Late-holocene coastal evolution in the Hanstholm-Hjardemaal region, NW Denmark. Morphology, sediments and dating

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Raised gravelly spits and beach ridges were studied as components of the late-holocene coastal evolution in NW Jutland.

Two gravelly spits up to 8-9 m above the present sea level were dated 4000-4700 YBP by oyster shells, i.e. of late Littorina/Tapes subboreal transgression. Dating of organic matter suggested general dune stabilization within the study area from 471 YBP.

The data suggest that the study area operated as a semi- enclosed and sheltered embayment. The ridges indicate transgression of sediment masses arrested from the longshore drift, superimposed by moderate eolian accumulation.

Keywords: *Raised beaches, transgression, regression, dune building, coastal morphology, sediments, C-14-dating, NW Jutland, Denmark.*

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The post-glacial uplift of NW Jutland has raised both submarine and coastal sediments which make up raised shorelines in the emerged areas in the form of beach ridges and gravelly spits. Ridge complexes were explained in Australia by Thom (1983) as swash-aligned, indicating regressive depositional sequences subject to episodic wind erosion. He found ridges to consist of an eolian cap of low- angle cross-bedded strata, a beach face and nearshore sediments. Hine (1979) observed that berm development at the outer end of recurved spits may appear as ridges and swales. Raised gravel spits have not received much attention in the literature compared to raised gravelly beach ridges (Petersen, 1976; Gry, 1979).

The aim of this study is to resolve and define the main morpho-sedimentological components in the Hanstholm-Hjardemaal region, NW Denmark and to date and relate them to the late-holocene coastal evolution.

STUDY AREA

The study area covers 49 km^2 on the NW coast of Jutland (fig. 1) and is located in a former sound. The low-lying

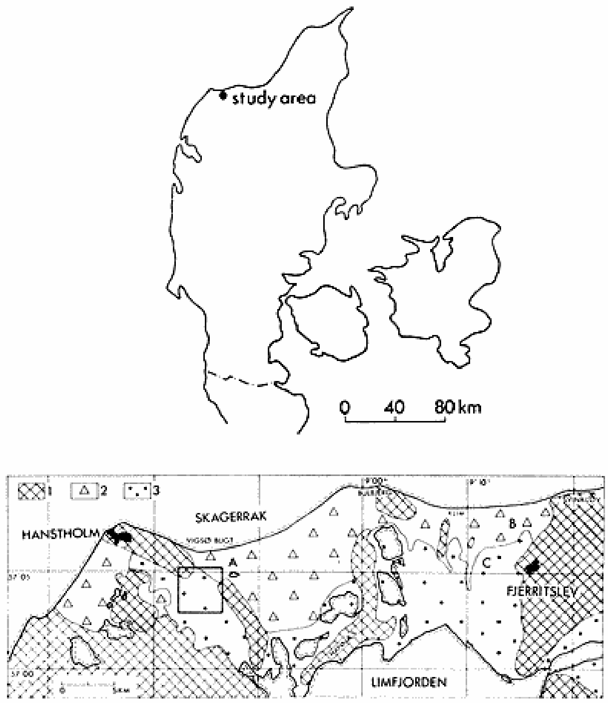

Fig. 1. Location map and characteristic geomorphological features in NW Jutland. 1) Glacial and fluvioglacial deposits. 2) Blown sand overlaying marine deposits. 3) Marine and coastal deposits.

Fig. 1. Oversigtskort visende studieområdet og karakteristiske geomorfologiske dannelser i NV Jylland. 1) Glaciale og fluvioglaciale aflejringer. 2) Flyvesand dækkende marine aflejringer. 3) Marine aflejringer.

areas express the entrenchment of the Weichsel ice into the Danian rocks, and also reflect the relatively erodible Senonian formations. Hanstholm and Hjardemaal stand out as stacks and indicate an arc of Danian chalk surrounding a Maastrichtian core. Their sharp and steep slopes may suggest marine undermining, or tectonic activity in the Tertiary and Quaternary (Hansen & Håkonsson, 1980). The main sediment drift along the coast bypassed the study area, and proceeded towards the northern tip of Jutland, forming the so-called Skagen formation in the Kattegat (Floden, 1973).

The general southward surface drainage in the study area results both from the general dip and from the dam-

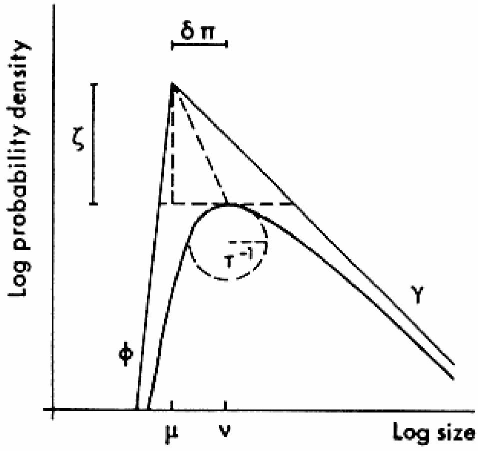

Fig. 2. Graphic interpretation of parameters from the hyperbolic distribution.

Fig. 2. Grafisk tolkning af parametre fra den hyperbolske fordeling.

ming effect of the coastal dunes. The latter show a progressive coastward increase in height, indicating an eolian phase nourished by the beach. The beaches show a pronounced retreat averaging 2.5 m/y (Hansen, 1968). A major period of coastal eolian activity in the study area is mentioned from 1550 AD to about 1800 AD (Bruel, 1918; Christiansen & Bowman, 1986).

Method

Field examination and air photos to a scale of 1:15,000 and 1:21,000 as well as topographic maps to a scale of 1:20,000, 1:50,000 and 1:100,000 were used for morphological analyses. In the field trenches were dug across the ridges down to a depth of 1.8 m. At each pit-exposure the structure, the stratigraphy and the soil profile were documented and the different sand units were sampled. Additional shallow pits and trenches were dug all over the area to ascertain former findings. Organic material, suitable for radiocarbon dating, was retrieved from several pits.

Sand size analyses were carried out using the standard sieving method. The log-hyperbolic distribution was fitted to the samples using the method of maximum likelihood (Barndorff-Nielsen, 1977). A computer program for estimating the parameters from the log-hyperbolic distribution (Jensen, 1983) was applied. Fig. 2 shows the graphic interpretation of the parameters. φ and ε are the slopes of the two assymptotes to the hyperbola. They are equivalent to the "fine grade" and the "coarse grade" of Bagnold (1941). μ is the location of the intersection point of the two assymptotes on the x-axis, and parameter σ is a sorting parameter. The skewness and the kurtosis of the hyperbolic distribution are very complicated functions (Barndorff-Nielsen & Blaesild, 1981). Throughout the triangle (fig. 3) χ and ζ express relatively, in a qualitative sense, the skewness and the kurtosis.

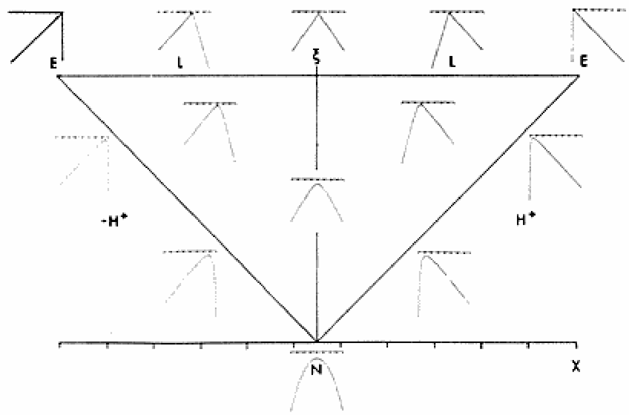

Fig. 3. The domain of variation of the invariant parameters χ and ζ of the hyperbolic distribution (the hyperbolic shape triangle). The letters at the boundaries indicate that the normal distribution (N), the positive and negative hyperbolic distributions (H^+ and $-H^+$), the Laplace distribution (symmetrical or skewed) (L), and the exponential distribution (E) are limits of the hyperbolic distribution. Also shown are representative log probability functions corresponding to selected (χ, ζ) values, including limiting forms of the hyperbolic distribution. (The distributions have been selected so as to have variance = 1).

Fig. 3. Variationsområdet for parametrene χ og ζ og fra den hyperbolske fordeling. Bogstaverne langs trekantens sider indikerer, at normalfordelingen (N), de positive og negative hyperbolske fordelinger (H^+ og $-H^+$), Laplacefordelingen (L) og eksponentialfordelingen (E) er grænsefordelinger til den hyperbolske. Endvidere er vist repræsentative log-sandsynlighedsfunktioner, der er valgt, så de har variancen = 1.

Radiocarbon measurements were done at the radiocarbon laboratory of the Weizmann Institute of Science, Rehovot, Israel. Carbonate samples were treated by acid and the organic matter was combusted in dry oxygen stream. The CO_2 was purified and converted to ethane. For measurements, proportional gas counting of ethane was performed (Carmi et al., 1971; Carmi, 1978). The half life used was 5568 years.

Ridge Morphology

The spacing and orientation of the multiple ridges in the study area follow a well-organized morphological pattern (figs. 4, 5). The ridges consist of continuous parallel lines of hummocky low relief 2.5-3.5 m high, including deflation saddles a few tens of meters wide. Strips of lowlands separate the ridges which are fully vegetated and stabilized through sand-binding grasses. Their cross section is almost symmetrical, i.e. the typically eolian asymmetry is not observed. The ridges also show no evidence of beach morphology; neither of berms, nor of washover surfaces.

The ridge morphology becomes very distinct and different from the eolian sheet morphology when using a contour interval of 1.5 m in the 1:20,000 topographic map.

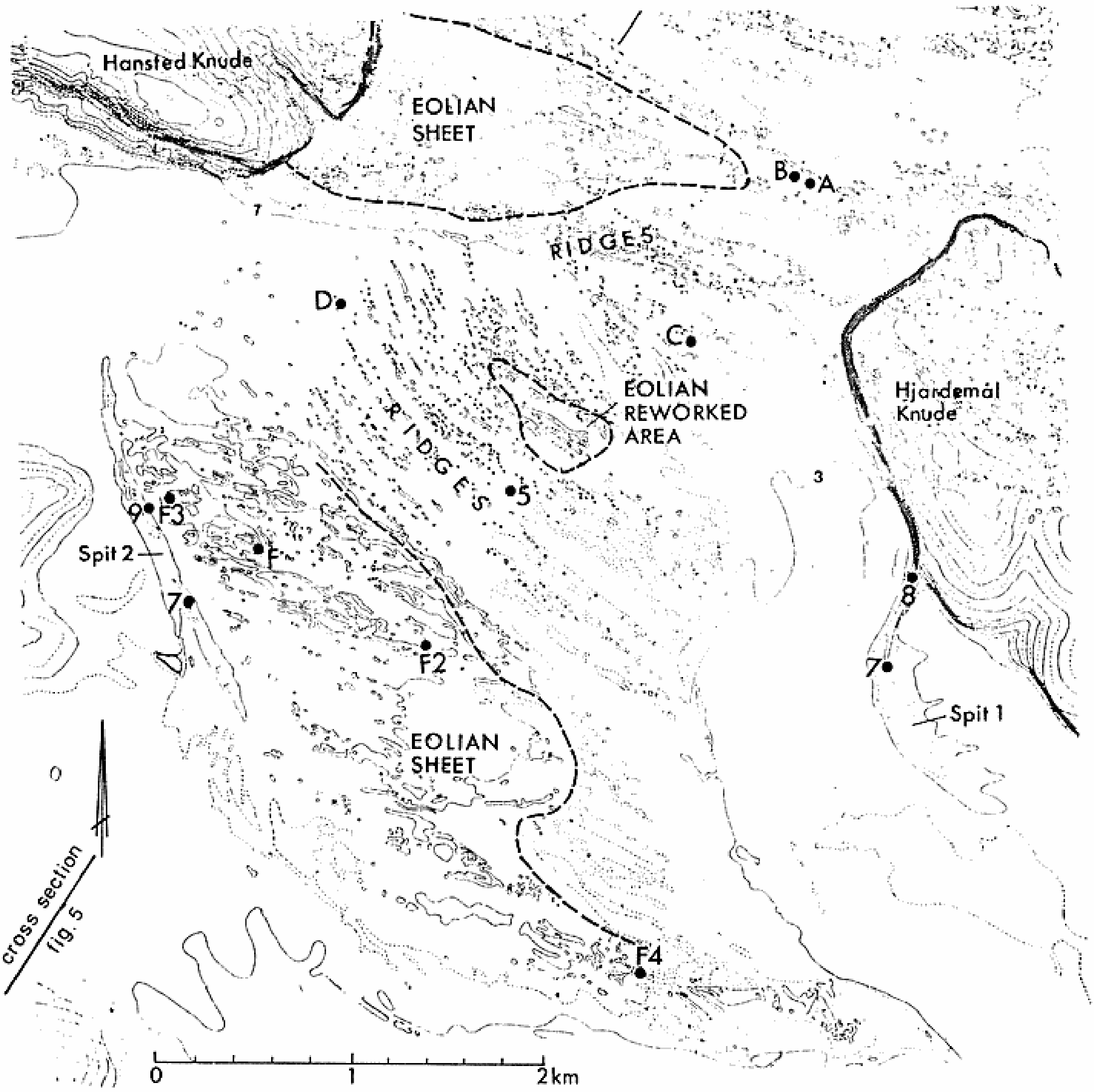

Fig. 4. The topography of the study area: Distribution of ridges and aeolian sheets. Also shown are sampling sites (A, B, C, D, F) and some altitude figures. Contour interval is 1.5 m. Reproduced with permission from the Danish Geodetic Institute.

Fig. 4. Studieområdets topografi med højdekurver for hver 1,5 m. Fordelingen af rygge og eolisk prægede flader såvel som prøvelokaliteterne (A, B, C, D, F) er fremhævet.

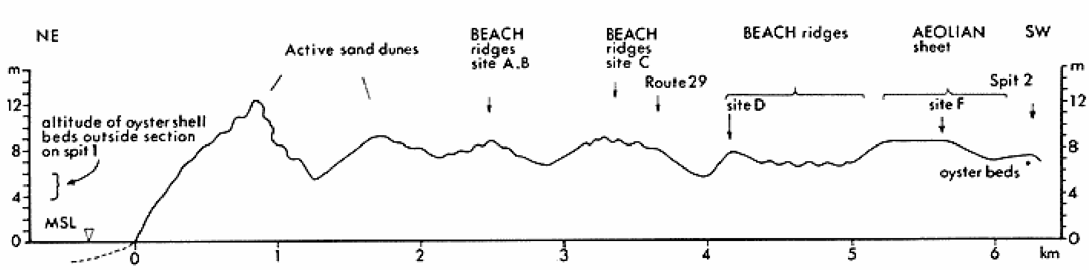

Fig. 5. Cross-section through the study area showing the main morphological units. Location of cross section is indicated in fig. 6.

Fig. 5. Profil gennem studieområdet med de vigtigste geomorfologiske enheder. Profilets beliggenhed er vist på fig. 6.

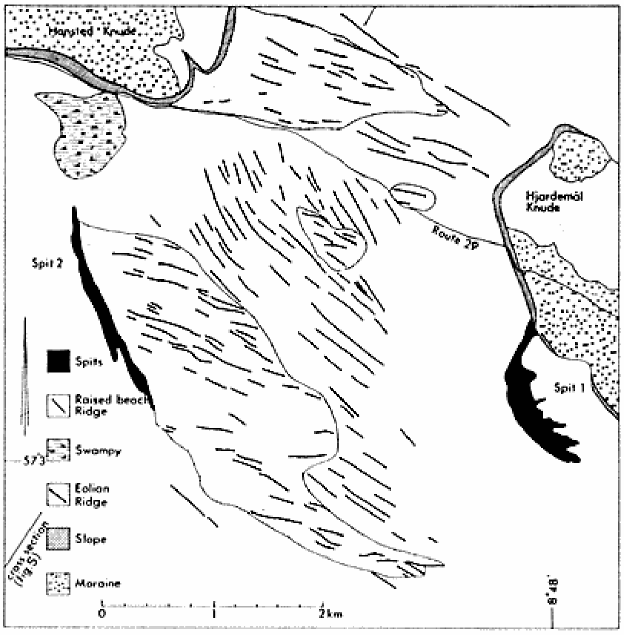

Fig. 6. Morphological lineaments and interpretation following Christiansen & Bowman (1986).

Fig. 6. Morfologiske lineamenter og tolkning efter Christiansen & Bowman (1986).

Each morphology is shown here by its preferred orientation (fig. 4). The ridges are typified by their overall longitudinal shape and parallel cluster which clearly manifest continuous, parallel, narrow and low-relief curved lineaments. Because of their gently arcuate plan-view form (fig. 6), their bearing gradually changes from N122°E (site A) to N172°E in the south (site D). Curved vegetated beach ridges are very common along spits and were studied by Reinson & Rosen (1982), Martini (1975), Swift (1968), and by Semeniuk & Johnson (1982). In southeast Australia the proposed modes of beach ridge formation were accreted bars and berms (Hine, 1979), and trapping of eolian sand within pioneer plant species, thereby composing a crest and swale topography of incipient and older foredunes (Hesp, 1984).

The area to the southwest distinctly lacks this sharp linearity and parallelism, and shows instead a patchy pattern, flatter surface, and a N67°E trend which clearly differs from that of the ridges. The sandy composition, patchy form and preferred orientation suggest a fixed eolian sheet, reflecting former eastward-moving coastal dunes. The directional discordance and the morphology separate the ridges most distinctly from the eolian sheets and permit defining within the ridge area patches which have already been reworked, i.e. which have attained, through eolian activity, the directions and the characteristic eolian sheet morphology (fig. 6).

Soil Development

The Atlantic climate combined with the sandy parent material and with Ericaceae and other heath vegetation-cover favor podzolization on both the ridges and the eolian sheets. The typical sandy soil profile on the ridges lacks multicyclic soil development. Peat does not underlie the ridges and is encountered only between them, implying a very young post-ridge stage. Over the entire ridge area the soil profiles are concordant with the topography, i.e. no major ridge truncation has occurred since the soil was formed except recent cattle deflation.

In the southwest area (fig. 4) two relatively well- developed, superimposed soil units are the rule, each followed by nondeposition and soil formation. On site F3 (fig. 4) four sequences of A0 +A2 horizons were observed, indicating higher dynamics and cyclicity. The soil sequences on the eolian patchy morphology suggest several eolian import episodes.

The internal structure of the ridges

Internal structures often serve as a clue to palaeogeography. Along rapidly accreting beaches, berm-ridges are the most abundant structures. Clifton (1969) showed the gentle dipping sets of parallel, tabular lamination to be characteristic of the foreshore-swash zone. Fraser and Hester (1977), Hine (1979), and Semeniuk & Johnson (1982) also observed low angle (8°-12°), seaward-dipping planar cross-stratification on tops of berms and ridges.

The ridges in the study area reveal internal structures mainly in their B horizon which is neither obliterated by roots, nor by the soil-forming processes. High-angle (23°-32°) planar cross-stratification was observed, dipping toward the south at site A and site C, and eastward at site D (fig. 7). Such high inclination, up to the angle of repose, typifies eolian activity. However, swash overtopping and ridges and runnel systems may also form landward steep (20°- 25°) dips (Hine & Boothroyd, 1978). Final ridge-welding and runnel-fill may result in moderation of the dip and even in its reversal (Dabrio, 1982). Such a process seems to be demonstrated at the NE flank of the ridge exposures at site A (fig. 7).

Sets of planar, low-angle lamination (2°-15°), dipping northward and southward, are the main component of the mega- tabular cross-stratification exposed in the trenches. No trough cross-bedding was encountered. The planar, low-angle, northward-dipping beds suggest beach face stratification and may reflect a swash bar, a berm or eolian windward topset laminae.

The present wind regime fits the main dip directions in the ridges N32°E-N90°E, including the northward dipping foresets at site A. The discordance of the inner ridge structure with the topography implies a modificational phase, predating final stabilization and indicating that the ridges are secondary sedimentary structures. In the swales the sand is overlain by peat which was, however, not

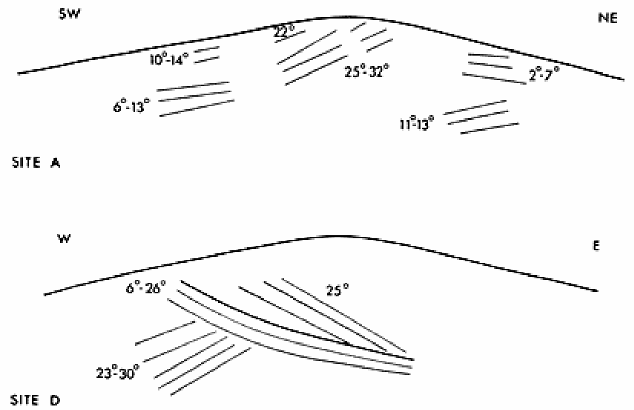

Fig. 7. Schematics of internal structures encountered in trenches across the ridges. Note the discordance of the structure with the topography.

Fig. 7. Skitse af den interne struktur i tværprofiler af ryggene. Bemærk strukturernes diskordans med topografien.

encountered below the ridges and therefore does not imply a basal disconformity.

Structure, pattern and morphology suggest that the ridges in the study area are stillsand features composed of beach face sediments topped by eolian activity. However, neither the internal structure nor morphology clearly differentiates between the beach and the eolian components.

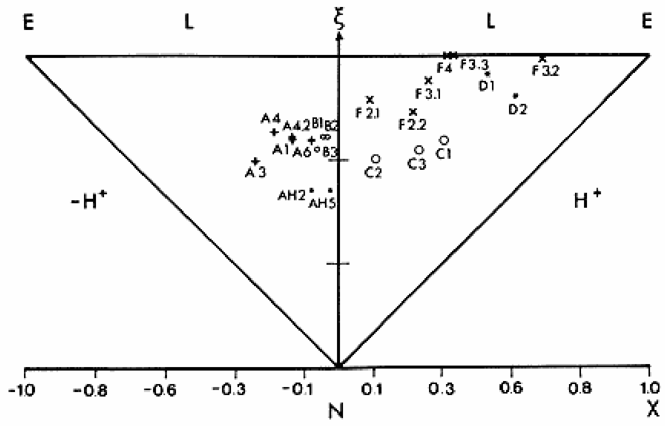

Fig. 8. The hyperbolic shape triangle of the ridge samples (A-D) and of samples from the eolian sheet (F). AH denotes samples from the lowland between the ridges near locality A. The numbers at each station indicate deeper samples from the top of the trench to its bottom. For further details see fig. 3.

Fig. 8. Den hyperbolske trekant med prøver fra ryggene (A-D) og det eolisk prægede område (F). AH prøverne er taget i det lavtliggende område mellem ryggene. Numrene ved hver station angiver prøvernes dybdebeliggenhed startende oppefra.

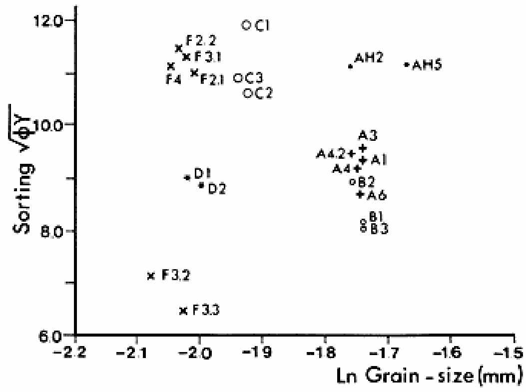

Fig. 9. Size versus sorting of the ridge samples (A-D), and of samples from the eolian sheet (F2-F4).

Fig. 9. Plot af kornstørrelse versus sortering. For beliggenhed af prøvestationer se fig. 4.

Environmental discrimination based on grain-size analysis

The hyperbolic shape triangle in fig. 8 clearly shows that none of the samples has a log-normal distribution. A few of the samples (e.g. Forest 3.2 and Forest 3.3) have a skewed log-Laplace distribution, which is very similar to the log- hyperbolic distribution (Fieller et al., 1984). The rest of the samples have a log-hyperbolic distribution.

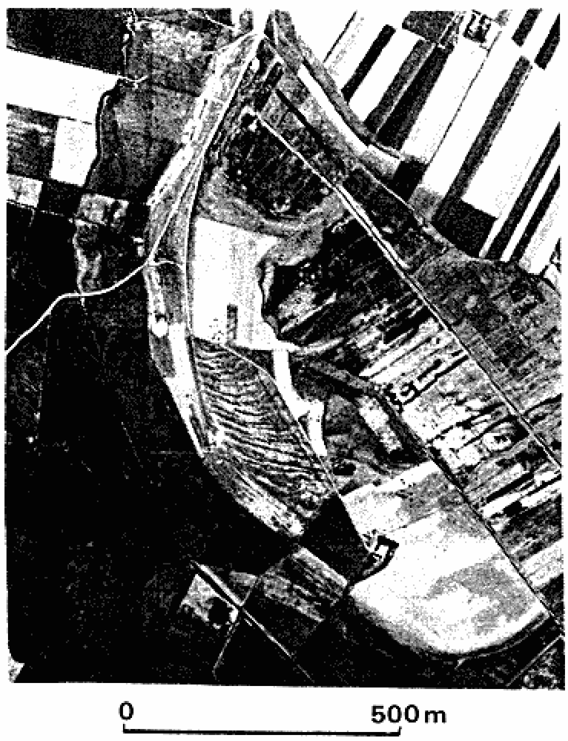

Fig. 10. Spit 1. *Fig. 10. Krumodde 1.*

Parameters from this latter distribution were therefore tried for environmental discrimination.

In the bivariate plot of size versus sorting (fig. 9) all samples of each station (except F3) are well concentrated and separated from each other, i.e. size-sorting characteristics change very little at each station down through the soil profile. No clear separation between the eolian (F) samples and those of the ridges (A-D) is evident. The data suggest that in the studied coastal plain, which transformed during upper holocene from a beach to coastal dunes; environmental discrimination, based on grain size parameters, is inconclusive. Hobday & Orme (1974) reported in a similar study that eolian sands, with steeply dipping-cross-bedding (up to 40), were almost indistinguishable from the beach washover deposits, except for some samples which were better sorted. The lack of environmental distinction within the ridges, between the lower, probably beach sands and the top units, point to the same beach-eolian resolution problem.

GRAVELLY SPITS

Two raised gravelly spits were observed in the study area. Spit 1, initially observed by Jessen (1920), demonstrates on air photos (fig. 10) and in topographic maps (figs. 4, 6) a typical recurved shape, including hooks, whereas spit 2 is linear. The spits are of similar length: spit No 1 is 1.6 km long and spit No. 2 is 1.8 km long. Their width ranges from 100 to 300 m and both reflect a southeastward logshore drift and show a typical asymmetric cross sectional form. Gravel mining exposed a stratigraphic section at the NW flank of spit 1 where three main sedimentary units stand out:

A. An upper, open-framework cobble unit with small boulders (260-270 mm) composing the coarsest size.
B. A pepply cohesive unit, supported by a sandy-muddy matrix, rich with oyster shells.
C. Pebbles and small cobbles in a well-sorted, chert-rich granule matrix.(xix

The granulometric characteristics of spit 2 are similar. Oyster beds (Oystria Edulis) were observed at the two top gravel units of spit 1 and the top of spit 2. The Oyster beds indicate relatively high sea temperatures, high current velocities and a high degree of oxygen saturation (Steeman-Nielsen, 1938). In addition to the two spits, gravel was encountered in many localities along the southern study area below the peat and sand, probably indicating a deeper bed, which predates both spits.

The overwhelmingly flat and tabular debris of chalk and chert observed along the Hjardemaal slopes suggests that the spit gravel should be traced back to the structurally-controlled debris along the encircling Danian chalky former sea cliffs, which served as eroding headlands. Inheritance is thus suggested as the dominating shape factor. The structurally-controlled bladed form of many of the clasts contributed towards a strong preferred fabric.

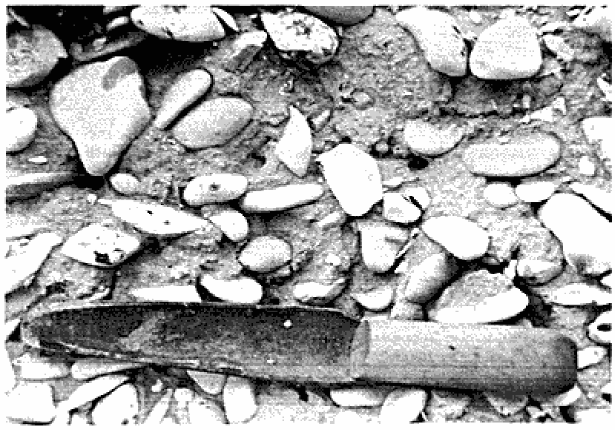

Fig. 11. Matrix-supported fabric of unit 3 spit 1.

Fig. 11. Den matriks støttede fabric i krumodde 1's enhed 3.

Pebble segregation has been suggested as a visual criteria for interpretation for the shallow marine environment (Clifton, 1973). Spit 1, however, displays some matrix-supported fabric, including muddy carbonate sand (fig. 11) with floating pebbles which suggests high-viscosity flows. The spit environment, however, lacks other diagnostic criteria of such slurry flows, i.e. poor sorting, poor roundness and a massive and chaotic structure. Infiltration of sand into the pores of gravel (Martini, 1975) would not form an unsupported framework. An initial process of clast- rounding and sorting in an open, clast-supported framework (Walker, 1975; Nemec et al., 1980) is therefore suggested, i.e. under the higher sea levels of the Littorina/Tapes stage, disturbance of the Hjardemaal slopes must have caused instability and transformed the muddy carbonate and the entrapped beach gravel into debris flows (Middleton & Hampton, 1973; Carter, 1975). Beach drifting later reshaped the sediment mass into a recurved spit in which the former flow texture is still evident.

UPLIFT AND DATING

Deduced from the general regional holocene isostatic upheaval (Mertz, 1924) the study area has been raised by 4.5 m to 5 m. The spits are, however, higher: 8-9 m. Their altitude may reflect the summed heights of different factors: set-up and uprush heights (~3 m) and an unknown, possibly higher than today, tidal factor (Steeman-Nielsen, 1938), possibly salt dome tectonic upheavel, (Hansen & Håkonsson, 1979), and the postglacial isostatic rebound. This implies that only about half of the altitude of the spits should be related to isostatic rebound, corroborating the range of rebound put forward by Mertz (1924). The southernmost area in Jutland covered by glaciation is 60 km south to the study area. The moderate isostatic rebound

Coordinate	Locality	Elevation (m)	Material	Years B.P.	Lab No.
57°03'22"N 8°46'16"E	Spit 1	5.20	Ostrea edulis	3980±122	RT 823 A
57°03'22"N 8°46'16"E	Spit 1	4.20	Ostrea edulis	4630±128	RT 823 B
57°03'53"N 8°42'23"E	Spit 2	6.50	Ostrea edulis	4696±111	RT 823 C
57°04'48"N 8°45'59"E	Ridge A	7.10	Organic matter	Post 1957	RT 824 A
57°04'27"N 8°45'24"E	Ridge C (lowland)	4.30	Organic matter	1020±160	RT 840 A
57°04'26"N 8°43'44"E	Ridge D	6.80	Organic matter	471±52	RT 824 B
57°03'45"N 8°43'08"E	Forest (F)	5.10	Organic matter	791±109	RT 840 E
57°03'45"N 8°43'08"E	Forest (F)	5.10	Organic matter	post 1950	RT 840 B
57°03'26"N 8°43'58"E	Forest 2 (F2)	6.30	Organic matter	1461±109	RT 840 D
57°03'54"N 8°42'41"E	Forest 3	7.30	Organic matter	1000±160	RT 840 C
57°02'39"N 8°45'08"E	Forest 4	5.5 approx.	Organic matter	1563±128	RT 824 C

Table 1. Summary of C-14 datings. Organic material was retrieved from 35 cm soil depth at Ridge A, 20 cm at Ridge C - lowland, 19 cm at Ridge D, 20 cm at the younger Forest and 90 cm at the older Forest sample, 60 cm at Forest 2, 40 cm at Forest 3 and 100 cm at Forest 4. Percent of modern carbon of Ridge A was 110.6 ± 1.34 and similarly 111.7 ± 2.0 at Forest 1. For location see fig. 7.

Tabel 1. C-14 dateringer. Organisk materiale blev udtaget i følgende dybder på lokaliteterne vist på fig. 7: højderyg A – 35 cm, C – 20 cm, D 19 cm, yngre skov – 20 cm, ældre skov 90 cm, skov 2 – 60 cm, skov 3 – 40 cm og skov 4 100 cm. Procent nutidig kulstof i A var 110,6 ± 1,34 og 111,7 ± 2,0 i skov 1.

encountered in the study area reflects the proximity to this zero isobase.

Table 1 summarizes the C-14 dating of the oysters and the organic soil samples within the study area. The dates of the oysters indicate the time they lived, their shells being later incorporated in the gravel, thus indicating the minimum age for the spits. Sample RT 823 A dated at 3980 ± 122 YBP was taken from an open-framework gravel unit at a height of 5.2 m (DNN), and was further followed up to +8 m. The open- framework suggest a transgression phase which can be correlated with the transgression at Bjerregaard, 30 km east of the study area, dated at 3990 YBP (Petersen, 1981). The datings thus confirm that the highest marine limit in this part of the country was reached at a subboreal transgression (Petersen, 1981).

The samples from the forested eolian sheet (F, F2, F3, F4) show older dates in a south-eastern direction. This might reflect a gradual weakening trend of the eolian activity, which is also shown by the relative complex soil profiles in the southern part of the study area. However, it might also indicate a coastline retreat towards the north, here recorded by successive eolian episodes.

Peat formed between the ridges since 1020 AD (sample "Lowland"). As the peat does not underlie the ridges but is encountered only between them, the ridges must have predated the peat. The two samples from the "Forest" (F)site provide dates of the same trench. The 90 cm deep soil indicates a post Middle Ages eolian flux, whereas the top soil is modern and most probably reflects reworking during the 1950s when the forest was planted to prevent further eolian activities (Ranger Nord, pers.com.). The post 1950 dating of sample RT 824 A seem to indicate

cattle deflation, frequently observed in the ridge zone.

These datings seem to corroborate the model put forward by Christiansen & Bowman (1986), that eolian activity took place around 500 AD and 1500 AD, both periods of low sea- level. During the high sea-level period around 1000 AD the low-lying areas were water logged and peat formation started. Apparently, the sixteenth century eolian flux only capped the raised beaches in the northern part of the study area and did not bury the major landscape features. Gry (1979) made similar observations to the east of the present study area.

SUMMARY AND CONCLUSIONS

The embayment configuration of the study area during the Littorina/Tapes period and its orientation relative to the eolian and longshore-driven sands suggest that the study area operated as a shallow, semi-enclosed and bedrock-bounded low- energy embayment, at the lee of the Hanstholm and Hjardemaal headlands. The study area was a sink, which acted as a sediment trap, similar to the barrier and spit model of Hine (1979) and that of Roy & Thom (1981). The eastward longshore sand transport caused an abundance of sediment bypassing (Petersen, 1981) with some leakage into the bay. The ridge system designates a landward sediment transgression, i.e. filling the embayment by advancing sediment masses, arrested from the general longshore drift, resulting in a stepwise shoreline propagation. The study area gradually became barred and finally land-blocked by ridges. The dying out of ridges eastwards reflects a deeper bathymmetry at the base of Hjardemaal Knude, where supposedly a deeper channel was located and no significant terrigeneous muds have been revealed.

Following this model the ridges are fingerprints of pulsatory accumulative beachlines, formed by beach-swash processes and capped by a moderate dune cover. The ridges, however, may also reflect a multiple bar system, typical of small water bodies with abundant sand supply (Exon, 1975; Nillson, 1979; Short, 1975). The ridge morphology bears many characteristics of multiple longshore sand bars which are linear, symmetrical or asymmetrical, occurring in large numbers, regularly spaced, oriented parallel to the coastline, and of limited fetch and depth-conditions, all of which produce a narrow-banded wave spectrum, typical of low- energy wave condition and uniform processes (Nillson, 1979). This explanation emphasizes mainly the shallow and protected submarine conditions. The data are, however, inconclusive as to which model is the true one.

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Sammendrag

På den hævede Littorina/Tapes havbund i området mellem Hansted Knuden og Hjardemål Knuden er der foretaget undersøgelser af den sen-holocene kystudvikling. Undersøgelserne har koncentreret sig om sandede strandvolde og andre rygge samt odder opbygget af materiale med grovere kornstørrelser. Den stratigrafiske og strukturelle tolkning bygger på tværprofiler gravet gennem voldene. Den morfologiske tolkning af området bygger dels på feltarbejde dels på flyfotos og kortblade. Sedimenternes kornstørrelser er blevet analyserede med henblik på differentiering mellem marin og aeolisk oprindelse. Organisk jordbundsmateriale samt marine muslingeskaller er blevet C-14 analyseret med henblik på udredelse af områdets tidsmæssige udvikling.

De marint dannede volde udgør et velorganiseret mønster, hvorimod den æolisk prægede morfologi er "rodet". Der er en klar retningsmæssig diskordans mellem disse to morfologiske enheder.

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