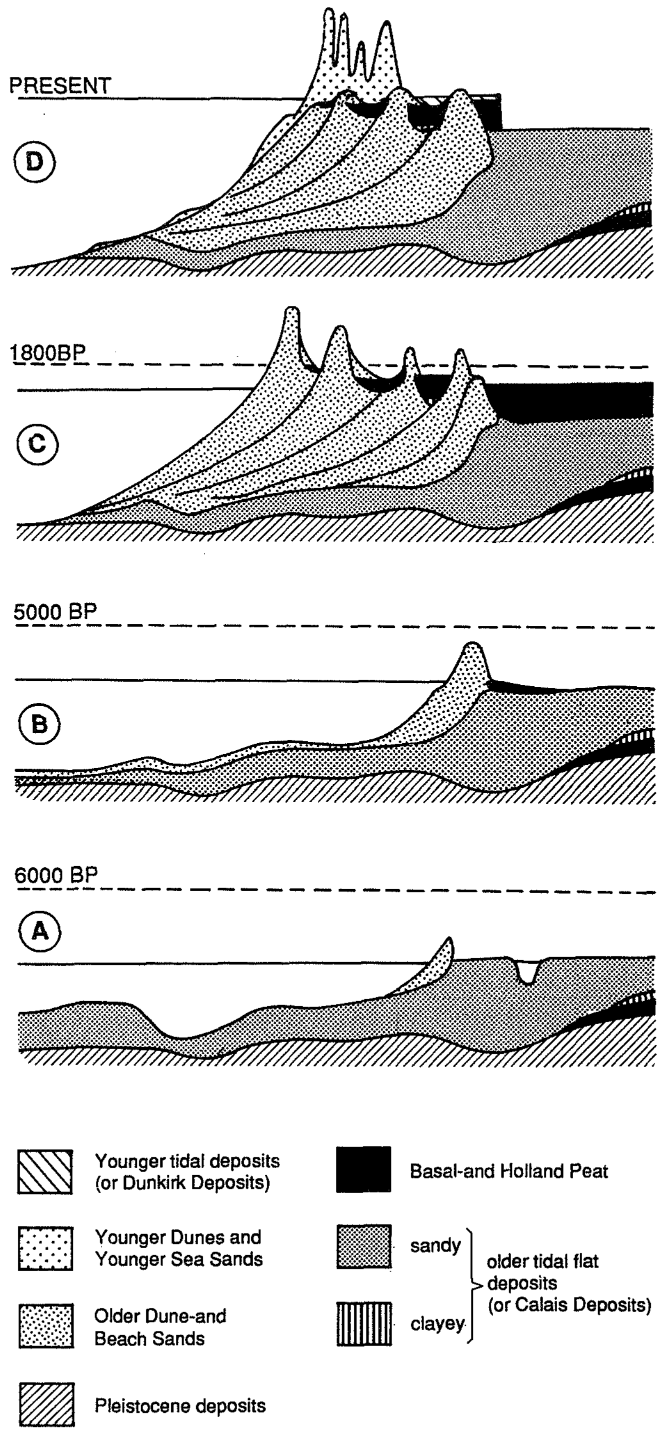


Fig. 37. Diagrammatic reconstruction of the evolution of the beach barrier complex between the estuaries of the Old Rhine and the Oer-IJ from 6,000 BP to the present day.

orientation was climatically forced. On the other hand, short-term changes in wind climate in historic times have been documented, which influenced aeolian deposition (Van Straaten, 1961; Hoozemans, 1990). At this moment it cannot be decided which process (sea level rise or climatic change) was the most important, but generally it is assumed that sea level rise was prevalent.

6. Due to the single-section approach used in this study, no quantitative remarks can be made with reference to the relative importance of cross-shore transport and long-shore transport. However, some qualitative remarks can be made. The general rule seems to have been that cross-shore transport prevailed during the first 1,500 years of coastal barrier formation, only to be influenced by long-shore transport associated with the development of the Haarlem inlet for short periods of time (Fig. 37).

The next 1,500 years of barrier formation may have shown a different picture: the shift to the north of the mouth of the Old Rhine river and of the inlet of the Oer IJ suggests such. Long-shore transport may have been much more important than in the period 5,200-3,800 BP. Truncation of the barrier area just north of the mouth of the River Rhine is supposed to have taken place in the period 3,800-1,900 BP and the sand of these deposits was used for the progradation near IJmuiden.

The end of progradation is considered to be the reaction of the barrier system to the disappearance of sea level rise. As a substantial SLR cannot be demonstrated on the Holland coast in post-Roman times, this indicates the possible start of the period of post-SLR. For the Haarlem area, Van der Valk & Pool suggest *c* 900 AD for the change from progradation into landward shift. Thus, the time lag involved may be estimated at several hundreds of radiocarbon years to about 1,000 radiocarbon years.

Another view is that the cross-shore transport invariably took place in shallow (less than 10 to 12 m) water depth -this is presumably what coastal engineers name the 'active zone'. In our opinion, the word 'active' should be interpreted in a relative rather than an absolute sense: in fact, the 'active zone' of the shoreface is more active than other zones of this area.

The general picture which emerges from the present study with regard to barrier progradation is one of a time- and place-dependent process, forced by:

- changes in the configuration of the southern North Sea during the Subboreal and Subatlantic with adjustments to more strongly wave-dominated circumstances
-rate of sea-level rise and
-availability of suitable sediment.

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CHAPTER VII

CONCLUSIONS

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1. The analysis of the coastal deposits in front of the recent western Netherlands coastal barrier showed the degree of wave reworking of these deposits. The zone of the breaker bars is reworked entirely to a depth of several metres in a period of years and to a shallower depth probably several times per year. The upper part of the upper shoreface is reworked to a depth of several decimetres, probably with every major storm. Descending the coastal profile, the degree of reworking is gradually decreasing in depth to a few centimetres and also decreasing in frequency. Below -16/-17 m (lower shoreface) below the present MSL the effect of storm waves is less discernable in the deposits probably due to more important activity of tidal currents in this zone as opposed to the upper shoreface.

2. The preservation potential for clay laminae and clay layers in the present-day coastal barrier deposits is low compared to the Subboreal and Subatlantic barrier deposits. Essentially, however, the recent barrier deposits can be compared well with the Subboreal/Subatlantic prograded barrier deposits.

3. The depositional mechanism of the barrier deposits below mean fair-weather wave base (roughly the lower boundary of the long-shore breaker bars) is essentially storm-dominated. Between individual storms shorter or longer periods of quiet circumstances occurred, as shown by bioturbated horizons.

4. The coastal barrier development in the western Netherlands is primarely related to the morphology of the top of the Pleistocene deposits and the rate of sea-level rise. These factors are of influence up to the present day.

5. Barrier progradation started during the end of the Atlantic in the south of the study area. Age differences between the start of barrier progradation in the south, near The Hague, and in the north, near Alkmaar, are estimated at about one thousand radiocarbon years (depending on the interpretation of the results of the datings).

6. The comparatively early progradation in the south of the study area is related to the availability of sand in front of the Rivers Rhine and Meuse outlets west of Rotterdam. When the rate of sea-level rise decreased between 6,000 Bp and 5,000 BP, the Holland tidal basin started to fill in, which could not be effectuated earlier, because tidal sedimentation could insufficiently keep up with sea-level rise. Roughly, the prograding barrier sequence enclosed between the two headlands of the former outlets of the Rivers Rhine and Meuse and of the Texel push moraine is forming a closed

system. Simultaneously with progradation of the barrier sequence, coastal retreat occurred in the area occupied by the headlands.

7. While progradation started in the south, the tidal sub-basins were still filled in in the north. Around 5,000 but probably somewhat later, the major outlet of the River Rhine shifted from the area west of Rotterdam to the Leiden area. From that moment on, erosion prevailed at the ancient outlet, while progradation accelerated at the River Rhine outlet west of the area of present-day Leiden.

8. After the start of barrier progradation, the inlets that remained open until about 2,000 BP (the Oer-IJ) and about 1,200 AD (the River Rhine) were connected to river branches. All other inlets in the barrier area disappeared during the coastal progradation.

9. The early prograding sequence south of The Hague is showing a different type of accretion as compared to later developments. The early type is reduced in the number of the longshore bars (one vs. a sequence of three in later times) and is showing lunate megaripples below the level of the bar vs. storm-related sediments later on. The differences are attributed to a lesser intensity of wave action on the early type of barrier coast. Apparently, a shallow area (probably the ebb-tidal delta area belonging to the tidal channel leading towards Zoetermeer) in front was effectively sheltering this early barrier coast.

10. Coastal progradation south of Haarlem occurred stepwise with marked retardations (or probably slight erosion) around 3,700 and 2,700 BP. In the course of progradation a general steepening of the coastal slope took place, as measured to a maximum depth of 14 m below contemporanous MSL. The concept of the Bruun rule of shoreline retreat during SLR cannot be applied in the western Netherlands situation of progadation.

11. A simple sand budget for the coast of Holland showed that a large part of the sand that was used for barrier progradation came from the North Sea, directly or indirectly, using the sand, which first was stored temporarely during the Atlantic in the ebb-tidal deltas of the tidal inlets active in that period. The River Rhine contribution of sand to progradation was minor.

12. SLR (declining in rate) and depletion of sand sources worked hand in hand, ultimately causing a halt to barrier progradation. At the location of the Haarlem cross-section progradation probably stopped shortly after 2,000 BP. Together with the increasing steepness of the shoreface profile, the two factors mentioned above probably caused an increase of wave activety on the coast, which in its turn enhanced aeolian transportation towards the backshore and the dunes due to the wind erosion of the dune cliff at the beach following wave attack. The morphology of the Early Subboreal shallow southern North Sea in front of the barrier coast changed considerably as an adaption to the new situation.

13. A tendency of a larger importance of long-shore drift vs. cross-shore transport may be noted from the Haarlem cross-section during barrier progradation. This shift of relative importance may be associated to the decrease of the rate of SLR and the disappearance of tidal inlets.

14. Barrier progradation, not only in the Haarlem area, is related to the development of the coastal inlets: differences in rate of progradation could be associated to the development of tidal inlets.

14. Provided samples are pretreated carefully (selection of the freshest habit of preferably one species), reworked shell material from sandy clastic marine deposits yields reliable radiocarbon dating results.