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Holocene storm surge signatures in the coastal dunes of the western Netherlands

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Abstract

On five different sites along the central Netherlands' coast one or more sequences of shell deposits in the dunes have been observed. They are believed to be the result of storm surge activity on the foreshore, either through swash or overwash action, and of subsequent preservation due to aeolian coverage of a basically sedimentary coastal system. Through their stratigraphical positions and radiocarbon dating of shell material their approximate age was determined.

By interpretation of the role of dynamic wave set-up and run-up the associated storm surge elevations relative to contemporary mean sea level are reconstructed. Although our data may not be statistically accurate, an increasing level of storm surge elevations over the recent Holocene is observed with a particular maximum during the Little Ice Age. It is our suggestion that climatic variations on the one hand and foreshore bathymetry on the other hand may be factors of relevance to explain these observations. If these findings are correct this would imply that for a proper analysis of exceedance frequencies of extreme storm surge events it would be relevant to base such an analysis not only on present climate and foreshore bathymetry.

1. Introduction

The shoreline of the Netherlands is a wind dominated, clastic shoreline subject to a meso- to microtidal regime. Three coastal landscapes can be distinguished: the estuaries of Rhine, Meuse and Scheldt in the southwest, a coastal barrier area centrally and in the north the Wadden Sea consisting of interconnected tidal basins bordered by barrier islands (Fig. 1).

Our study focuses on the extensive dune area in the central part of the Netherlands. On this part of the coast three coastal sedimentary units can be distinguished: an up to 10 km wide sequence of prograding barriers and inlets, overlain by dune sands of the Older Dunes, part of which are covered by Younger Dunes.

The prograding barrier sequence developed during the early Subboreal until the early Subatlantic, a process which seems to be related with the slowing down of relative sea-level rise (Van Straaten, 1965; Beets et al., 1992). Associated with the prograding coast are Older Dune deposits (with a thickness of 10 m maximally). Subsequently, the outbuilt coast started to erode, and a largely aeolian coverage of the barrier and Older Dune sequence took place by the Younger Dunes. Field observations from excavations in the dune area indicate that the aeolian deposition was not a continuous process but was interrupted

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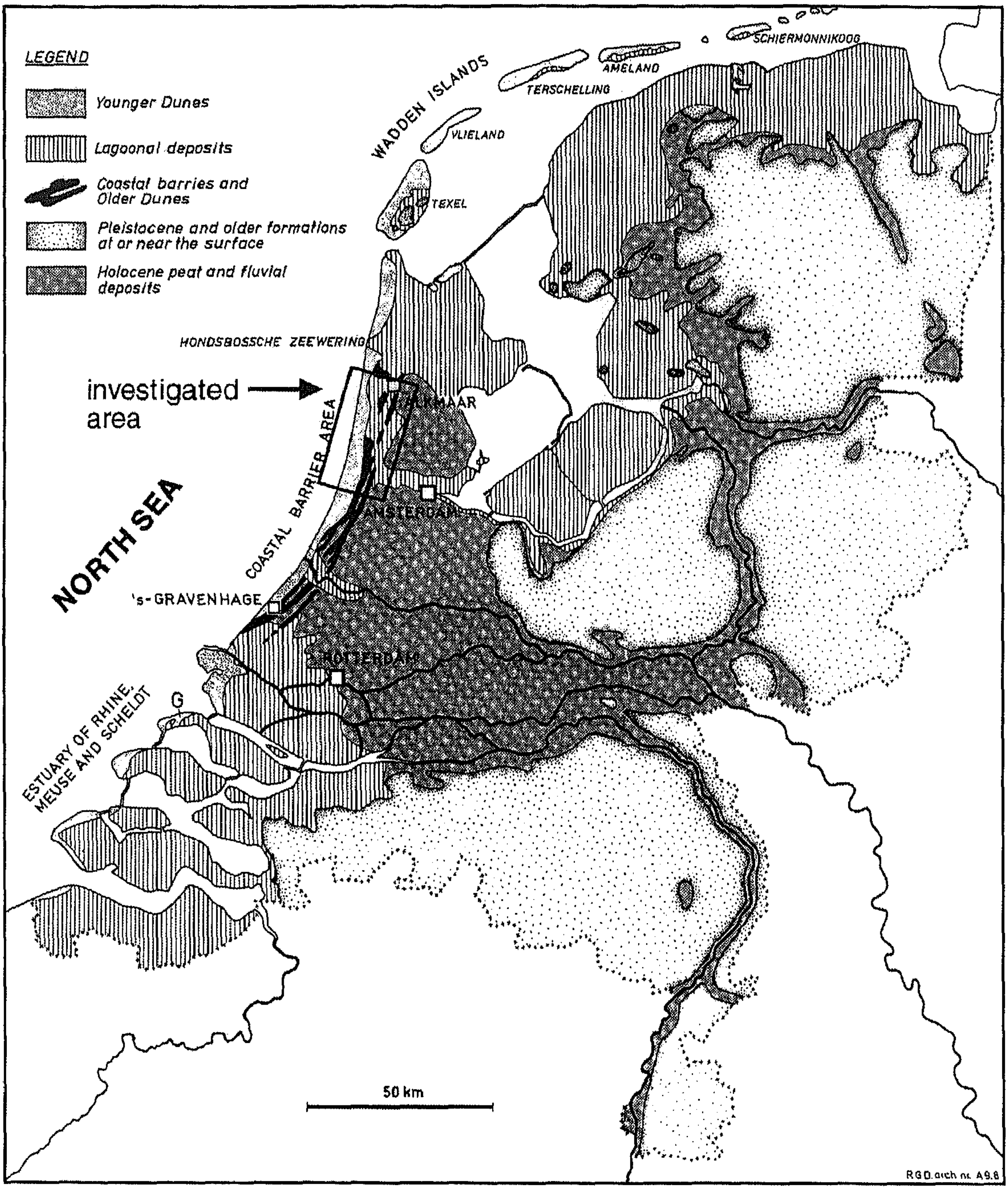


Fig. 1. Generalized geological map of the Netherlands. The study area is located in the Province of North-Holland.

repeatedly by periods of colonization by vegetation. This is illustrated by the occurrence of several soil and peat beds intercalated in the sand of the Older Dunes (Jelgersma et al., 1970). The formation of the Older Dunes was largely finished before the Roman period and a more or less dense vegetation covered the dune area. The western part of the Older Dune area is covered by the Younger Dunes which in contrast with the Older Dunes are much higher (up to 50 m). Another difference compared to the Older Dune phase is the enormous volume of sand that is involved: a sand sea invaded the coastal landscape which only later developed into the recent vegetated parabolic dunes. The major part of these aeolian sands must have been deposited between the 10th and the 16th century (Jelgersma et al., 1970).

The objective of this paper is to describe and discuss the occurrence and possible significance of Holocene shell deposits which have been found intercalated in the dune sands. Their approximate age has been determined through radiocarbon dating and analysis of their stratigraphical position. We believe that these deposits may well be the signature of extreme storm surge levels as they are present several meters above contemporary mean sea level and are likely deposited by wave induced swash or overwash processes.

In coastal environments, storm deposit sequences are known to have a higher preservation potential than fair weather deposits. For example, Kumar and Sanders (1974) describe this phenomenon in the sedimentary record of the nearshore zone of Fire Island (New York State, USA). The observations of shell layers in the storm deposit sequences described here are to our opinion mainly attributable to the high preservation potential of the storm deposits associated with a prograding coastline as was the case for the western Netherlands during the middle and late Holocene up to early Medieval times. It is only during recent times (from the early Middle Ages on) that this coastline receded. This clearly hampers the study of high (supratidal) shelly storm layers, as these are easily destroyed by aeolian reworking, human disturbance and reworking by the sea. Exceptionally, as is the case in one of the shell deposits discussed in this paper, these deposits have been saved from further erosion. There are few data on shell-rich storm deposits from the older barrier sequences of the western Netherlands, as most of the isolated shell were removed by leaching during subsequent stages of soil formation.

2. Observations of shell deposits

The shell deposits which are described below, were observed on five different sites (Fig. 2). The deposits found on four of the five sites are situated in the Younger Dune area. Two of these sites are located on top of former inlets, viz. the Bergen inlet in the north (site 1) which silted up about 3300 yr B.P. (Before Present) and the Oer IJ inlet in the south (site 2) which silted up about 2000 yr B.P. Sites 3, 4 and 5 are situated in an E–W section through the coastal barrier area of IJmuiden, approximately perpendicular to the present coastline. The first two of these sites are located on a coastal barrier which like the shoals of both former inlets have been overblown by dune sand: the Older Dunes which in turn have been covered by the Younger Dunes. Site 5 is located just east of the occurrence of the Younger Dunes, it is situated in the Older Dune area.

Except for site 1, the data have been derived through excavations which took place for different reasons. The excavations from which we took the observations for sites 3, 4 and 5 have been made to enlarge the harbour of IJmuiden and the Noordzee Canal to the Amsterdam harbour. Due to the speed of the excavation works the time to study the sections was very short.

2.1. Site 1: Bergen foredune

Presently, the foredunes on the Bergen site (for location see Fig. 2) are subject to strong erosion during storm surges. Observations over the last 60 years indicate that the foredunes erode at a rate of nearly a meter per year. From 1981 to 1990 regular inspections were made by one of us after storm surges on the nearly vertically eroded foredunes.

In the lower part of the dune cliff peaty layers and soils alternated with aeolian sands are exposed, belonging to the Older Dune sequence. These are covered by about 10 m of dune sand, at lower elevations characterized by parallel bedding and grading upwards in low angle cross bedding: Younger Dune sands. This is a typical sequence for the dune cliffs in this area. However, a striking post-storm observation was the occurrence of a

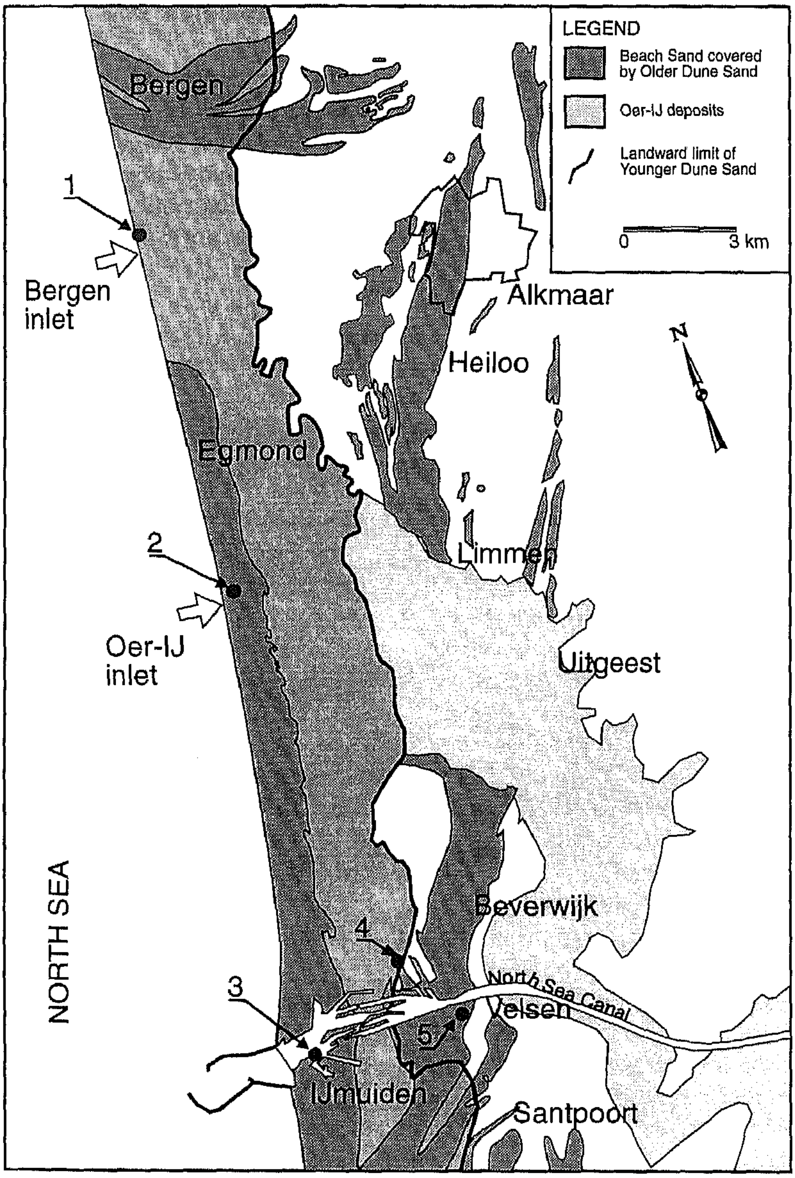


Fig. 2. Situation map of the investigated sites (simplified after Jelgersma et al., 1970).

shell layer intercalated in the Younger Dune sand, which was not present in other sections on this part of the coast (Fig. 3 illustrates the situation of the Bergen beach, Fig. 4 the sedimentary observations). Our interpretation is as follows.

Geologically, the site is situated at the Bergen inlet which closed about 3300 yr B.P. On top of the shoals of the inlet aeolian sands were deposited with intercalated peat layers. The top of the lowest peat layer was dated at 2400±30 yr B.P. (GrN-2112). Above this peat layer two soil horizons, separated by aeolian sands, are present which are thought to be formed after the Roman period and before the early Medieval. The upper soil layer is separated from the overlying sequence of low-angle to horizontal parallel bedded sets by a

Fig. 3. Bergen foredune (site 1) after a severe storm. On the beach a pre-Roman peat layer is exposed.

pronounced unconformity. On top of the parallel bedding a layer of convex-up lying lamella branch shells was observed. Usually, the thickness of this layer is that of one valve, but occasionally, two layers of convex up shells and small nests of shells occur. The shell assemblage consists predominantly of *Spisula subtruncata* with subordinately *Cerastoderma edule* and *Donax vittatus* indicating a shallow, open marine North Sea fauna. It is our hypothesis that the shells have been deposited by water flow as a result of a storm surge event due to which waves breached through the foredune and an overwash type current of water, sand and shells invaded a dune valley. If our hypothesis is true, the exposure in the recent dune cliff must be a cross-section through that valley which is now exposed due to the recent erosion of the shoreline.

The high elevation of this marine deposit, situated at 5 m above NAP (Dutch Ordnance Datum, about equal to present Mean Sea Level), would be indicative of an extreme storm surge level. The deposit was present over a length of 750 m in the exposed dune cliff and levelled upwards and disappeared at the south end at an altitude of +6.55 m NAP (Fig. 4). In the north this could not be observed due to the slumping of the dune cliff.

About the age of the observed deposit the following can be stated. The stratigraphical position of the level situated in the Younger Dunes indicates an age younger than the 10th century. The occurrence of a piece of red brick in the shell layer points to an age younger than the 14th and the absence of *Mya arenaria* to an age older than the 17th century (*Mya arenaria* was introduced in the Dutch coastal area in the early 17th century). Although the shell material might have been reworked two AMS radio datings were carried out:

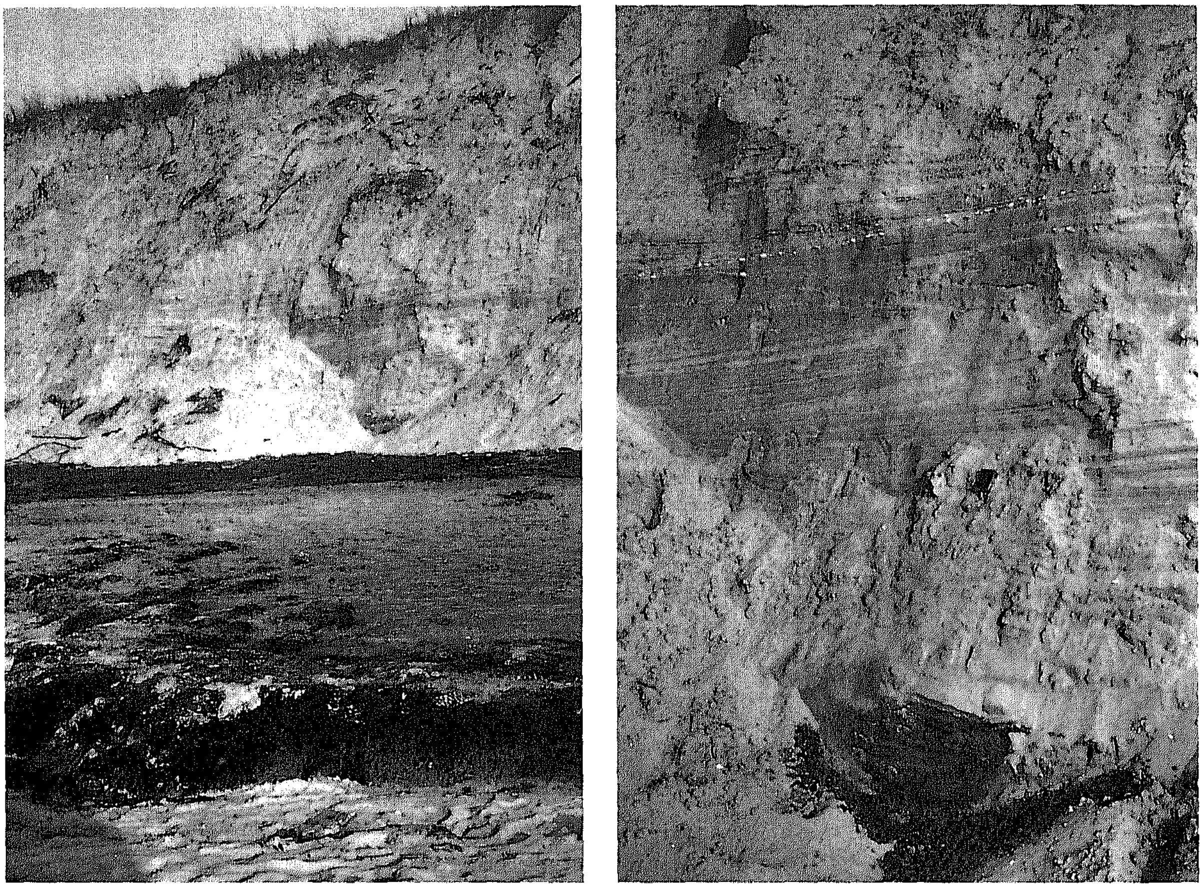


Fig. 4. (a) Bergen (Province North-Holland, site 1): state of the dune cliff following the February 1984 storm surge. The beach is significantly eroded, only a lag deposit of heavy mineral sand (approx. 80% garnet) is present in front of the dune cliff. In the foreground a 30 cm thick peat layer of pre-Roman age is seen (top between 0 and +1 m relative to NAP). Covering the peat layer, a soil horizon of dune sand is developed. At higher elevations cross-bedded late Medieval Younger dune sand is deposited, truncated by the shell-rich storm surge deposit. On top aeolian low-angle cross-bedded early historic Younger Dune sand is deposited. (b) Detail Bergen foredune (site 1): at the base of this section the dark coloured Older Dune sands are visible, influenced by soil formation. On top of these, two-phased Younger Dune sands were deposited, separated by the proposedly 1570 A.D. storm surge level, marked by the presence of shells between elevations of 5.10 and 6 m above NAP.

(1) a fragment of *Spisula subtruncata*: 2650±70 (Utc-1828)

(2) a fragment of juvenile *Spisula subtruncata*: 710±50 (Utc-1829)

The first age predates the unconformity and consequently is considered much too old; the second dating indicates (after calibration) the periods 1255/1296 Cal A.D. and 1360/1378 Cal A.D. These last datings seem to be more realistic in view of the stratigraphic position but may be too old in relation to the presence of the red brick fragments indicating a date from the 14th century onwards.

2.2. Site 2: Bakkum dunes

This site is situated in the area of the Oer IJ inlet which silted up and closed during the Roman period. Excavation activities in 1990 at a site 700 m from the present coast line in dune sand deposits very rich in marine shells yielded the observations which we report on below. The sedimentology and lithology of the discussed section is presented in Fig. 5a, the lacquer peel is given in Fig. 5b.

The top of the aeolian sands of the Younger Dunes is situated in a dune valley at about 3 m above NAP. Intercalated in the dune sand is a shell rich layer in and on top of a pronounced zone of slumping structures (load cast). The encountered deposit is interpreted as due to a sand rich flow laid down in the dune valley by a storm surge event. The elevation of the top of the marine deposit is at 2.30 m above NAP, the base at 2.0 m above NAP. The associated shell assemblage is a shallow open marine North Sea fauna rich in *Spisula subtruncata* and *Mactra corallina*.

Peaty soil on top of the Older Dunes that was expected underneath the surveyed section separating the Older from the Younger Dune deposits was not present, as appeared from a boring which penetrated the dune sand layer and the top of the underlying beach deposits (approximate depth NAP). This could be due to the fact that this soil has been deflated by the activities of the blown

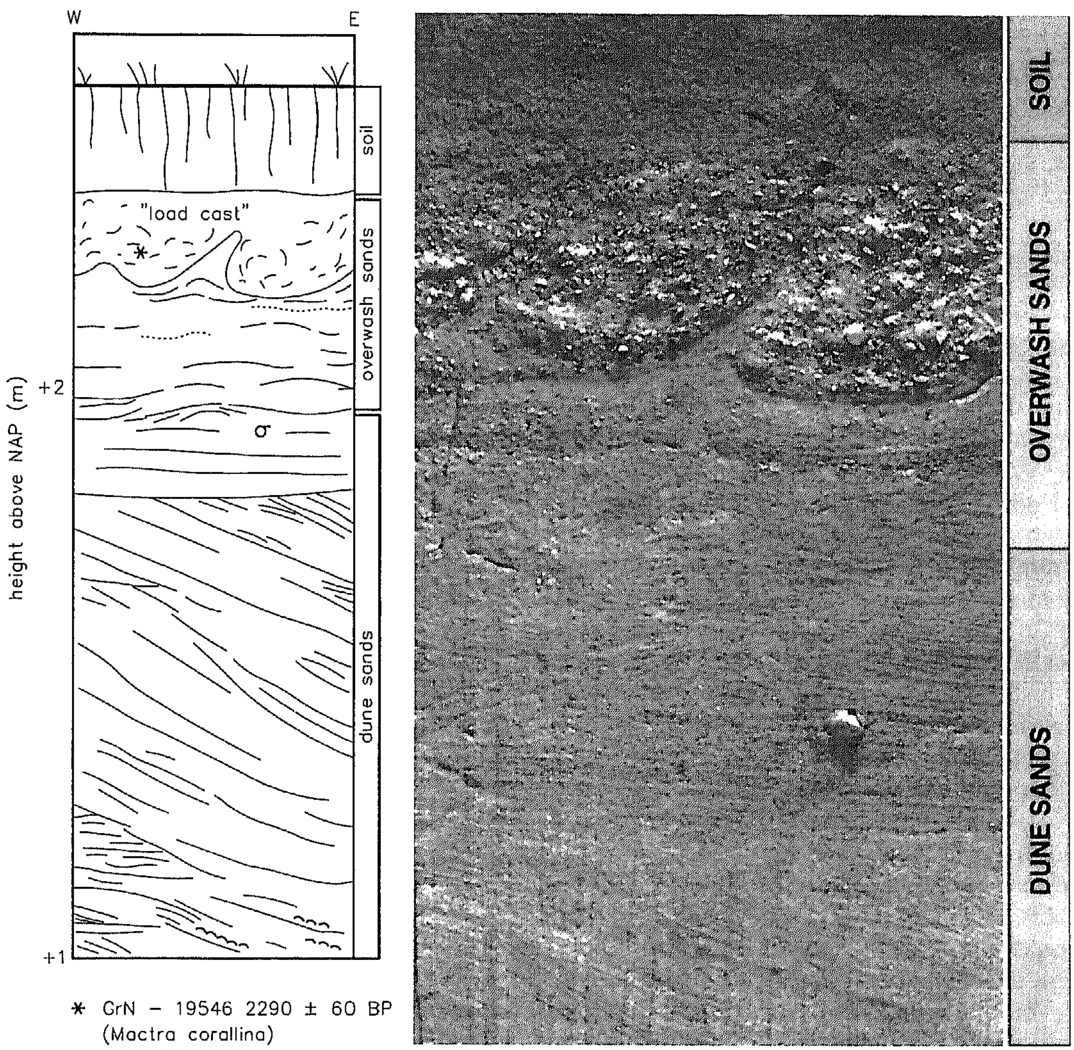


Fig. 5. (a) Sedimentology (cf. lacquer peel: Fig. 5b) and (chrono-)stratigraphy of the Bakkum site. For legend of symbols see Fig. 6. (b) Lacquer peel of the Bakkum site: shell layers in a low angle seawards dipping lamination (dip of slope 1:17–1:40).

sand deposits of the Younger Dunes or the observed site is much older and the deposits relate to a storm surge that took place shortly after the closing of the Oer IJ inlet. The stratigraphical position of the site does not resolve this point and indicates an age either Roman or historical. We therefore rely on a radiocarbon dating of fresh looking *Mactra corallina* to date the deposit by mean of the radiocarbon method. The age of the shells (2290±60, GrN-19546) would indicate that the storm surge deposits are laid down during the final stage of the Oer IJ inlet shortly after the Roman period.

2.3. Site 3: IJmuiden fishing harbour

Excavation works to enlarge harbour facilities in IJmuiden made it possible to survey an E–W section over a length of 40 m. The section is situated about 300 m from the present coastline. The upper 3 m of the location were already removed a few decades ago. An outline of the lithology and sedimentology of the section is given in Fig. 6; Fig. 7 illustrates some details of the north side of the section. A most interesting aspect of the 3 m deep excavation is the occurrence of several seawards sloping shell layers of marine origin. The gradient of the seaward slope is between 1:17 and 1:40 which is similar to gradients found at present beaches along the Netherlands' North Sea coast (Roep, 1986). On the western side of the 3 m deep excavation the following sedimentary sequences were observed (Roep, 1989; Van der Valk, 1991):

Sequence 1: the upper meter of the excavation consists of aeolian sands with a base of two convex up shell layers, mainly composed of *Cerastoderma edule* shells. These shell layers show a low angle seawards dipping lamination, which indicates a swash zone environment. The shell layers are present between 3.10 m and 3.40 m above NAP.

Sequence 2: a section between 3.00 m and 2.50 m above NAP consists of aeolian sand characterised by low angle cross-bedding, the basal part containing snails of the terrestrial gastropod *Cepaea nemoralis*. The lower part of the exposed section, +2.10 m to +1.40 m, shows aquatic conditions, the three convex-up shell layers dip seawards at very low angles.

The configurations displayed by both these sequences make it very likely that these deposits were formed in a swash zone. It is our interpretation that the aeolian sedimentation which took place on top of the underlying coastal barrier was

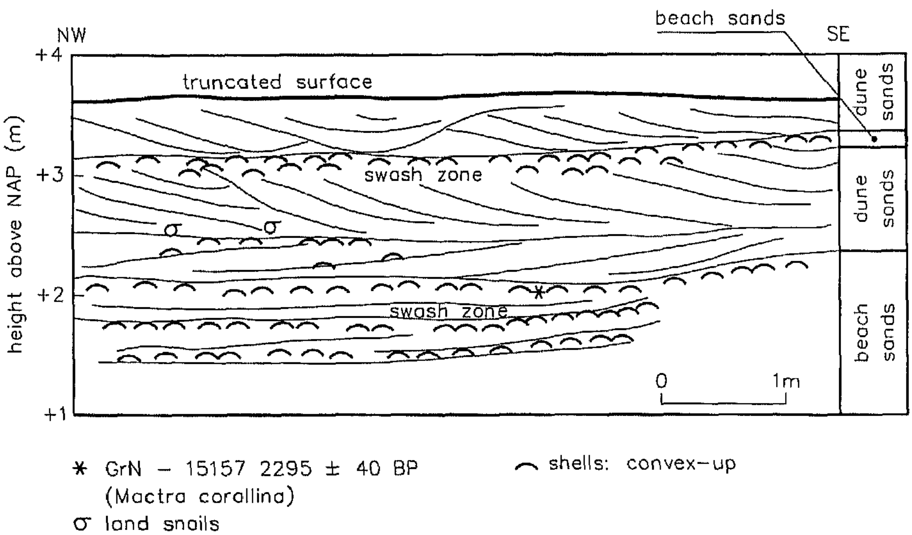


Fig. 6. Sedimentology and (chrono-)stratigraphy of the IJmuiden fishing harbour section. Note the interfingering of beach and aeolian sediment.

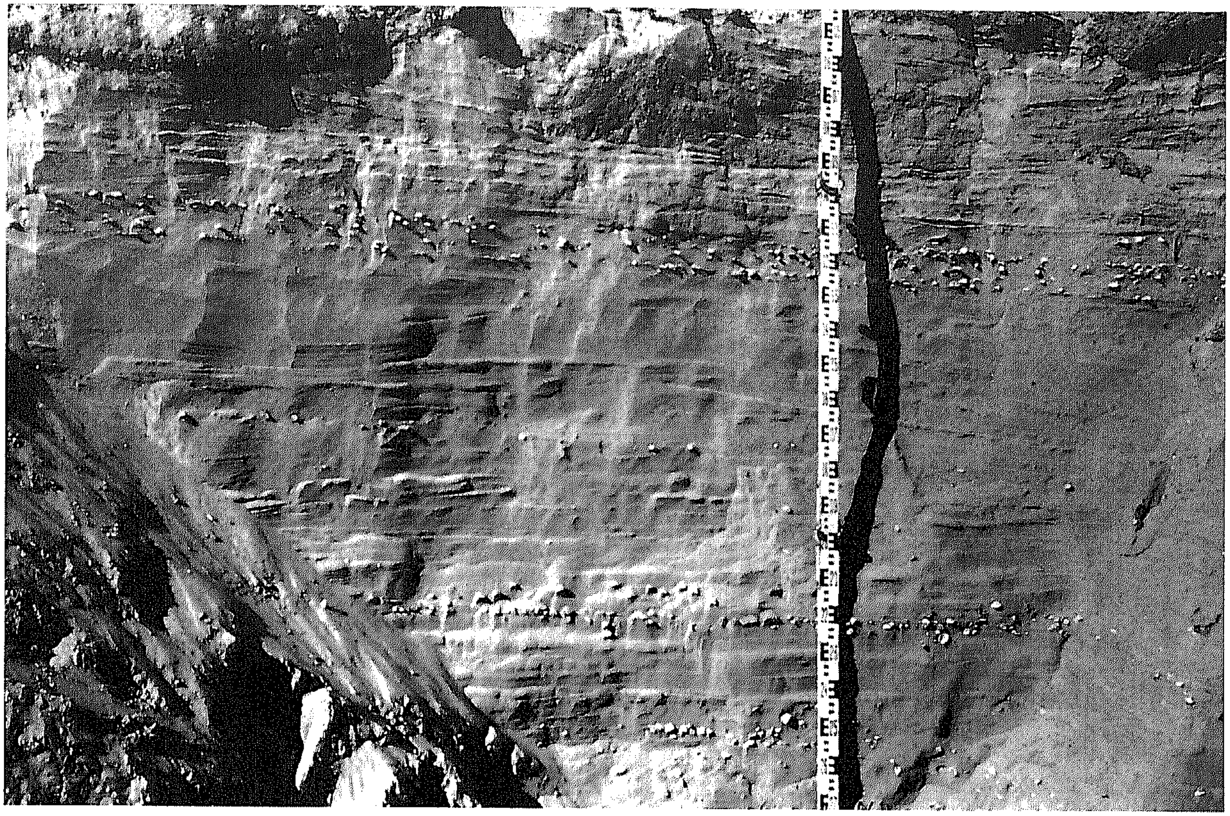


Fig. 7. IJmuiden fishing harbour: bivalved and juvenile shells in a beach deposit on top of dune sand. For legend of symbols see Fig. 6.

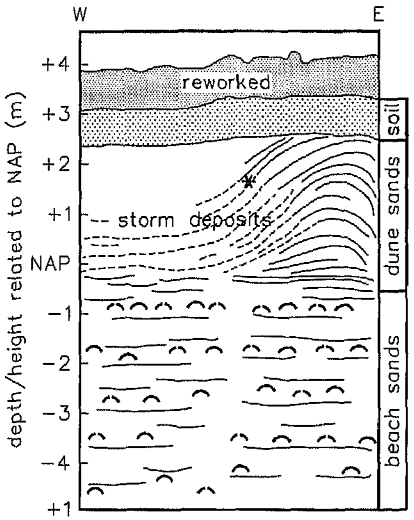
interrupted several times by swash activities. This resulted in storm surge deposits intercalated into the aeolian sands. The observed sequences in the studied excavation confirm the swash induced deposition levelling upwards and disappearing in the dune area to the east.

The age of the marine swash deposits is given by a radiocarbon date of the shells *Mactra corallina*: 2295±40 yr B.P. (GrN-15157). More details about the sedimentology of the discussed excavation can be found in Van der Valk (1991).

2.4. Site 4: Velsen P.E.N.

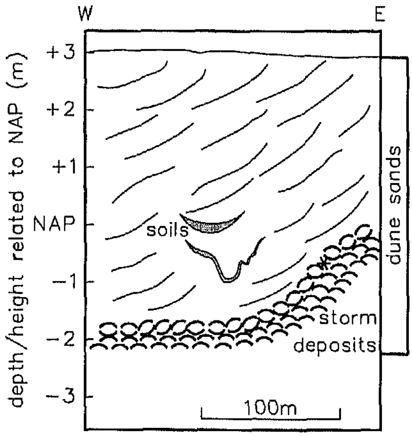
Data of the excavation at the Velsen site presenting a detailed sequence of beach sand grading upwards into aeolian sands with intercalated soils have been published by Jelgersma et al. (1970). The excavation was situated on the edge of the Younger Dunes, accordingly only a thin layer of these deposits is present. The present discussion focuses on the convex up shell layers intercalated in the aeolian sands levelling upwards in eastern (landward) direction. The highest level of the shell layers at the excavation is situated at 1.30 m above NAP, the lowest at 0.20 m below NAP.

As indicated in Fig. 8, a zone containing several layers rich in organic material and juvenile *Spisula subtruncata* shells is intercalated in the cross-bedded dune sand. The shell zone is interpreted as a storm surge deposit laid down in a dune slack near the shoreline. The surge waves were pushed upwards on the dune ridge on the east side where a well developed set-up of the storm deposit can be observed. The juvenile *Spisula* shells are dated by the radiocarbon method: 3400±55 yr B.P. (GrN-4566). This date should be closely indicative of the occurrence of the responsible storm surge event.



* GrN – 4566 3400 ± 45 BP
(Cerastoderma edule)

Fig. 8. Sedimentology and (chrono-)stratigraphy of the Velzen P.E.N. site (modified after Jelgersma et al., 1970). For legend of symbols see Fig. 6.



* GrN – 5853 3845 ± 45 BP
(Cerastoderma edule)

Fig. 9. Sedimentology and (chrono-)stratigraphy of the North Sea Canal site. Modified after Zagwijn (1992). For legend of symbols see Fig. 6.

2.5. Site 5: North Sea canal

In 1969 a very large excavation (perpendicular to the former shorelines) along the North Sea canal could be inspected. In an internal report of the Geological Survey, Zagwijn (1992) described the observed sedimentological record (Fig. 9) and an interpretation of the section is given. The data presented below are derived from this internal report.

Part of the section is situated east of the Younger Dunes where Older Dunes sands are present at the surface. The sands of the Older Dunes are intercalated by several soil and peaty layers which have been dated by the radiocarbon method and which indicate the stand still phases of the aeolian process. At the base of the excavation a beach is present, characterized by three shell layers intercalated in the beach sands. From top to bottom: a shell layer of bivalved *Cerastoderma edule* and *Spisula subtruncata*, a layer with mainly small *Spisula subtruncata* shells and finally a layer of *Cerastoderma edule*. The last two shell layers show a typical convex up position. The bivalved *Cerastoderma edule* are living in the foreshore at waterdepths between 7 m and 15 m (Van der Valk, 1991). Severe storm waves should be held responsible for removing the molluscs from their living position, washing them ashore and depositing them on a storm beach line. If the three observed shell layers are assumed to be deposited during the same storm surge they may represent three subsequent high tide levels during the storm period. If this were true it implies that the storm lasted more than a day and a half. The base of the storm surge beach plain is situated at 2.00 m below NAP but eastward the three shell layers could be observed on the upwards slope of a duneridge. The highest level of the bivalved *Cerastoderma edule* layer was observed at NAP. It was concluded that the *Cerastoderma edule* bivalves and the shells of the underlying layers are storm surge deposits that were pushed upwards by wave energy on the slope of the foredune (see also the illustration in Fig. 10).

The radiocarbon age of the bivalved *Cerastoderma edule* was measured to be 3845±45 yr B.P. (GrN-5853). Also in this case we believe that this date should be closely indicative of the occurrence of the responsible storm surge event.

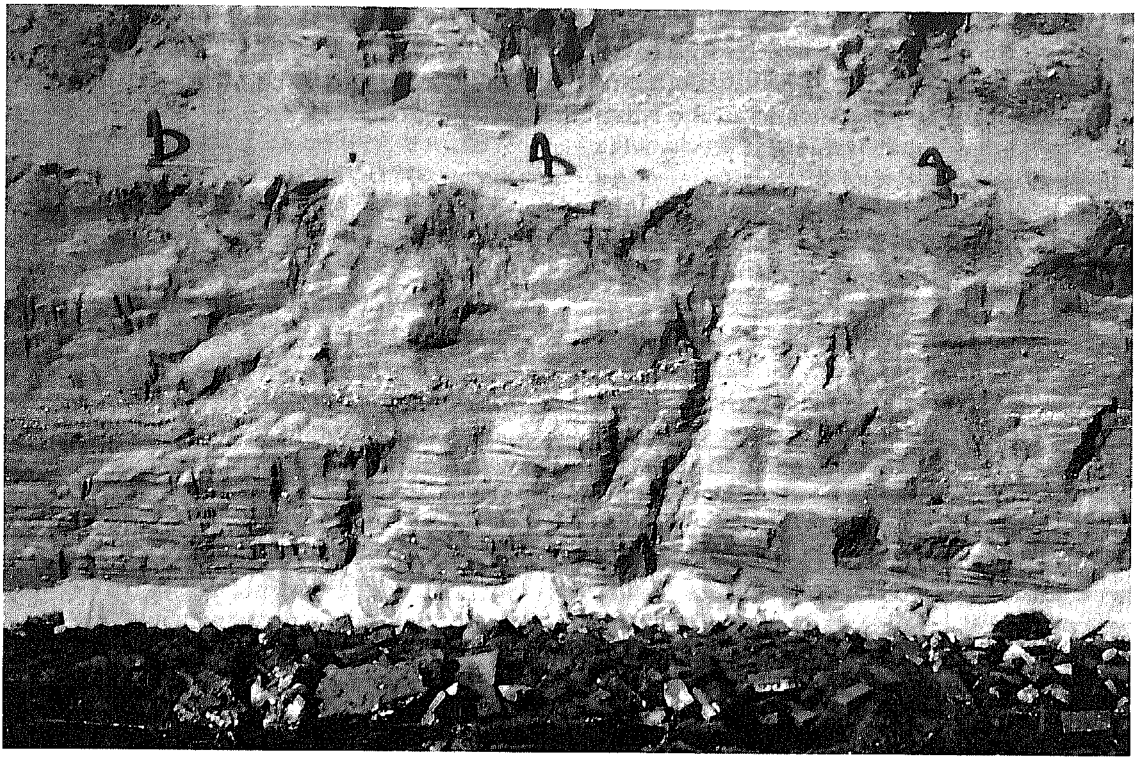


Fig. 10. Section of the North Sea Canal site: shells on the upwards slope of a dune ridge.

3. Reconstruction of storm surge levels

As described above, we hypothesize that the above shell deposits are the result of storm surge activity on the foreshore and of subsequent preservation due to aeolian coverage of a basically sedimentary, prograding coastal system. A primary objective of this study is to assess the levels of the extreme storm surges that we think are associated with the deposits. However, a fundamental and interesting aspect which we find difficult to resolve is what the deposit levels tell us about the actually occurred nearshore mean storm surge levels. The indications that we have, lead us to believe that in some cases the deposits are the result of swash zone processes on the foot of the dune. In that case the swash zone level is determined by the storm surge level including the dynamic wave set-up and run-up. This implies that the average storm surge level near the waterline could be increased by 10% to 20% of the offshore incident wave height (Battjes, 1974). In other cases, the deposits are the result of overwash of the swash deposits after failure of the dune. If, in this latter case, the overwash penetrates relatively far into the dune valley the level of the deposit is probably much closer to or maybe even below the mean storm surge level.

The above implies that there exists some uncertainty in the derivation of the storm surge levels from the shell deposit elevations. For instance, other variables like the slope of the beach and foreshore, the duration of storm surge and the offshore incident wave height may all influence the swash and overwash processes which may increase the actual nearshore storm surge level. As we will discuss later, it may be that the slope of the foreshore especially is of crucial importance. Obviously, we have no accurate quantitative knowledge of these "other variables" during the time span of our observations, and our estimates must be considered best guesses only.

The general approach that we have taken to derive the storm surge level associated with the respective deposits is as follows. Firstly, in case of swash deposition or overwash close to the initial waterline we assume that the lowest level of the deposits is most indicative of the nearshore storm surge level, since we expect the higher levels to be influenced by dynamic wave set-up and run-up. In the case of deeper penetration of the overwash we have taken the maximum observed elevation as more correct. Secondly, these absolute levels need to be related to the contemporary mean sea level, which stresses the importance of an accurate dating of the deposits. The relative mean sea level curve of Roep and Beets (1988) is considered the most accurate to date and is thus used as an indicator of the contemporary mean sea level elevations. The mean high water curve is situated 0.80 above the mean sea level curve, where it is assumed that the present MHW level (0.80 m above NAP) in this region reached the same elevation in the past. The present tidal range along this part of the coast is 1.65 m.

The observations of the top and base of the shell deposits of all investigated sites is presented against time, using the respective datings, in Fig. 11. The assumed associated storm surge levels, which are discussed directly below, are indicated in meters above the contemporary MSL.

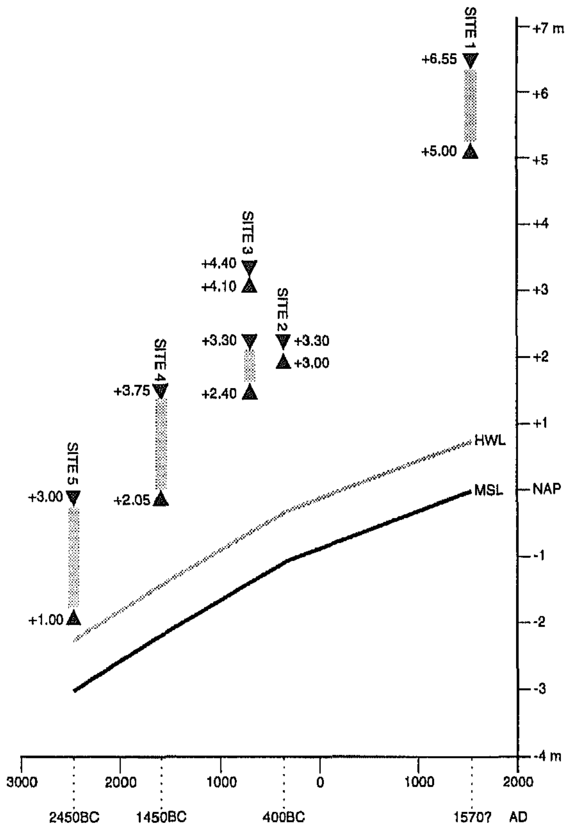


Fig. 11. Absolute and relative elevations of storm surge deposits versus time. The absolute elevations (vertical axis) are relative to NAP; the relative elevations (indicated in the figure) were corrected for contemporary Mean Sea Level (*MSL* and *HWL* curves after Roep and Beets, 1988). Radiocarbon ages were transferred to age B.C./A.D.

3.1. Site 1: Bergen foredune

The shell deposits in the Bergen foredune were observed at an elevation of 5.00 m above NAP laterally levelling upwards to 6.30 m above NAP. In this case we presume that this deposit is primarily caused by overwash of the shell assemblage collected in the swash zone after failure of the foredune. As stated before we hypothesize that the lower elevations are indicative of the mean storm surge level, since the higher elevations are influenced by wave run-up and set-up against the former foredune.

In this context it should be mentioned that the present foredune elevation of about 15 m is due to the planting of bent-grass (*Ammophila arenaria*) in order to prevent the moving of sand landinwards. Before this human interference (which started by law at 1850 A.D.) the foredunes were supposedly much lower. Consequently, waves due to storm surges before that time could more easily breach through the foredunes and enter dune valleys. About 3 km north of this site the foredunes are still low and as a result the storm surges of 1928, 1953 and 1972 breached through the foredunes and flooded the low lying dune slack as far as the second dune ridge. During the severe 1953 storm surge the foredune was breached over a length of 350 m and a flow of seawater and debris penetrated 450 m landinwards until the second dune ridge. We expect that the present deposit is an analogue to this event. The observed rising level that disappeared on the southside could be a dune ridge bordering the flooded valley.

Regarding the dating of this deposit we recall the uncertainty that was mentioned in that the shell dating indicate the 13th century, but the red brick fragments make a dating of the 14th century or even somewhat more recent possible. With respect to the storm surge elevation relative to contemporary mean sea level the precise dating is less relevant, since the mean sea level according to Roep and Beets (1988) is assumed to be close to present MSL from the 13th century onwards. In the discussion below we will place these findings in the context of historic descriptions, and make a more definite conclusion regarding the dating.

3.2. Site 2: Bakkum dunes

The observed site is most likely situated landwards of the contemporary shoreline as indicated by its position on top of the former Oer IJ inlet. In contrast with the other observed deposits we have indications that this encountered deposit is due to a sand loaden overwash flow laid down in the dune valley by a storm surge event. The highest elevation of the marine deposit is at 2.30 m above NAP. This would imply that this elevation of the deposit is the best educated guess of the concurrent storm surge level.

The datings described earlier make a Roman age most probable. The relative mean sea level curve of Roep and Beets (1988) indicates a mean sea level during the Roman period of 1.00 m below the present MSL. Accordingly, an extreme storm surge level of 3.30 m above contemporary MSL during this "Roman" storm surge occurred. Hypothetically, this could have been a signature of the same storm surge that is observed at site 3, but this cannot be asserted due to the uncertainties of the datings. If so, these elevations would be 0.50 m to 1.00 m below the nearshore storm surge level.

3.3. Sites 3, 4 and 5: IJmuiden fishing harbour, Velsen P.E.N., North Sea canal

The deposits observed in sites 3, 4 and 5, all taken along the same cross-shore transect, have each been found to display the character of swash zone deposits. Therefore, we assume that the lowest elevations of each sequence are indicative of the concurrent mean storm surge level.

At site 3 the series of convex up shell layers intercalated in the aeolian sand are the signatures of at least two storm surge events. The lowest elevations reach 3.10 m and 1.40 m respectively above NAP. The contemporary mean sea level is about 1.00 m below the present one as indicated by the data of Roep and Beets (1988), so that absolute storm surge elevations of 4.10 m and 2.40 m are found around 2295 yr B.P.

At site 4 the shell deposits range in elevation between +1.50 m and −0.20 m relative to NAP. The mean sea level of this age is estimated to be some 2.25 m below NAP (Roep and Beets, 1988). Consequently, we estimate the concurrent storm surge level of 3400 yr B.P. (1700 B.C.) to reach 2.05 m above its contemporary mean sea level.

The bases of the three deposits at site 5 are present between 2.30 m and 2.00 m below NAP, showing a levelling upwards in eastward direction to approximately NAP. The relative mean sea level according to Roep and Beets (1988) is approximately 3.00 m below NAP, so that we infer the occurrence of a storm surge levels of 1.00 m above contemporary MSL around 3845 yr B.P.

4. Recent and historical storm surge levels

Shortly after the 1953 flood disaster, which caused severe damage both in terms of lifes and land loss in Zeeland, the Dutch Minister of Public Works installed the Delta Committee and commissioned it to draw up a plan to protect the Netherlands against flooding disasters. One of the Committee's primary achievements was the assessment of storm surge levels which could be exceeded once per 10,000 year for a large number of primary water level recording stations. Along the central Netherlands' coast there exist two such primary water level recording stations with long term registrations, viz. Hoek van Holland and Den Helder. Uninterrupted, homogeneous registrations are available from 1887 and from 1932 respectively. The Delta Committee assessed the 10^{-4} frequency of exceedance (in number of storms per year) levels for these stations at 5.00 m and 5.05 m above NAP respectively. The 1953 registered level at Hoek van Holland was concluded to have reached 3.85 m above NAP.

Recently, a reassessment of the Delta Committee's exceedance frequency findings was done (Rijkswaterstaat, 1993), using both the—meanwhile—longer recordings, new statistical methods and physical, meteorologic and hydrodynamic models. This assessment included a best estimate for Station IJmuiden, which should be considered most representative for our sites. Using the longest recorded time series, the methodology used indicates a 10^{-4} frequency of exceedance level of 5.30 m $\pm$ 2.10 m for IJmuiden, where the accuracy range encompasses twice the standard deviation. The highest recorded level at Hoek van Holland amounts 4.05 m above NAP with an expected exceedance frequency of 10^{-2} approximately.

If we assume that this analysis also holds for the time span considered by our data, the above findings indicate that the majority of the storm surge levels that we inferred have exceedance frequencies below 10^{-2}. Only site 1 displays an exceedance frequency of the storm surge elevation which is severely extreme and deserves further evaluation, also since we have some uncertainty regarding the precise dating of this event. To this end we consider historical data.

Many descriptions have been published about historical storm surges in the Netherlands by Gottschalk (1975) and around the North Sea by Lamb and Frydendahl (1991). The reports are mostly qualitative in that they are limited to a description of the amount of land lost or flooded and how many people lost their life. Also, there exists the possibility that a lot of disasters were caused by bad maintenance of the dikes and not be the result of the severeness of the reported storm. However, little is know about the heights reached by these many storms. Only Gottschalk (1975) published data of the height of the water level reached by the All Saints Flood in 1570.

Regular readings by means of tide gauges do not go back before 1805 (Van Malde, 1992). Van Malde (in press) was, however, able to trace more reliable data about these historical storm surge levels. Not all data were used as Van Malde selected only those data available on "so called stable and lasting constructions" like churches near the seafront. The oldest and highest level that could be traced occurred during the very severe All Saints storm surge of 1570 which caused great damage all over the coastal lowlands of the Netherlands. In the church of Scheveningen a water level of 4.00 m above NAP was reached; near Petten a newly reclaimed polder was inundated "13 ft deep", which would amount to a water level of 4.00 m above NAP. In Friesland near Metslawier a level at least 3.75 m above NAP could be traced. Near the German–Dutch border, in East Friesland, a level of 4.70 m above NAP was reached.

The few levels of severe storms 1682, 1775, 1825 traced by Van Malde were all lower than the All Saints Flood and also lower than the severe 1953 storm surge (water level 3.85 m above NAP). Van Malde concludes: "the 1570 storm surge caused the highest levels known ever along the Dutch coast between Scheveningen and Den Helder. Off the northern provinces and the adjacent German coast the storm surge levels were very near to the highest ones having occurred ever since".

The shell deposit was dated between the 14th and the 17th century. This age indicates that the deposits were laid down during the storm surges of either 1421 A.D. the Elizabeth Flood, the 1530 A.D. the Zealand flood or the 1570 A.D. All Saints Flood. The storm surges in 1421 A.D. and 1530 A.D. had their most serious impact mainly in the southwest of the country. In the region of site 1 it was reported that 7 km to the north the church of the village of Petten with 400 refugees disappeared into the storm waves of the Elizabeth Flood. In the region of our investigations the All Saints Flood had according to the early 17th century poet and historian P.C. Hooft, a most disasterous impact (Hooft, 1642). He refers to the spring tide, new moon, and the duration of the severe storm, two full days; the inundations, breaches of the dikes of the newly reclaimed Zijpe polder with the lost of many houses and that fishing boats on the beach were swept by the storm waves into the villages destroying the houses. The severity of these impacts accord very well with the height of this storm surge near Petten of 4.00 m above NAP, as indicated by Van Malde (in press). In accordance with these data, we suggest that the observed storm surge level in the present Bergen foredune is caused by the All Saints storm surge.

5. Discussion and conclusions

Our indications are that the shell deposits found at five different sites along the central Netherlands' coast are signatures of storm surge events. Since the stratigraphical positions and radiocarbon datings indicate that their occurrences cover a large time span of the recent Holocene, these observations may provide additional and valuable insight into recent Holocene levels of extreme storm surges. This should enhance our comprehension of the likelihood of extreme storm surge events, and the possible role of different climatic and/or geometric (bathymetric = foreshore) conditions.

Taking account of the contemporary mean sea level an interpretation was given of the surge level elevations associated with the depositions. These levels are presented in Fig. 12, where we have indicated the uncertainties related to the respective dating procedures and where we have included some of the more recent registered extreme levels.

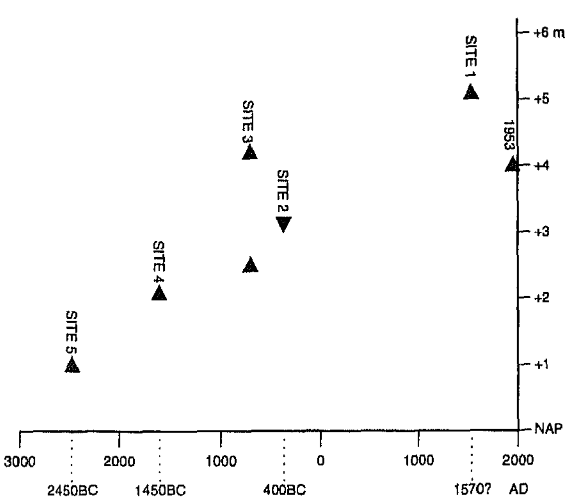


Fig. 12. Inferred storm surge levels relative to contemporary mean sea level versus time.

We note that there seems to occur an increase in the storm surge levels with increasing time. This is especially true for the elevation related to the most recent observations of site 1. Although statistically acceptable, we wish to make the following comments.

Sedimentological investigations in the coastal barrier area have indicated that the slope of the foreshore becomes steeper if the age becomes younger (Van der Valk, in press). After 800 A.D. this process caused serious shoreline erosion resulting in the formation of the Younger Dunes. These changes in the topography of the foreshore will influence the dissipation of the wave energy. It is likely that the shoreline of a steep foreshore will be more subject to wave energy than a less steep one. These changes in the slope of the foreshore that started after 4000 yr B.P. and culminated after 800 A.D. could in our opinion be responsible for the observed rise in storm surge levels.

Lamb (1984) has given a relation between climate changes during the Holocene and the occurrence of severe storms. In historical time a warm period occurred between 900 and 1300 A.D., called the Medieval Warm Epoch. A marked cold epoch followed, the so called Little Ice Age, with greatest extremes between 1400 and 1800 A.D. According to Lamb (1984) between 1675 and 1704 A.D. the water temperature of the Faeroes was 5°C lower than today. This low sea water temperature indicates changes in the penetration of polar water to the south. The boundary between the cold Arctic water and the warm Gulf Stream was pushed southwards during this period. This significant advance of the East Greenland Ocean current (polar current down the east side of Greenland) must have started already about 1200 A.D. but no data are available for this period (Lamb, 1984). We agree with Lamb that this could be the explanation of the occurrence of severe storms during the Little Ice Age as they are thought to be related to enhanced thermal gradients between 50° and 65°N.

In conclusion, we comment that—although our data may not be statistically accurate—we seem to observe an increasing level of storm surge elevations over the recent Holocene with a particular maximum during the Little Ice Age. It is our suggestion that climatic variations on the one hand

and foreshore bathymetry on the other hand may be factors of relevance to explain these observations. If these findings are correct this would imply that for a proper analysis of exceedance frequencies of extreme storm surge events it would be relevant to base such an analysis not only on present climate and foreshore bathymetry.

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