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ORIGINAL ARTICLE

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Late Holocene stratigraphic evolution of a back-barrier tidal basin in the East Frisian Wadden Sea, southern North Sea: transgressive deposition and its preservation potential

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Abstract The late Holocene stratigraphic evolution of a back-barrier tidal basin in the East Frisian Wadden Sea, southern North Sea, was investigated on the basis of a conceptual model relating the rate of sea-level rise to the rate of sediment supply. For this purpose, more than 20 vibracores and box-cores were evaluated, complemented by ^{14}C ages of in situ peats and historical charts. In spite of interspersed short regressive events, the late Holocene stratigraphy generally reveals upward-coarsening grain-size trends indicative of transgressive deposition in the course of sea-level rise rather than erosion and redeposition by migrating channels. A particular feature is the general absence of down-core bioturbation traces, which stands out in sharp contrast to the intensely burrowed modern surface layer. Thus, in the Wadden Sea, high sediment turnover in the course of rapid transgression evidently obliterates most bioturbation traces and other tidal signals such as minor regressive deposits, thereby emphasising the importance of preservation potential.

Keywords Holocene · Stratigraphy · Transgression · Facies analysis · Back-barrier tidal deposit · Preservation potential · East Frisian Wadden Sea

Introduction

The stratigraphic evolution of tide-dominated coastal depositional systems is mainly controlled by interactions between rates of sea-level rise, supply of sediment from external sources, and effects of wind- and wave-generated energy fluxes (Carter and Woodroffe 1994; Flemming 2002; FitzGerald and Buynevich 2003). Together these factors determine local sediment budgets. A change in one of the parameters affects the sediment budget which, in turn, triggers morphodynamic adaptation processes. Thus, if the sediment supply from external sources exactly compensates the volumetric deficit created by sea-level rise, then the depositional system produces an aggradational succession in which the character of a facies at any particular location remains unchanged with depth. If, on the other hand, the sediment supply exceeds the deficit, then the system progrades seawards while often aggrading vertically (Galloway and Hobday 1983).

The exact opposite arises when sediment supply is insuffcient to compensate the deficit created by sea-level rise. In such cases, the barrier system draws on its own sediment reservoir by transferring material from the shoreface towards the land. Such systems are said to be transgressive (e.g., Kraft and John 1979). If the deficit is low, then only part of the reservoir needs to be mobilised and the resulting transgressive displacement is slow. In the course, a thick transgressive systems tract consisting of stacked back-barrier sedimentary successions may be preserved in the rock record. On the other hand, if the deficit is large, and little nor no sediment is available from external sources, then most of the seaward reservoir is reworked and transgressive displacement is rapid. In the course of this bulldozing effect, only deeper channel fills and the final highstand systems tract are retained for potential preservation in the rock record.

Since the controlling parameters are independent of each other, it stands to reason that the relative influence of these can change in the course of time. The system then responds by switching from one budget mode into another, each switch being accompanied by a corresponding change in the stratigraphic evolution (Flemming 2002; Coe 2003). For example, with an unchanged sediment supply but an increase in the rate of sea-level rise, an aggrading system would switch to a transgressive system, whereas in the opposite case it would switch to a prograding system, and

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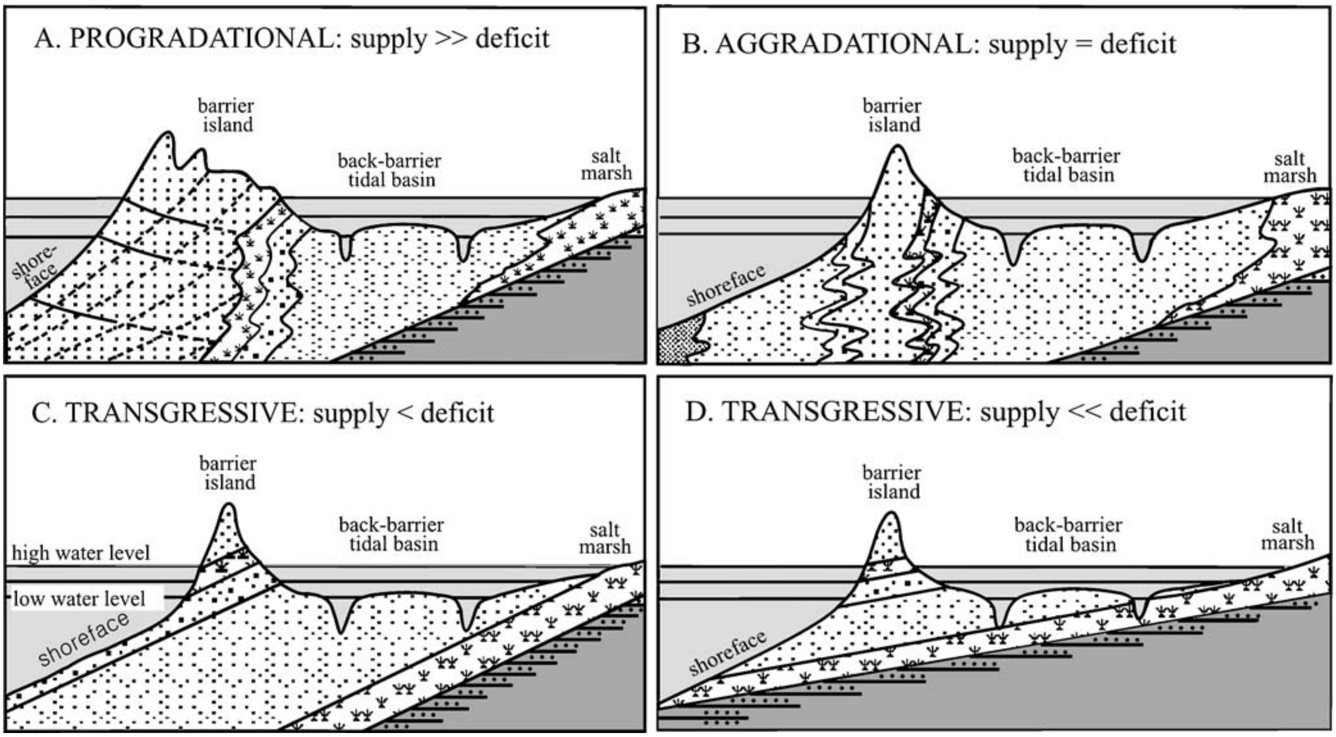


Fig. 1 Stratigraphic evolution of barrier-island depositional systems in response to the rate of sea-level rise and the rate of sediment supply from external sources (adapted from Flemming 2002)

so on. In the case of barrier-island depositional systems, the stratigraphic expression of the principle outlined above can be illustrated by four corresponding stratigraphic models (Fig. 1, after Flemming 2002).

The evolution of the Wadden Sea barrier island system along the North Sea coast commenced at 7.5–8 ka BP when the rising post-glacial sea reached the southern margin of the North Sea basin and entered the lower courses of the local rivers, turning these into estuaries (Flemming and Davis 1994; Streif 2002). Due to the shallow water body, the tidal range at that time barely exceeded 1 m and the coastal regime accordingly was microtidal. With the rising sea, the North Sea basin gradually deepened and, in response, the tidal range progressively increased to its present upper mesotidal regime characterised by a mean tidal range of about 2.8 m off Spiekeroog island (Fig. 2), the penultimate barrier island of the East Frisian Wadden Sea sector. Since about AD 1000, the evolution of the Wadden Sea was severely influenced by human interventions in the form of land reclamation and dike construction (Streif 1990; Flemming 2002).

The existence of extensive peat layers encased within the late Holocene back-barrier deposits indicate that, in spite of the generally rising post-glacial sea level, intermittent short-lived regressive phases occurred in the Wadden Sea region (Streif 2002; Behre 2003). This contradicts the smoothly rising sea-level model originally proposed by Jelgersma (1979) for the adjacent Dutch Wadden Sea coast, a model which was more recently also applied by Vos and van Kesteren (2000). In addition, as revealed by historical charts, land reclamation and dike construction along the mainland coast of the Wadden Sea over the past millennium have led to substantial changes in tidal basin morphology (Flemming and Hertweck 1994). Thus, in order to unravel site-specific Holocene sedimentary records as a function of sea-level rise and sediment supply, basin-wide stratigraphic investigations are required, focussing on old core regions that have remained unaffected by channel displacements. This is all the more important since the stratigraphic evolution of the Wadden Sea as a whole was not uniform over time, different areas experiencing different sediment budgets at different times. The purpose of the present study is to unravel the stratigraphic evolution of the back-barrier tidal basin in the rear of Spiekeroog island (Fig. 2) on the basis of cores and age datings.

Study area

The tidal basin investigated in this study is located in the rear of Spiekeroog island, one of the East Frisian barrier islands along the coast of Germany, southern North Sea (Fig. 2). The basin drains an area of 73 km^2 and has a tidal prism of about 114×10^6 m^3. The tide is semidiurnal with a mean tidal range of 2.8 m, the area corresponding to the upper-mesotidal regime as defined by the classification of Hayes (1979; cf. also Flemming 2005). The base of the Holocene sedimentary succession is characterised by a number of former river valleys which drained towards the north and reached down to over 20 m below the modern sea level (Streif 1990). The valleys were separated by topographic highs or ridges which also dip towards the north, reaching elevations of less than 5 m below the present sea level near Neuharlingersiel, and still less than 7 m below the western tip of Spiekeroog island (Krüger 1922; Asp 2004; Fig. 2).

The stratigraphy of the area is complicated by the fact that the morphodynamic adjustments of the islands and tidal basins triggered by land reclamation and dike construction over the past millennium resulted in large displacements of inlets, tidal channels, watersheds, and even the islands themselves. In the process, older Holocene deposits were reworked or deeply excavated by new channel systems, while former channels were infilled. The physiographic changes incurred by land reclamation are documented in a series of physiographic charts dating back to AD 1650 (Homeier and Luck 1969).

Materials and methods

More than 20 vibra-cores were taken at selected locations (Fig. 2). Care was taken to avoid areas of major channel displacements. For this purpose, an electrical concrete-vibrator system was modified for use on the tidal flats. In principle, the system is similar to the vibra-corer originally described by Lanesky et al. (1979), except that an electrically driven rather than mechanically driven vibrator is used, the latter being limited by the length of the flexible drive shaft, whereas the length of the electrical cable is unlimited and even allows underwater operations. The vibrator head is fitted to a clamp which is then attached to the top of long aluminium pipes. The pipe is held in a vertical position during coring, penetration being achieved by fluidisation of the sediment below the lower contact rim of the pipe caused by the vibration. The electrical power unit is operated at 42 V, the vibrator oscillating at 14 kilocycles/min. There is no evidence that the vibrations distort the primary sedimentary structures, although the grain fabric is probably disturbed as suggested by core compactions of up to 5%.

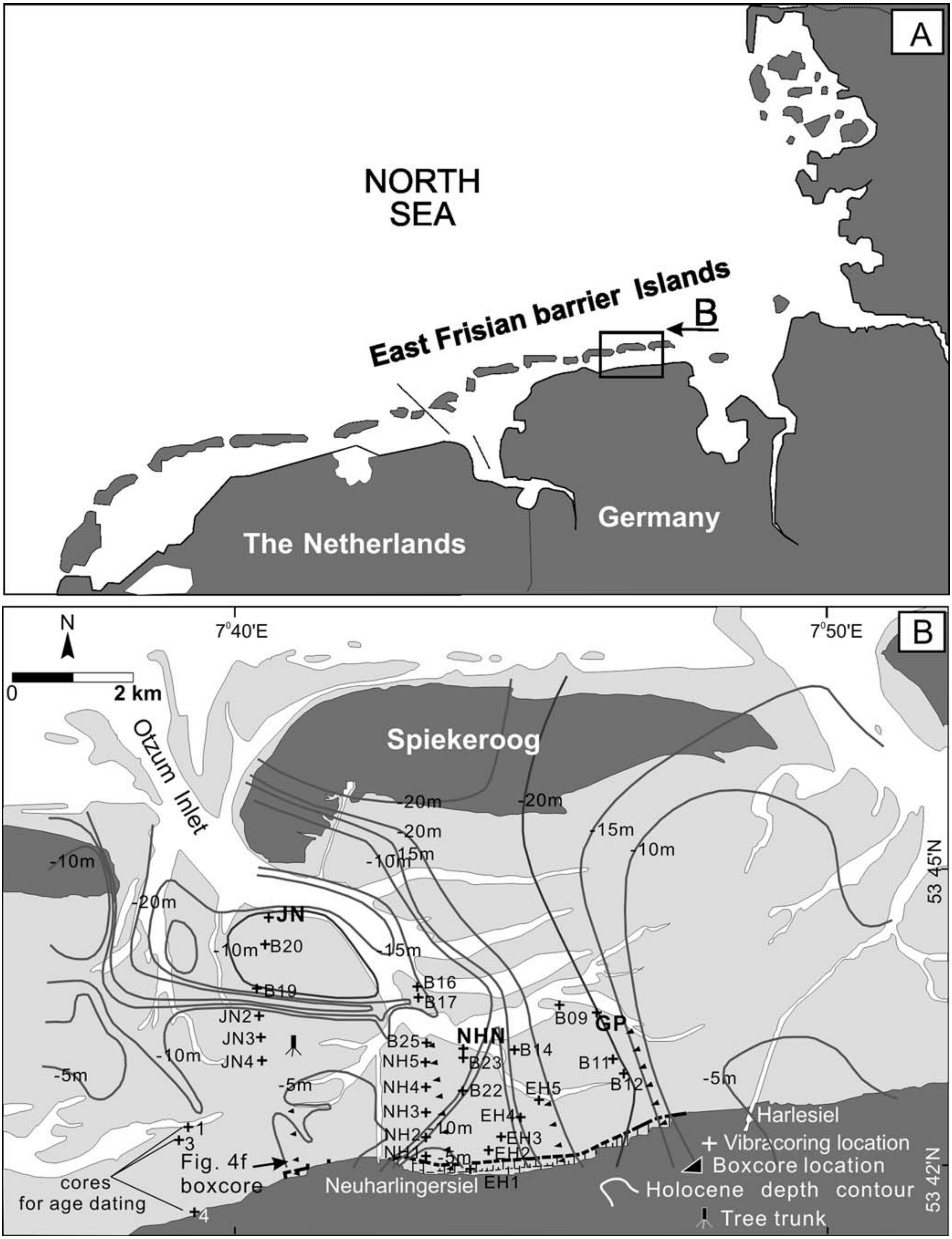
Before extraction, the upper, empty section of the core pipe is filled with water and then sealed with a rubber stopper to create a vacuum. The full core pipe is extracted by means of a chain pulley suspended from a tripod. Recovered core lengths range from 3 to 6 m, depending on the packing density of the sediment, the general rule being that the denser the packing, the more difficult the penetration. In the laboratory, the core pipes are cut open lengthwise, one half being stored, the other half being treated with epoxy for the preparation and conservation of sediment peels. The epoxy peels are then used for core description in terms of lithology, grain size, colour, and sedimentary structures. After removing the peels, the remaining core can be sampled for grain-size analysis. In addition, a number of box-cores were collected along intertidal transects near the mainland shore for a better assessment of sedimentary structures in the upper 30 cm of the tidal flat deposits.

Results

Core logs and facies analysis

After careful examination and evaluation of the epoxy peels, eleven facies types were identified by which the sedimentary structures, bioturbation traces, and artifacts (e.g., shell, mud lumps) displayed in the cores could be characterised (Table 1). Since many sedimentary structures repeat themselves in any particular core, the three most variable cores, namely Janssand North (JN), Neuharlingersieler Nacken (NHN), and Gröninger Plate (GP), were selected to illustrate the facies sequences (Fig. 3; for location see Fig. 2):

1. *Storm bed facies*: These are characterised by massive sand layers with scattered shell fragments and organic debris, rare mud lumps and chips, and occasional bioturbation structures. Such deposits can form on most intertidal flats and are commonly preserved because of the depth of sediment reworking during storms.
2. *Swash bar facies*: These are characterised by parallel-laminated and low-angle cross-laminated sands sometimes containing organic debris. Unlike the swash bars on ebb-deltas, these back-barrier swash bars are commonly found along the margins of all major channels, especially in wave-exposed locations, e.g., opposite inlets, where they sometimes form low, levee-like ridges. In modern tidal flats these may be enhanced by ship-generated waves.
3. *Subaqueous dune facies*: Large-scale cross-bedded sands indicate the former presence of subaqueous dunes *sensu* Ashley (1990). Such dunes can be ebb- or flood-oriented and commonly occur at the bed of tidal channels, intertidally along ebb-dominated channel margins, or subtidally on flood-dominated channel slopes (Davis and Flemming 1991; Flemming and Davis 1994).
4. *Ripple facies*: In back-barrier environments, wave-generated ripples occur both on sand flats and mixed flats, extending subtidally a few decimetres below low-tide level where their preservation potential rapidly decreases in favour of current ripples and dunes, the former being restricted to shallow intertidal creeks and subtidal channel sections where current velocities are too low to generate dunes.
5. *Convoluted sand facies*: Convoluted beds and other deformation structures generally form in very loosely packed and water-logged sands after loading by more densely packed sediments or hydrostatic pressure variations induced by waves, which explains why they are often associated with cross-laminated sands produced by current ripples and dunes on tidal flats and in intertidal creeks (Klein 1977).
6. *Channel lag facies*: Channel lags are characterised by densely packed shell beds above an erosional base. The lag deposits form by lateral channel migration in the course of which shells dispersed in the reworked



A
NORTH SEA
East Frisian barrier Islands
B
The Netherlands
Germany
B
N
0
2 km
7°40'E
7°50'E
53 45'N
53 42'N
Spiekeroog
Otzum Inlet
-20m
-15m
-10m
-5m
JN
B20
B19
JN2
JN3
JN4
B16
B17
B25
NH5
NH4
NH3
NH2
NH1
NHN
B23
B22
B14
B09
GP
B11
B12
EH5
EH4
EH3
EH2
EH1
1
3
4
cores for age dating
Fig. 4f boxcore
Neuharlingersiel
Harlesiel
+ Vibracoring location
Boxcore location
Holocene depth contour
Tree trunk

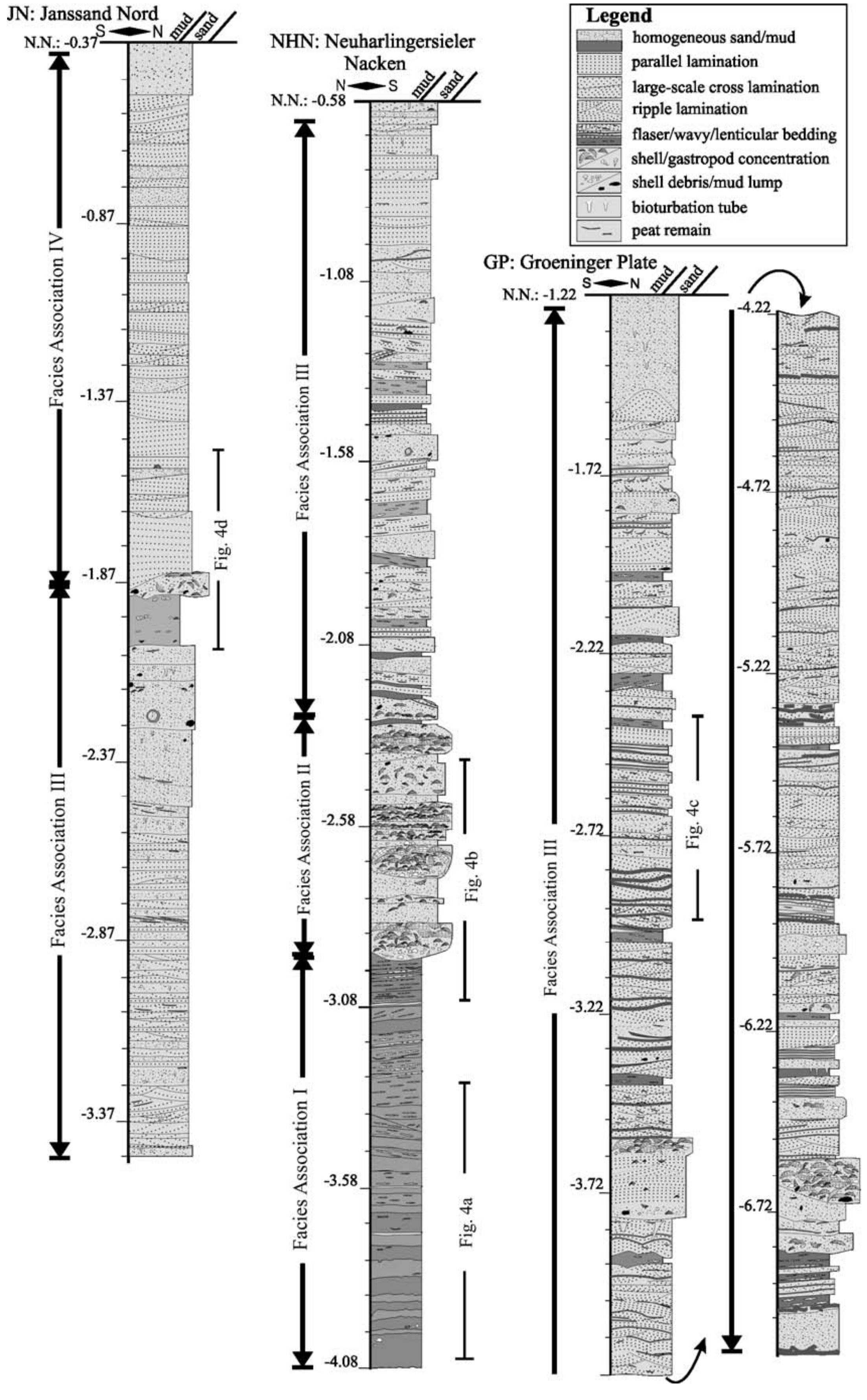
Table 1 Classification of 11 facies types on the basis of characteristic sedimentary structures and artefacts (e.g., shell, mud lumps) observed in vibra-cores

Facies types	Characteristic feature	Interpretation
Facies Sm	Massive sand with scattered shell fragments and organic debris, rarely containing mud chips and lumps, partly bioturbated	Storm bed
Sp	Parallel (subparallel) laminated sand, partly including organic debris	Migrating bar
Sx		
Sxd	Large-scale cross-laminated sand	Migrating dunes
Sxr	Small-scale cross-laminated sand, flaser-bedded sand common, climbing ripples present	Migrating ripples
Sd	Deformed sand, highly deformed and convoluted cross-laminated sand	Deformation by differential loading
Ssh	Shelly sand, shell densely concentrated and aligned, sharp erosional base, small gastropods present	Channel lag
Facies SMp	Parallel-bedded inter-laminated sand and mud, alternating sand/mud laminae, wavy beds	Tidal bedding
SMx	Cross-laminated sand and mud, mud drapes	Tidal bundles
Facies Mm	Homogeneous mud, plant stems and leaves, shell fragments present	Supratidal flat, salt marsh
Mp	Parallel-laminated mud, thin sand streaks, lenticular bedding, greenish-grey colour	Upper tidal flat
Facies Ps	Condensed layer of plant leaves and wood stems, no clastic sediments, dark-brown colour	Swamp/raised bog

overlying sediment are concentrated on the bed by gravitational processes (Flemming et al. 1992).

7. *Tidal bedding facies*: Horizontal tidal bedding consists of rhythmically alternating sand and mud layers deposited in the course of individual tidal cycles. The sand layer forms during maximum current flow and is followed by the deposition of a mud layer at slack tide. Since both ebb and flood currents may be involved, the sand-mud successions can take on a multitude of forms, ranging from beds of similar thickness to alternating thick sand beds (dominant tide), followed by a thin mud drape (slack water), followed by a thin sand bed (subordinate tide) which is once more followed by a mud drape. In the latter case, one speaks of mud couplets. The bedding may also be wavy in the direction of the current. On intertidal flats they commonly occur in point bar deposits of shallow intertidal creeks. Thicker sequences can occur in subtidal settings where complete neap-spring cycles may be preserved (e.g., Boersma and Terwindt 1981).
8. *Tidal bundle facies*: Tidal bundles are the cross-bedded counterparts of horizontal tidal bedding. Individual bundles form by the migration of dunes in the course of a tidal semi-cycle, the slip faces getting draped by a thin mud layer at slack tide. Again a multitude of rhythmic forms may be observed, as in the case of tidal bedding, and long successions commonly display neap-spring cycles with waxing and waning bundle thicknesses (Visser 1980; Yang and Nio 1985). Such cycles are difficult to recognise in cores because the narrow sections may only cut two or three bundles at a time.
9. *Supratidal flat/saltmarsh facies*: This facies is characterised by homogenous muds with root structures and plant remains typical of the land-sea transition in saltmarsh environments. Shell fragments and thin layers of very fine sand or coarse silt are frequently intercalated in these deposits which have been transported into the marsh from adjacent tidal flats by the action of storms (Reineck and Gerdes 1996, 1997).
10. *Upper tidal mudflat facies*: This facies is typically associated with mixed tidal flats, i.e., the transition from muddy sand flats to sandy mudflats and mudflats proper. In complete successions, the sequence commences with flaser bedding in muddy sands, parallel-bedded sand-mud laminae at the transition from muddy sands to sandy muds, and lenticular bedding in sandy muds (Reineck and Wunderlich 1968; cf. also Flemming 2003).
11. *Freshwater swamp facies*: This facies is characterised by a condensation layer of dark-brown peats, mostly comprising plant leaves and wood stems. In contrast to saltmarsh facies, little or no clastic material is contained in these peat layers, indicating deposition in freshwater swamps or mires where the influx of clastic sediments was strongly inhibited (Behre 2002).

◀ **Fig. 2** Location of vibra-core stations in the Otzum tidal basin in the rear of Spiekeroog, one of the barrier islands along the East Frisian coast of Germany. The cores marked by bold letters are illustrated in the text. The bold lines denote the base of the Holocene in metres below modern chart datum (≈ mean sea level; Geologische Übersichtskarte 1973). JN and + B20: vibra-core stations


JN: Janssand Nord
S N
mud
sand
N.N.: -0.37
-0.87
-1.37
-1.87
-2.37
-2.87
-3.37
Facies Association IV
Facies Association III
Fig. 4d
NHN: Neuharlingersieler Nacken
N S
mud
sand
N.N.: -0.58
-1.08
-1.58
-2.08
-2.58
-3.08
-3.58
-4.08
Facies Association III
Facies Association II
Facies Association I
Fig. 4b
Fig. 4a
Legend
homogeneous sand/mud
parallel lamination
large-scale cross lamination
ripple lamination
flaser/wavy/lenticular bedding
shell/gastropod concentration
shell debris/mud lump
bioturbation tube
peat remain
GP: Groeninger Plate
S N
mud
sand
N.N.: -1.22
-1.72
-2.22
-2.72
-3.22
-3.72
-4.22
-4.72
-5.22
-5.72
-6.22
-6.72
Facies Association III
Fig. 4c

Definition of facies associations

The back-barrier tidal deposits can be divided into five major facies assemblages, each characterised by a number of environmentally diagnostic sedimentary facies: (a) saltmarsh/mudflat deposits, (b) shell lag deposits, (c) intertidal flat and channel deposits, (d) intertidal swash bar deposits, and (e) swamp/raised bog deposits (Figs. 3 and 4). A more detailed description of these assemblages is given below:

(a) Facies association I: saltmarsh/mudflat

The mud-dominated *facies association I* was only detected in the lower sections of the cores from the Neuharlingersieler Nacken and the south of the Janssand. This association is characterised by greenish-grey or pale-olive mud containing abundant plant remains. It mainly consists of homogeneous (facies Mm) and parallel-laminated muds (facies Mp). Plant stems and leaves, as well as shell fragments occur in some layers. The presence of sand streaks, shell debris and plant remains in the lower part of this association indicate that the muddy sediments were deposited in a saltmarsh/mudflat environment intermittently exposed to inundation during storms (Reineck and Gerdes 1996; Fig. 4a). The dominance of lenticular bedding in the upper part of the sediment column is considered to represent deposition in a high-lying mudflat environment (comprising slightly sandy muds) rather than in a saltmarsh.

(b) Facies association II: shell lags

This association unconformably overlies *facies association I* and is conformably overlain by sandy sequences of *facies association III*. The succession is characterised by coarse shelly sand with an erosional base (facies Ssh; Fig. 4b). It also contains massive sand beds with scattered shells (facies Sm). These are considered to be transgressive lag deposits formed during sea-level rise (Flemming et al. 1992; Hori et al. 2001). A similar succession was also found in some box-cores along transect I (Fig. 4f).

(c) Facies association III: intertidal flat and channel

This association represents sandy tide- and wave-dominated sequences consisting of large-scale cross-laminated sands (facies Sxd), rippled sands (facies Sxr), and parallel-laminated and cross-laminated muddy sands (facies SMp and SMx). It also contains massive sand beds, shelly sands (facies Sm and Ssh), and deformed sands (facies Sd). Horizontal tidal bedding and cross-bedding with tidal bundles and mud drapes dominate the upper part of

◀ **Fig. 3** Typical stratigraphic features of back-barrier tidal deposits based on detailed core descriptions. The cores show a coarsening-upward stacking pattern indicative of transgressive conditions in the course of deposition

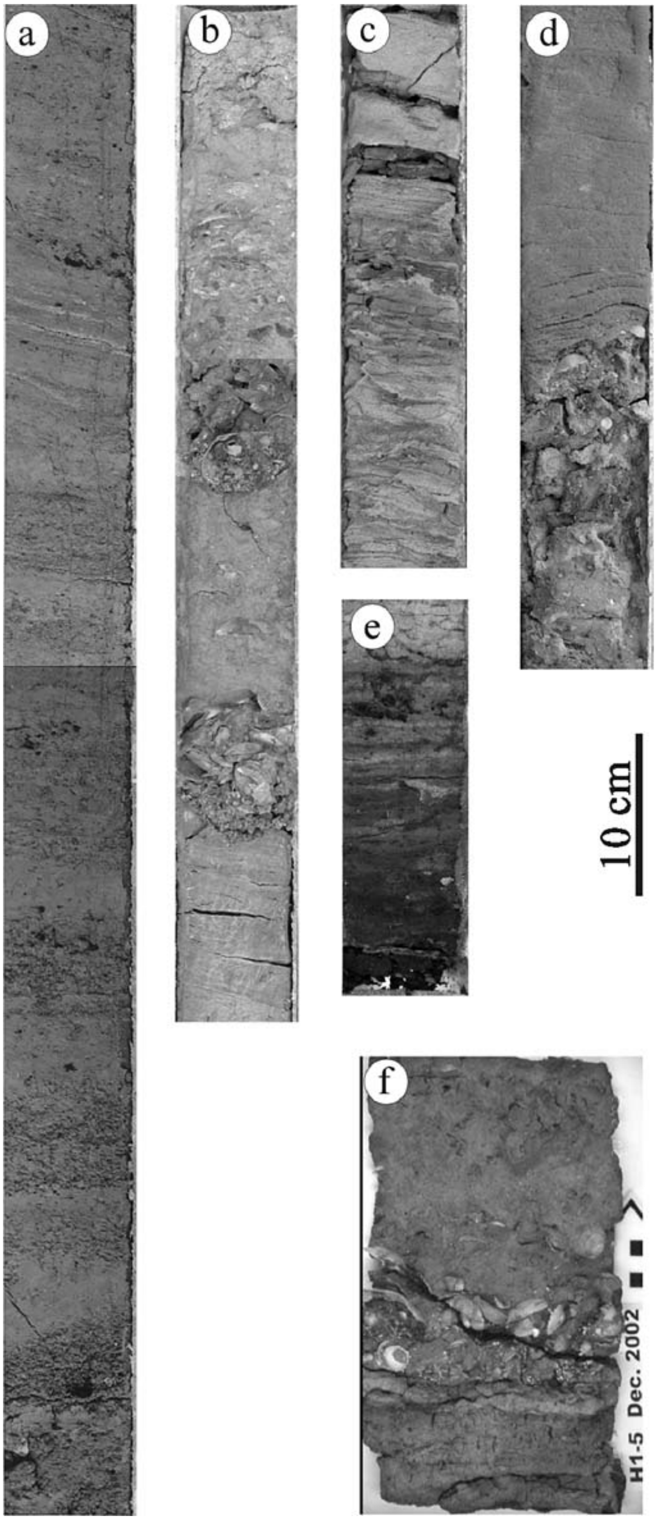


Fig. 4 **a** Muddy saltmarsh deposits displaying thin sand streaks and intermittently supplied shell fragments. **b** Sequence of transgressive shell-lag deposits with sharp erosional bases overlain by mudflat deposits. **c** Tidal bedding with mud couplets and alternating sand and mud layers. **d** Near-horizontally laminated sands suggestive of back-barrier swash bar deposits. **e** Condensed peat layer at the base of a core from the southern Janssand. Note that the peat is overlain by a gradual development of saltmarsh mud deposits. **f** Box-core epoxy peel from transect I (cf. Fig. 2) displaying a well-developed shell-lag deposit

the sedimentary sequence (Fig. 4c). This suggests deposition in sand flat to mixed muddy sand flat environments which were regularly reworked by marginal tidal channels to generate large-scale cross-bedding (Davis and Flemming 1995). Some small-scale fining-upward successions were also found. These are considered to have been deposited by small migrating tidal creeks. The presence of thick, deformed sand layers suggests deposition near channel margins.

(d) Facies association IV: intertidal swash bar

The sand-dominated *facies association IV* was only found in the core from Janssand North (JN). It is characterised by parallel-laminated and low-angle cross-laminated medium sands (facies Sp; Fig. 4d). Little or no bioturbation and well-developed near-horizontal lamination in this association are suggestive of an intertidal swash-bar environment under high-energy conditions, an interpretation which is confirmed by the position of the core location opposite the tidal inlet which is frequently exposed to North Sea waves penetrating the inlet throat.

(e) Facies association V: swamp/raised bog

This association was only found in the lowermost section of the cores from the southern Janssand (see core location in Fig. 2). It is characterised by a condensed peat layer composed of plant leaves/stems and wood remains (facies Ps; Fig. 4e). The clean peat lacking any trace of clastic sediment is normally indicative of freshwater swamp or locally raised bog environments. However, as it is overlain by the gradual development of a saltmarsh mud sequence associated with *facies association I*, it may suggest deposition in a progressively more brackish environment rather than a freshwater swamp remote from marine influences.

Transgressive stratigraphy of the back-barrier tidal deposits

As revealed in the core logs of Fig. 3, individual site-specific facies dominate the stratigraphic record. Most cores obtained from the Gröninger Plate, among them core GP, show somewhat monotonously rippled and flaser-bedded sands, almost no bioturbation, and very little mud. The Janssand North cores (e.g., core JN) are dominated by parallel-laminated sands, whereas the cores from the Neuharlingersieler Nacken (e.g., core NHN) and Janssand South (core JN3 and JN4) show the greatest down-core variations in grain sizes, a basal mud deposit being overlain with a sharp contact by two to three generations of shell lags and intertidal sands displaying upward-coarsening grain-size trends. In spite of this site-dependent domination of a particular facies, the late Holocene stratigraphy of the back-barrier basin, by and large, reveals a general upward-coarsening

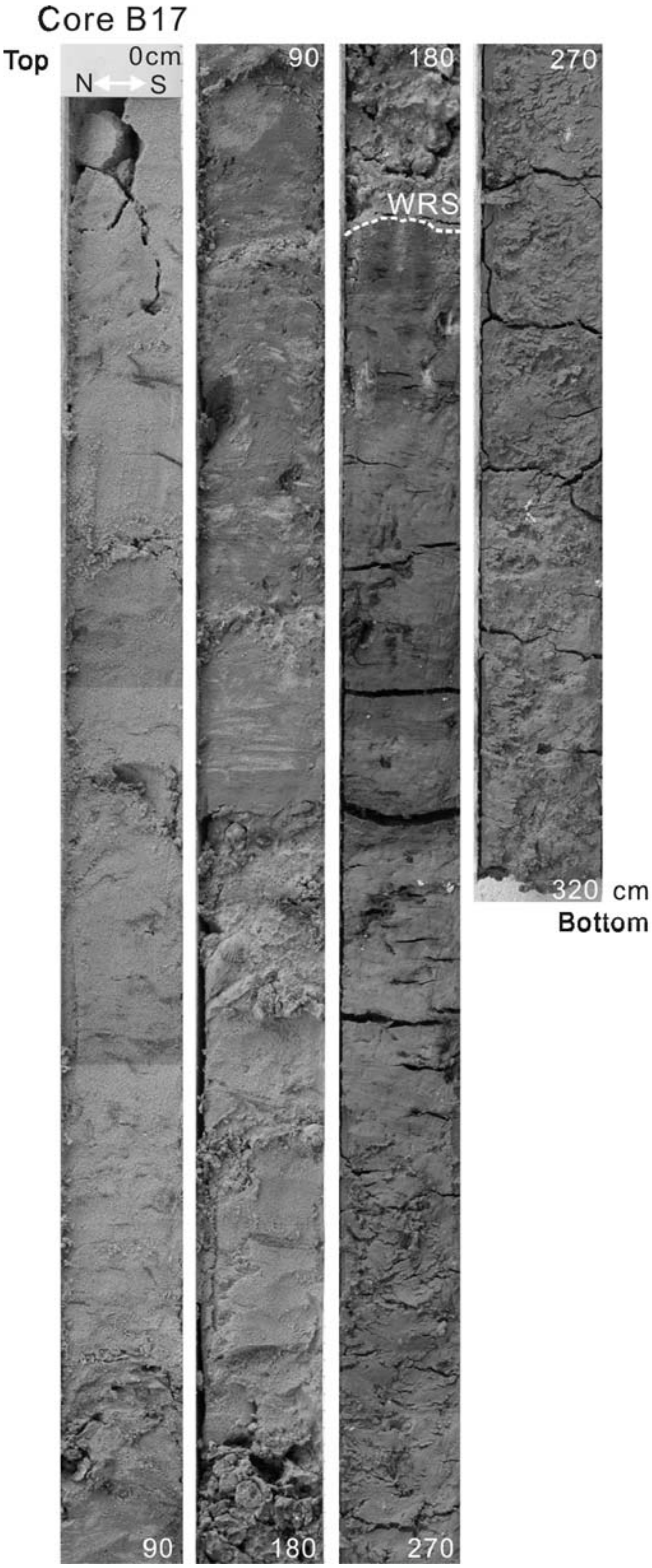


Fig. 5 The down-core section of core B17 displaying an upward-coarsening sedimentary sequence. Note the existence of a wave-generated ravinement surface (WRS). Mud deposits are erosively overlain by shell lags and sand-dominated sequences. This reflects transgressive deposition as illustrated in model D of Fig. 1 where the supply of sediment from external sources is very much smaller than the deficit created by sea-level rise

Table 2 Radiocarbon datings of peat samples recovered from the tidal flat located west of Neuharlingersiel (age datings by courtesy of Ralf Wöstmann, Research Centre Terramare, Wilhelmshaven, Germany)

Sample location	Core depth (m)	Core no	Analysed material	Years BP
Benser tidal flat (53°42′42″N, 7°38′95″E)	0.39	1	Peat	2990 ± 40
Benser tidal flat (53°42′37″N, 7°38′79″E)	0.18	3	Peat (plant remains)	2370 ± 25
	0.43	3	Peat	2465 ± 30
	0.56	3	Peat	2635 ± 30
Benser tidal flat (53°41′42″N, 7°39′00″E)	0.19	4	Peat (plant remains)	2835 ± 30
	0.36	4	Peat	2990 ± 30
	0.48	4	Peat (plant remains)	2975 ± 30
	0.63	4	Peat	3090 ± 30
Benser tidal flat, intertidal surface			Birch tree-trunk	3700 ± 30
Neuharlingersiel, beach surface			Peat (plant remains)	3920 ± 80

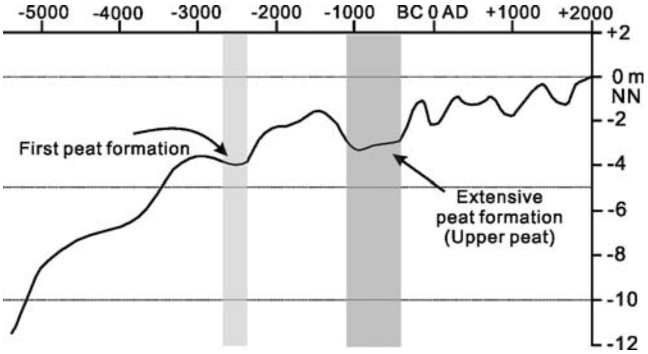


Fig. 6 Recent sea-level curve for the southern North Sea coast after Behre (2003). The depth scale of the curve was readjusted to mean sea level (NN). The occurrence of peat at the base of a core from the southern Janssand corresponds in elevation to the short-lived regressive phase during which the "Upper Peat" formed

Fig. 7 Rooted tree-trunk found in modern intertidal flats on the southern Janssand (53°43.327′N, 7°40.691′E). It corroborates the interpretation that, although intermittent short-lived regressive phases did occur, the region has generally been exposed to transgressive conditions

sequence with mudflat/saltmarsh deposits which are unconformably overlain by sand-dominated intertidal successions indicative of transgressive deposition in the course of sea-level rise (Figs. 3 and 5). Shell lags with an erosive base encased between the two facies are interpreted as representing transgressive lag deposits, the sharp lower boundary indicating a wave-cut ravinement surface (Fig. 5).

Radiocarbon datings of in situ peats found in cores from the Benser mudflats located in the tidal basin immediately west of Neuharlingersiel (Table 2) (see locations in Fig. 2) have revealed ages ranging from about 2500–3000 years BP. These peat horizons are located at depths of approximately 20–50 cm below the present intertidal surface. The ages correspond to a period of extensive peat formation (Fig. 6) associated with a short-lived lowering of sea level (Behre 2003). Such a short-lived regressive phase was also detected at the base of some cores from the southern Janssand (e.g., Fig. 4e). In spite of such well-documented intermittent regressive events, the overall sedimentary sequence clearly reveals a predominance of transgressive deposition over the last several thousand years. An as yet undated, rooted tree-trunk found on the southern Janssand (Fig. 7) provides strong additional support for this interpretation.

Discussion and conclusions

Regressive-transgressive sedimentation

The existence of condensed peat layers at the base of some cores clearly reflects short regressive events (Fig. 4e). In general, three major peat layers intercalated in the Holocene sequences have been identified (see Fig. 6 for two periods of peat formation; Streif 2002; Behre 2003, 2004). When comparing the elevations relative to modern mean sea level of the peat layers found in our cores with the elevations and age datings of peats from the adjacent tidal basin and the regional sea-level curve, we find excellent agreement. This would suggest that the peats all correspond to the period of the so-called "Upper Peat" which formed between 3100 and 2400 years BP. The sea-level curve reveals a complex history of sea-level fluctuations during the Holocene, incorporating phases of still-stand, retardation and acceleration, regressive phases being associated with intercalated peat layers. However, with the exception of the peats, other intertidal deposits formed during regressive phases in the

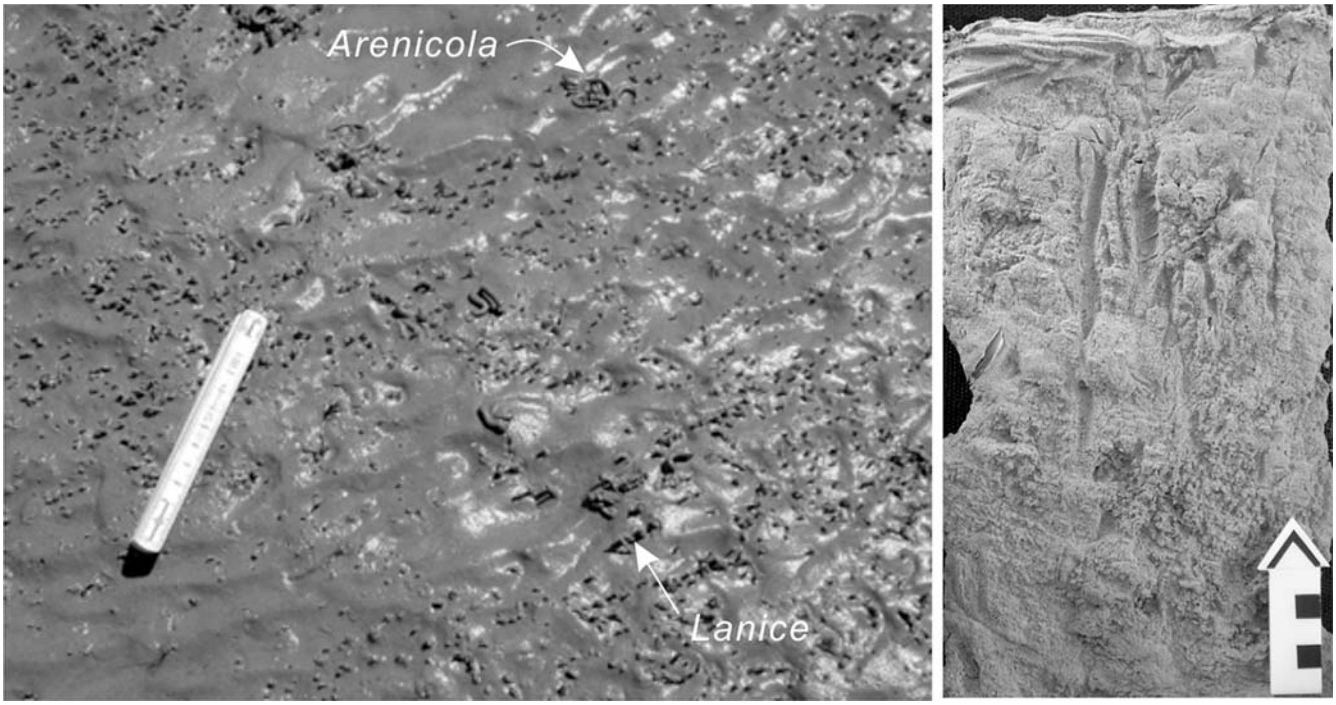


Fig. 8 Surface traces of the polychaete *Arenicola marina* and a colony of the tube-building polychaete *Lanice conchilega*. Box-core showing bioturbation structures by the same worms. The rule scale is approximately 10 cm long

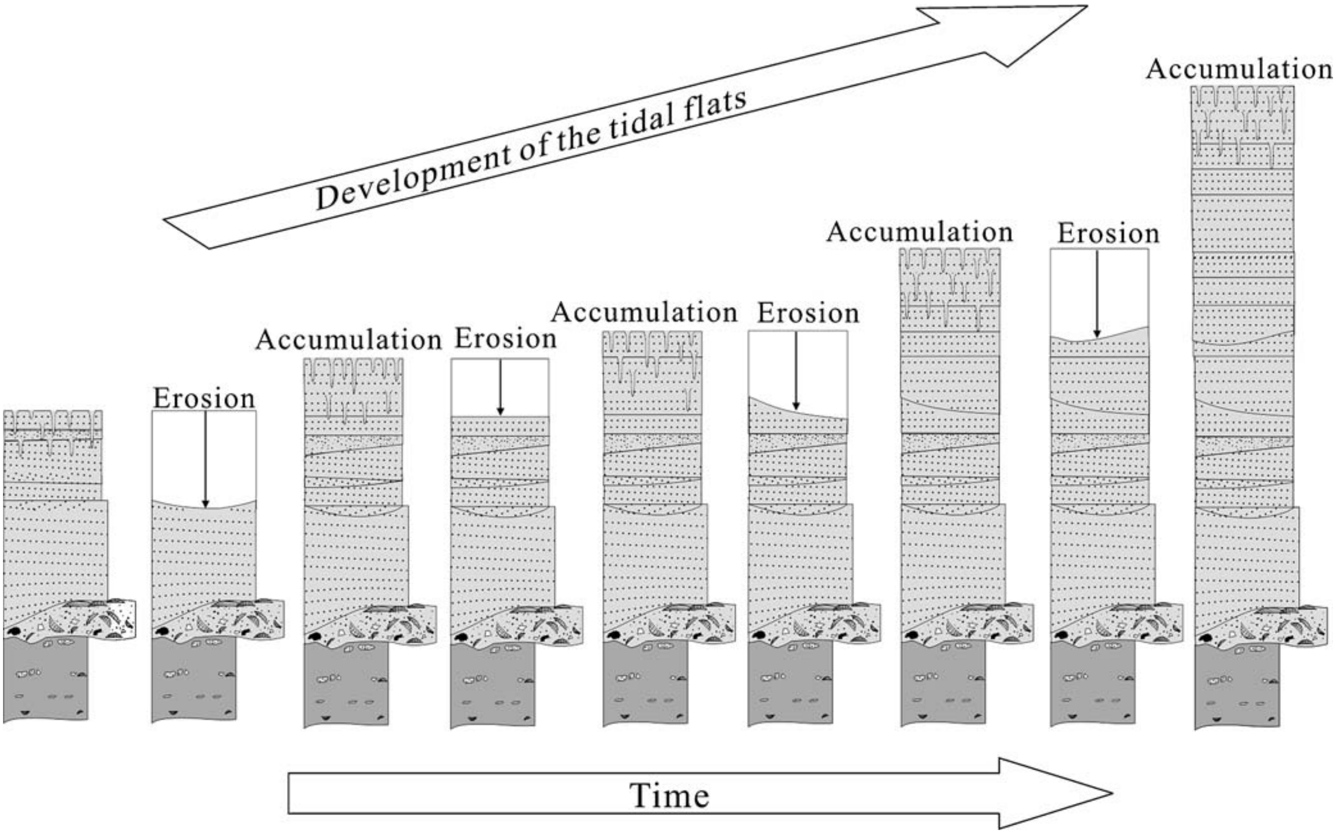


Fig. 9 Conceptual model illustrating the mechanism by which bioturbation structures are lost in the course of transgressive accretion (modified after Tilch 2003)

back-barrier tidal basins appear to have been rarely preserved in the sedimentary record of the Wadden Sea. This could be due to the fact that the duration of sea-level lowerings were too short-lived (perhaps 100–300 years) to allow more substantial deposits to develop before transgressive conditions resumed (Freund and Streif 1999). In addition, the relatively thin regressive deposits probably had a very low preservation potential in the face of the resuming transgression which either completely reworked or at least obliterated the diagnostic character of the regressive deposits. Consequently, the peat layers are considered to be the best indicators for sea-level changes in the Wadden Sea.

In spite of the existence of several regressive phases documented in the regional sea-level curve, the depositional system is essentially dominated by upward-coarsening sequences (e.g., Figs. 3 and 5), basal mudflat/saltmarsh deposits being unconformably overlain by sand-dominated intertidal successions. This clearly favours an interpretation of transgressive deposition in the course of sea-level rise. In addition, ^{14}C ages of in situ peats and rooted tree-trunks found in the modern intertidal flats strongly support this interpretation, while they preclude a migrating tidal channel model of the type proposed by van der Spek (1996) in a study of apparently similar deposits in the Dutch Wadden Sea.

Mudflat deposits found just 20 cm below the modern sand flats in some places suggest that there is a substantial sediment deficit for the infilling of newly created accommodation space in the course of sea-level rise. As a result, even the vertically stacked, transgressive depositional facies sequences are relatively thin. The Spiekeroog barrier-island complex therefore most closely resembles the transgressive model D in Fig. 1, which illustrates the stratigraphic evolution in the case where the supply of sediment from external sources is very much smaller than the deficit created by sea-level rise. Consequently, the transgressive displacement of the barrier-island system towards the mainland shore will continue as long as the sea level continues to rise at its present rate, or even accelerate should the rate of sea-level rise increase as postulated by global warming models (e.g., Flemming 2002).

Loss of biogenic structures in subsurface deposits

A particular feature of the Wadden Sea depositional system is the general lack of bioturbation structures at depth in the cores. This is all the more surprising as intense bioturbation activity is observed in the entire surface layer throughout the tidal basin (Fig. 8), the only exceptions being high-lying "dry" sands where the water table drops below the burrowing depth of most organisms at low tide, and the highly mobile ebb-delta sands.

As previously pointed out by Davis and Flemming (1995) and Tilch (2003), this widespread lack of bioturbation at depth in the cores can – in the face of the intensely burrowed surface layer – only be explained by an extremely low preservation potential under environmental conditions which have prevailed in the Wadden Sea for several thousand years now. The most likely mechanism is frequent and deep reworking of the surface layer by wave action. In this process, two conditions must be fulfilled in order to produce the stratigraphic signal observed in the cores: (a) the greatest reworking depth achieved by episodic storm waves must exceed the bioturbation depth of the local organisms in order to obliterate all traces of biological activity, and (b) subsequent resedimentation must be rapid and again exceed the bioturbation depth of the organisms. This process, which has not previously been documented for the Wadden Sea depositional system with such clarity, is schematically illustrated in Fig. 9 (modified after Tilch 2003). Other models, which all postulate a higher preservation potential for bioturbation than that documented in this study, were proposed by van Straaten (1954) and Reineck and Singh (1980). This discrepancy is put down to the fact that none of these other studies had long cores at their disposal.

The fact that all long cores show the same phenomenon, which was originally observed in the adjacent tidal basin to the east by Davis and Flemming (1995), suggests that this is not a geographically isolated feature but applies to the Wadden Sea as a whole. It is a reflection of the relatively high energy conditions occurring in the southern North Sea and emphasises the fact that not everything which is observed in the upper sediment layers of modern environments will ultimately survive to be registered in the rock record, thus demonstrating the central role which the concept of "preservation potential" plays in the depositional process. Since back-barrier tidal basins are commonly regarded as relatively low-energy environments, the surprisingly rare preservation of biogenic structures at depth may lead to misinterpretations of the rock record, especially in subsurface core analysis. Such deposits could easily be mistaken as reflecting macrotidal, wave-dominated open coast settings instead of mesotidal back-barrier tidal flats of the Wadden Sea type.

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