

Vertical patterns of grain-size parameters of shoreface-connected ridges in the German Bight

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Abstract

This report evaluates the vertical variation of grain-size parameters of shoreface-connected ridges off Spiekeroog Island (German Bight). It is based on eight, 1.5 to 2 m-long, vibrocores retrieved along a single transect from successive morphozones of two ridges. The ridges are situated in water depths of 12 to 18 m, have a relief of 2 to 5 m, and are 1 to 1.5 km wide. The colour and textural composition of the ridge sediments suggest a two-fold grain-size facies. The surficial facies is mainly composed of medium to coarse-grained, relatively poorly sorted, brownish to orange-brown sands, and is usually about 60 cm thick. The subsurficial facies consists of gray-coloured fine sands with discrete occurrences of coarser sand layers that are probably storm-deposited. In general, four vertical grain-size patterns are displayed in the cores: sharp (relative to facies transition), gradational, fluctuational and homogeneous. As observed for the surficial cross-ridge pattern, the subsurface sediments of the landward flank and trough of the outer ridge are in general coarser and more poorly sorted than those of the crest and seaward flank. Similarly, the subsurface sediments of the inner ridge crest are coarser and less sorted than their counterparts from the outer ridge crest. These observations suggest that ridge sedimentation processes have always been coherent in time, even prior to the deposition of the surficial facies. The latter is considered to reflect a vertical growth of the ridges. Its origin is probably related to the present-day supply of Pleistocene sediments from the inlet channels during ebb-storm-surge conditions, rather than an *in-situ* reworking process.

Introduction

The process of generation and growth (or non-degradation) of shoreface-connected ridges in the German Bight (southeastern North Sea) and elsewhere is still elusive. The importance of evaluating the vertical variation in grain-size parameters of shoreface and shelf ridges is intrinsically tied to understanding their geological evolution and the present-day hydraulic regime maintaining them. Such evaluations were made on the Mid-Atlantic shelf of the United States (e.g. Swift et al. 1972, Stubblefield et al. 1975, Rine et al. 1986), and also on the shelves of Brazil (Figueiredo et al. 1982) and Canada (Hoogendoorn & Dalrymple 1986).

This report evaluates the vertical pattern of grain-size parameters of shoreface-connected ridges off Spiekeroog Island in the German Bight. The obtained

data enable a comparison of shoreface-ridge sediment patterns from the highly dynamic environment of the German Bight with those from other localities. However, the present data base differs in some respects from those documented in the literature. Importantly, analyses are not limited to mean grain size as is mostly the case, but other grain-size statistical parameters and percentage proportion of sediment fractions are considered also. Furthermore, vibrocore samples used in this study have been obtained from the troughs, landward flanks, crests and seaward flanks of two adjacent shoreface ridges.

Study setting

The island of Spiekeroog is situated at the southeastern corner of the German Bight (Fig. 1). The significant

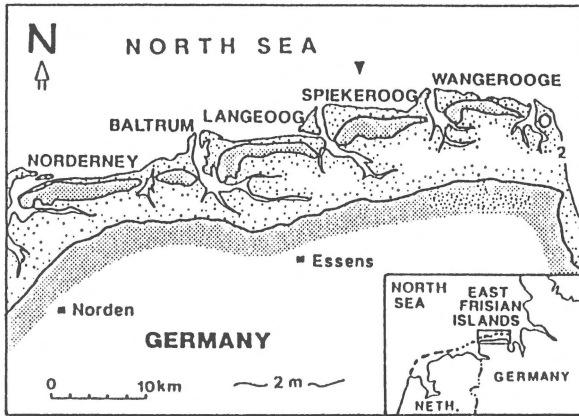


Fig. 1. Map of the German Bight showing the location of Spiekeroog Island (after Davies 1992).

nearshore (10 m water depth) wave height is 1.5 m, with a period normally ranging between 4 and 8 s (Dette 1977). The mean tidal range is about 2.5 m. FitzGerald et al. (1984) described the study area as one of mixed (wave and tidal current) energy. Numerous tidal current measurements made offshore of Spiekeroog Island in water depths of 3 to 25 m over spring, mean and neap tidal conditions, indicate a peak flow in the range of 30 to 60 cm/s at 1 m above the sea bed (Antia 1993a).

The implication of the latter result, as also noted in Antia (1993b), is that medium and finer sands blanketing the ridge morphology can be mobilized by tidal and wave currents on a daily basis, as frequently as 80% of the time. This is in sharp contrast to the situation along the Atlantic sea board of North America, where bottom sediment mobility is exclusively storm-current-related (e.g. Swift et al. 1973). In the German Bight, storm-generated currents are estimated to occur between 10 and 30 days yearly (Antia 1993a).

The two investigated shoreface-connected ridges are herein referred to as inner and outer, and are respectively designated with the letters (I) and (O) in Fig. 2. These ridges are located in water depths of 12 to 18 m, and are shore-oblique (WNW-ESE) in orientation. They have a relief of 2 to 5 m and a width of 1 to 1.5 km. Their landward flanks are generally steeper ($< 1^\circ$) than the seaward counterpart.

Data set and analysis

The data set for this study consists of grain-size statistical parameters (mean, sorting, skewness and kurtosis) and weight percentage of sand fractions (very fine, fine, and medium-coarse sands) from a total of eight, 1.5 to 2 m-long, vibrocore samples. The cores were retrieved along a single transect (longitude $7^\circ 45.00'E$), and their positions on the ridge morphology are indicated in Fig. 2 as well as in Figs 4 and 6.

The aim of coring each morphozone, namely trough, crest, and seaward and landward flanks, of the adjacent shoreface ridges was to enable an assessment of the pattern and consistency of sedimentation processes operating within these morphozones over time. This approach is considered fundamental to a proper interpretation of shoreface ridges in the rock record. Disparities in sedimentation patterns within the ridge morphozones have been inferred from their surficial grain-size distribution (e.g. Swift et al. 1978) and, more recently, from their sedimentary structures (Antia 1993a).

The cores were systematically sampled at 10 cm intervals, except where distinct lithologic changes were evident. Grain-size analyses, following standard laboratory procedures, were performed for the sand fractions using an automated settling tube system at the Senckenberg Institute of Marine Geology in Wilhelmshaven. A computer software coupled to the settling-tube device enabled the calculation of percentile statistical parameters of the size distribution. In this report, sand fractions are classified according to the Wentworth scale, whereas the verbal description of grain-size statistical parameters is based on Folk & Ward (1957). Only unimodal sediment samples have been employed in the latter case.

Results

Grain-size statistical parameters

The patterns of grain-size statistical parameters of surficial sediments of the investigated shoreface ridges have been discussed in detail in Antia (1993b), based on box-core samples. As exemplified by Fig. 3, the mean grain size ranges from fine to coarse sand. Pebbles and gravelly sands are sometimes observed in the uppermost 10 cm of box cores from the inner ridge trough (Antia 1993a). Note the temporally consistent pattern of cross-ridge mean grain size in Fig. 3. Sed-

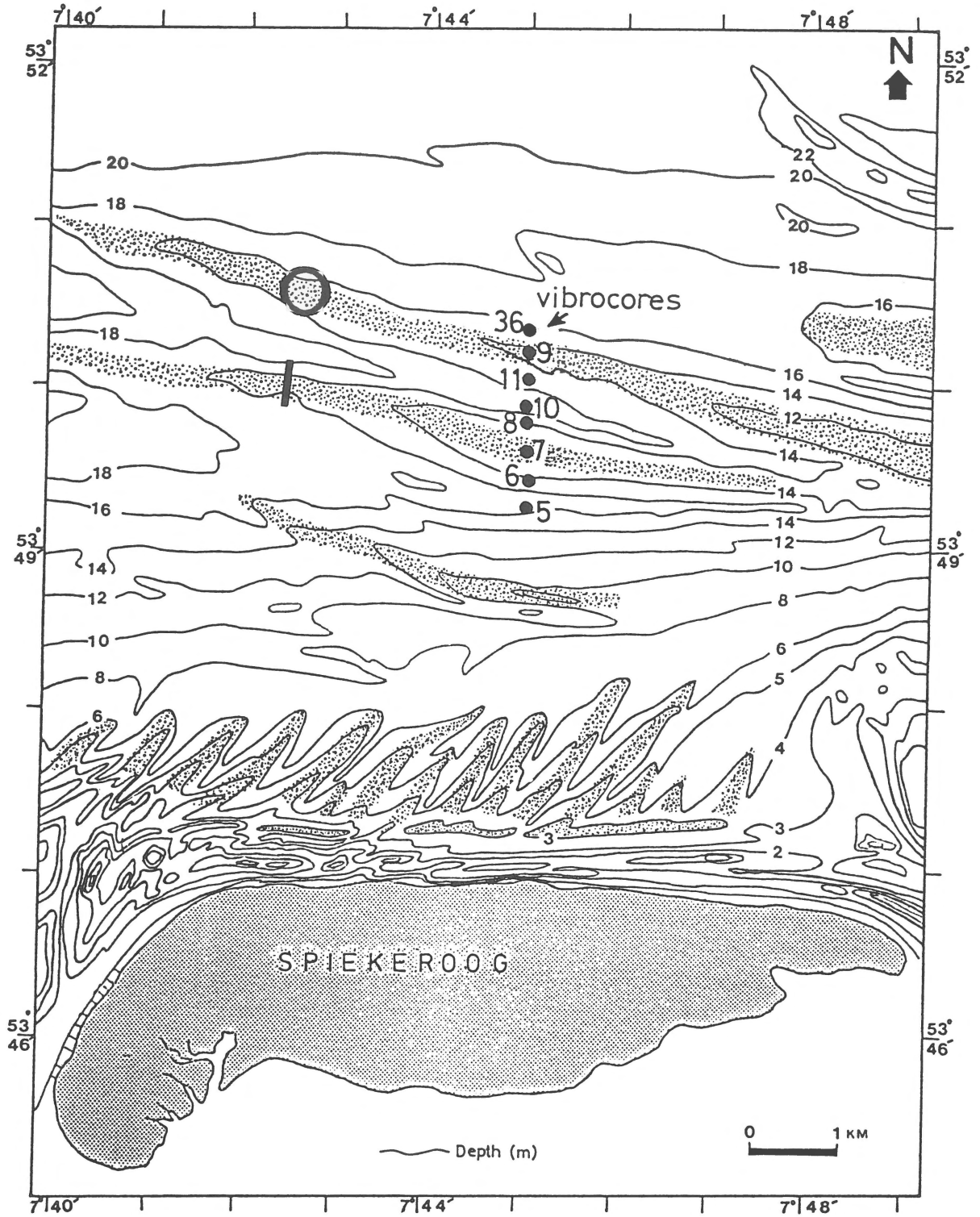


Fig. 2. Bathymetry of Spiekeroog showing the inner (I) and outer (O) shoreface-connected ridges investigated and the location of the cores (dark circles). Depths are in metres relative to NN (German topographic chart datum).

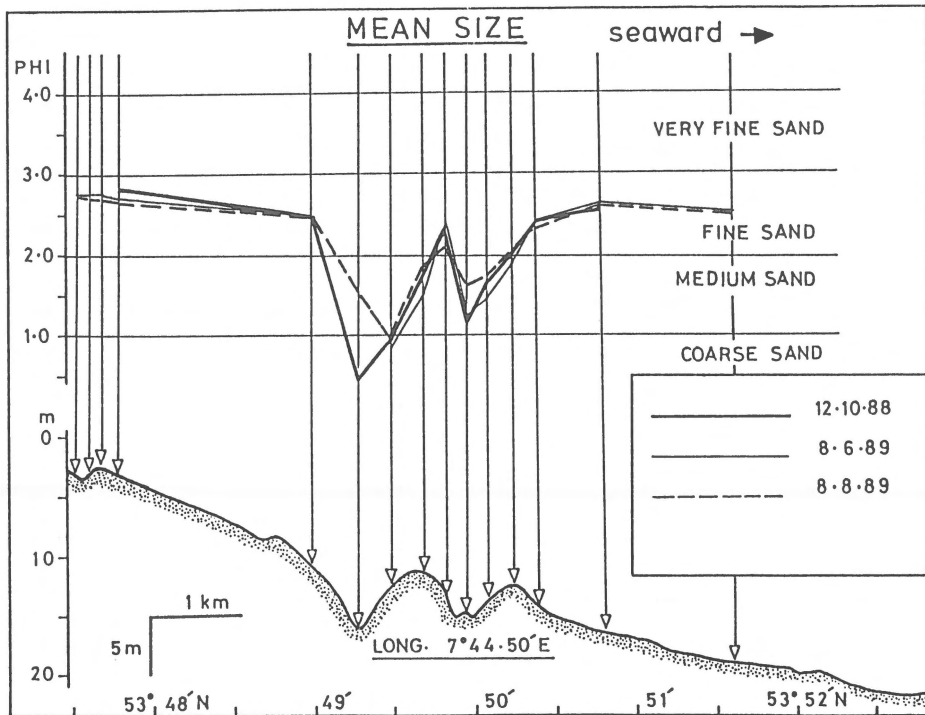


Fig. 3. Cross-ridge variations in surficial mean grain-size (after Antia 1993b). The data are based on box core samples from the transect shown in Fig. 2.

iments gradually fine from the trough toward the seaward flank of each ridge.

The vertical variation in the mean grain sizes within the cores (Fig. 4a) reveals four main patterns: a sharp discontinuity at about 60 cm of core depth (cores no. 6 and 9), a gradational (cores no. 7 and 8), a fluctuational (cores no. 10 and 11), and a uniform or homogeneous trend (cores no. 36 and 5). No given morphozone displays a consistent vertical pattern.

The sharp discontinuity in the $> 2 \phi$ (250 microns) mean grain size at about 60 cm evident in cores no. 6 and 9 can also be correlated in three other cores, with the exception of cores no. 5 (inner ridge trough), no. 7 (inner ridge crest) and no. 36 (seaward flank of outer ridge), where sands are typically fine-grained. The vertical variation in mean grain size of the inner ridge morphozones displays a converse trend, whereby the percentage proportion of coarser than 2 phi is least in the trough, but increases distally on the landward flank and crest. Core no. 5 shows that the mean grain size of the subsurface sediments of the ridge is largely finer than 2 phi.

Sorting generally improves from the trough toward the seaward flank (Fig. 4b). This pattern is observed

both in the surficial and subsurficial grain size facies, especially on the outer ridge (Fig. 5). The surface and subsurface sediments in Fig. 5 represent those from the upper 50 cm and from the lower 70–150 cm core depth respectively. Vertical discontinuity in sorting is subtle and is most apparent on the landward flanks and in the troughs. This break also occurs at about 60 cm and, with the exception of the inner trough, it is indicated by a progressive improvement in sorting with depth.

The kurtosis pattern shown in Fig. 4c also depicts a vertical discontinuity of variable character on the ridge morphozones at a core depth of about 60 cm. With the exception of the troughs, sands which are platykurtic are rare or rapidly diminish beneath 60 cm.

Although some cores (no. 6, 11, and 9) show a marked variation in skewness at about 60 cm depth, the skewness sign lacks a discernible trend between adjacent morphozones (Fig. 4d). The disparity in the skewness sign of the surficial sands on the crest and seaward flank of both ridges is, however, noteworthy. While the sands of the inner ridge crest and seaward flank show a similar negative skewness sign, those of the outer ridge display the opposite.

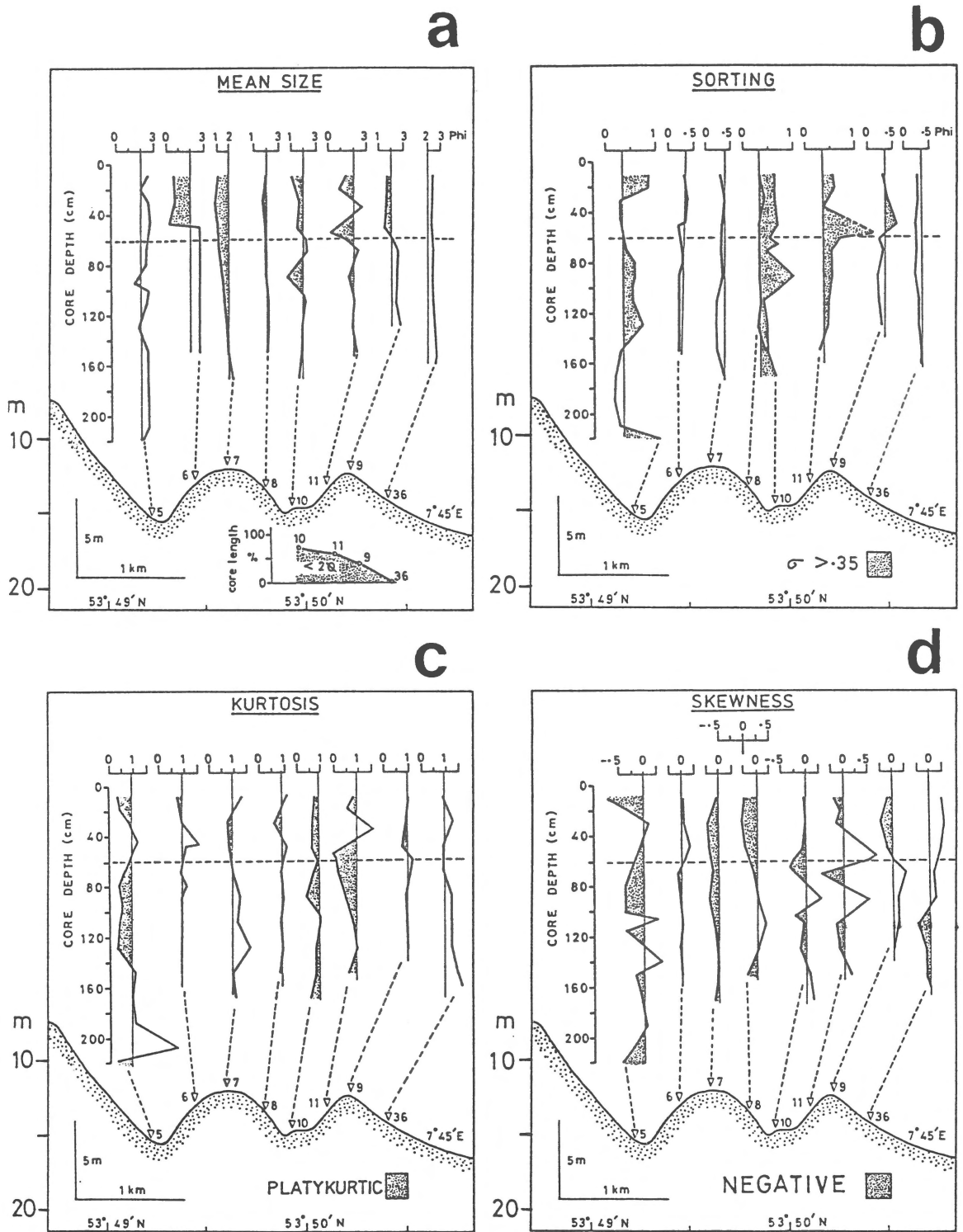


Fig. 4. Vertical profiles showing grain-size parameters in cores from the transect shown in Fig. 2. (a): mean grain size; inset shows percentage (relative to core length) coarser than 2 phi across the outer ridge; (b): sorting, (c): kurtosis, (d): skewness. Note the tendency for a sharp discontinuity of the parameters in some of the cores at a depth of about 60 cm.

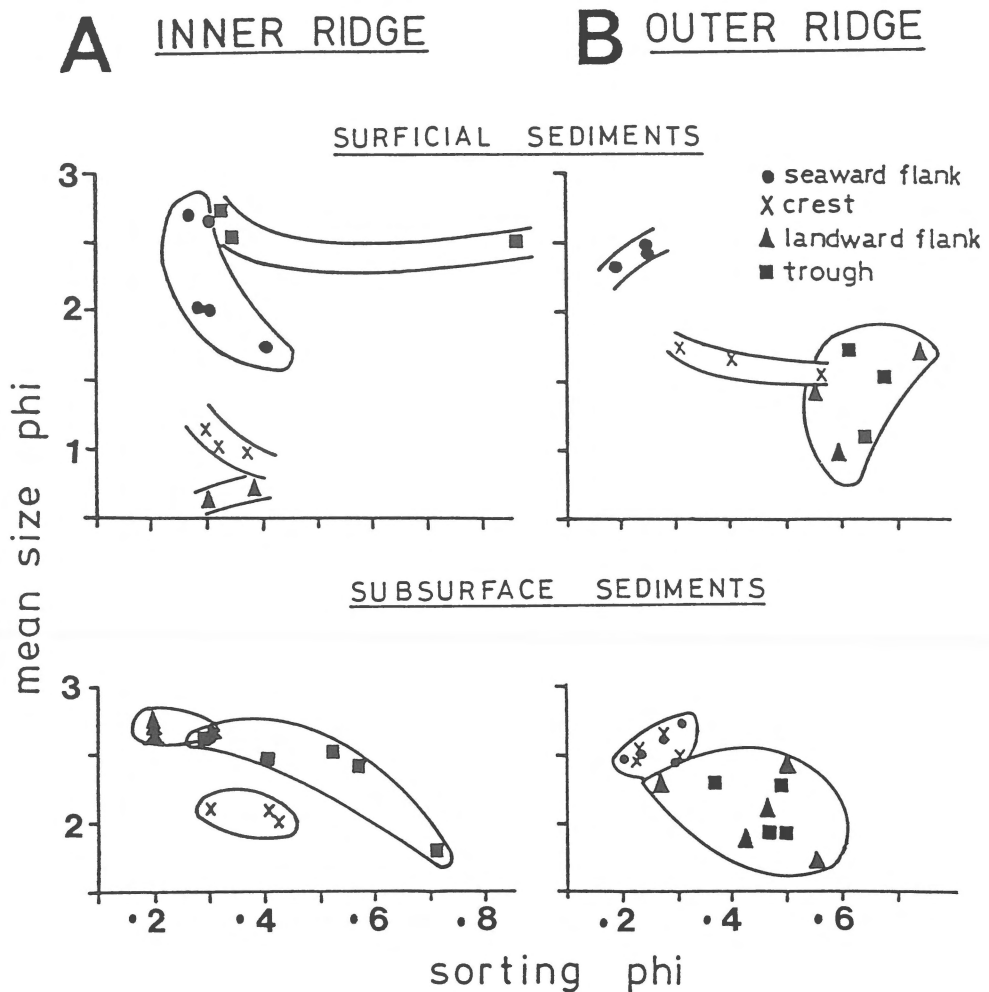


Fig. 5. Bivariate plots of mean grain size versus sorting for the surficial and subsurface sediments of the inner (A) and outer (B) ridge morphozones as cored in the transect shown in Fig. 2. The surficial and subsurface sediments are respectively from the upper 50 and the lower 70–150 cm core depth. Note the genetic relationship of surficial and subsurficial sediments of the outer ridge.

Grain-size fractions

The variation of the grain-size fractions in the cores indicates that the very fine sand fractions generally constitute less than 10% by weight (Fig. 6a), a notable exception being the landward flank of the inner ridge with almost 90% in the subsurface (core no. 6, 60–140 cm core depth). The adjacent ridge crest (core no. 7) shows an increasing proportion of the very fine sand fraction with core depth. Compared to the above two ridge morphozones, the inner ridge trough (core no. 5) is most depleted in this sand fraction.

The fine sand fraction is most abundant in the inner trough and at the seaward flank of the outer ridge (Fig.

6b). A sharp vertical discontinuity at 60 cm core depth is indicated on the outer ridge crest. The high proportion (> 50%) of fine sand fraction displayed in core no. 5 (inner trough), this penetrating the sea bed the most, indicates fine sands to be the modal sediments in the ridge subsurface. However, medium to coarse-grained sands occur intermittently within this morphozone (Fig. 6c). The pattern of variation of the weight percentage of medium and coarse-grained sands in the cores depicted in Fig. 6c is similar to that of the mean grain size.

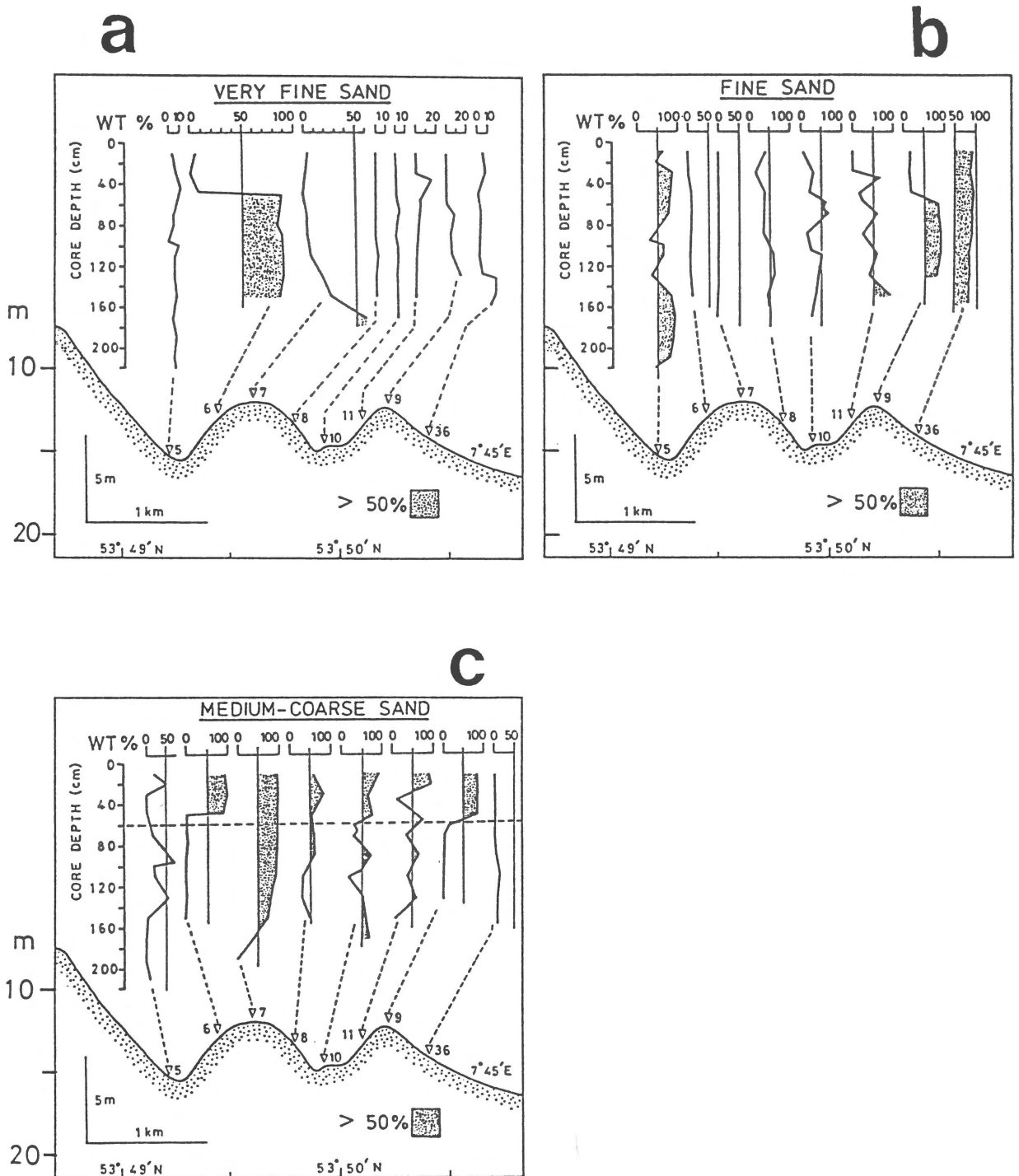


Fig. 6. Vertical profiles showing grain-size fractions (weight %) in cores from the transect shown in Fig. 2. (a): very fine sand, (b): fine sand, (c): medium-coarse sand.

Discussion

Ridge grain-size facies and sedimentation processes

Based on the textural composition and colour of the sands, the ridge morphology can generally be viewed as being comprised of two grain-size facies. The surficial (upper 60 cm) facies is distinguished from the subsurficial counterpart by its brownish to orange-brown coloured sands which are also generally coarser and less well sorted. The subsurficial sands are normally fine-grained and gray-coloured. The inner ridge crest (core no. 7, Fig. 6c) is the only exception to the generally low proportion of medium to coarse-grained sand fraction in the subsurficial facies. In most other cores, this fraction occurs intermittently.

Earlier workers on shoreface and shelf ridges in the U.S. Mid-Atlantic Bight, such as Field (1980) and Stubblefield et al. (1984), have also reported a variety of vertical mean grain-size patterns, including coarsening and fining-upward, as well as size trends which are uniform or fluctuating. The above diversity in vertical grain-size patterns as well as the intermittent occurrences of coarse-grained layers in cores noted by Field (1980) might suggest a similarity in process of ridge sedimentation in the German and U.S. Mid-Atlantic Bights.

The sequences of sedimentary structures of the investigated shoreface ridges are presented in Antia (1993a). Box-core data show primary and biogenic structures to be highly variable, temporally and spatially. On the other hand, besides occasional graded bedding, vibrocore data showed little variation in the type of sedimentary structures (horizontal lamination) in the subsurface. The earlier noted occurrences of coarser grains in the surficial facies of Spiekeroog ridges are normally associated with the graded beds, and hence attributed to storm events.

The inset of Fig. 4a shows a seaward decrease in the percentage proportion (relative to each core length) of mean size coarser than 2 phi across the outer ridge. This observation, coupled with the similar surficial and subsurface patterns of textural segregation between the ridge morphozones, especially for the outer ridge shown in Fig. 5, suggests that the sedimentation pattern in the ridge field has always been consistent in the course of ridge genesis and growth. The study of Swift et al. (1978) provides examples of surficial mean grain-size patterns from other ridge fields, both in the German Bight and elsewhere, that are similar to that

given in Fig. 3. One may, by implication, expect that the subsurface sediment pattern of the ridges in the German Bight as a whole would be comparable to that of Spiekeroog Island.

The surficial grain-size facies of the outer and inner ridges is, however, better segregated than the subsurface counterpart. It is noteworthy that in the bivariate plots (Fig. 5), the landward-flank and trough sediments depict a genetic relationship. The exception is the surficial sediments of the inner ridge. This is probably because of the greater influence of sedimentation processes on the upper shoreface. For instance, an increased deposition of wave-winnowed and/or rip-current-transported finer fractions in the inner ridge trough could cause the large disparity in textural composition, compared with that of the adjacent landward flank, indicated in Fig. 5. Note that in both the surficial and subsurface sediments of the inner ridge, the trough sediments are markedly finer than those of the crest, which is not the case for the outer ridge.

It was noted that, with the exception of the inner ridge trough, sorting generally improves with depth. The highly variable sorting with depth of the inner trough sediments (core no. 5) shown in Fig. 4b is easily explained by the influx of fines from the upper shoreface, probably during storm conditions. Three major influx events are recorded in core no. 5, at the following depths: < 30, 50–150 and > 210 cm. By contrast, the relatively poorer sorting of the outer trough sediments (core no. 10), compared with the inner trough, may relate to the weaker flow intensity in the former, due to its relatively greater width and larger distance from the shoreline. The elevated values of kurtosis beneath 60 cm core depth revealed by many of the cores (Fig. 4c) are consistent with the noted downcore improvement in sorting.

The predominantly negative skewness in the inner trough would be inconsistent with an interpretation based on the truncation of the fine tail of a grain-size distribution, since this should give rise to larger mean grain sizes and better sorting. This is in conflict with the results given in Figs 4 and 5. Similarly, addition of sediment fractions to the coarse tail of the distribution is feasible but not favoured, because this would result in coarser mean grain-size.

A logical explanation for the negative skewness and the fine grain-size character of the inner trough sediments is the addition of finer fractions (2.5 to 3 phi) in a very large proportion, this range of size classes being largely represented in the native sediments of the trough. Where a broader range of grain-size class-

es than those constituting the native sediments of the inner trough is added, as would probably be the case during major storms, sorting might deteriorate; this is as a consequence of the resuspended fines gradually settling onto the sea bed and in the process filling the intergranular spaces of the substrate. Three such major sediment influx events have already been suggested from the sorting pattern of core no. 5.

The skewness pattern of the outer ridge trough (core no. 10) appears to be due to episodically added coarser sands, the size classes of which are not represented in the native sediments. Such a process would give rise to a larger mean grain size, negative skewness, and poorer sorting as documented in Figs 3, 4 and 5.

The earlier observed disparity in the skewness sign of the surficial sands of the inner and outer ridge crest and seaward flank suggests that sedimentation events on both ridges are not necessarily synchronous, as one would expect, if the morphology owed its origin and maintenance to an *in-situ* (shoreface) reworking process by, for example, a helical flow or flow-transverse pattern. The fact that both ridge trends are not parallel further argues against the above flow types. It is therefore instructive to view both ridges as having evolved independently and subjected to a similar pattern but a different intensity of sedimentation processes.

In this respect, the similar negative skewness of the surficial crest and seaward-flank sands of the inner ridge would simply imply that a sufficiently large supply of coarse sands was available during the sedimentation process over the ridge. The comparable mean grain-size profile of both morphozones shown in Fig. 4a is consistent with this view. The opposite must have been the case on the outer ridge, since coarse-grained sands are depleted on the seaward flank.

The overall lack of the very fine sand fraction in the inner trough, compared to the adjacent landward flank and crest, observed in Fig. 6a, would imply either that the inner trough as a depocenter was 'overpassed' by the seaward sediment-transporting flows, or that the very fine sand deposits have been completely reworked in the inner trough soon after deposition. The process of reworking better explains the deficiency of the very fine sand fraction in the trough of the inner ridge, because this fraction is also lacking in the upper 1 m of the crest and seaward flank of the same ridge.

The thin or discontinuous capping of coarser materials on the sea bed of the inner ridge trough could have facilitated the reworking of the very fine sands, compared to the adjacent crest or landward flank where coarser materials are thicker and thus more effectively

shield the very fine sands occupying their intergranular spaces. Thus, given a similar flow intensity, the very fine sand fraction should be less susceptible to winnowing on the landward flank where it is shielded by coarser grains than in the more exposed situation in the adjacent trough.

Source of sediments and growth mechanism of shoreface ridges

It is noted in Fig. 6c that, with the exception of core no. 7, medium to coarse-grained sands are depleted beneath 60 cm core depth. The above result, coupled with the observation that these sands occur in amounts typically < 10% by weight on the upper (< 7 m) and lower (18–25 m) shoreface of Spiekeroog Island (Antia 1993a), makes it difficult to conceive *in-situ* winnowing as a (sole) cause for the concentration of the coarse sands in the ridge region. It is not clear how processes acting *in-situ* can concurrently give rise to the upward, landward, and proximally (ESE) coarsening grain-size patterns in the ridge region reported in this study and in Antia (1993a, b).

An important implication of the vertical patterns of grain-size data in the study area is that the ridge morphology could not have developed simply from an *in-situ* scouring of troughs and aggradation of crests as implied by the helical and other flow models discussed, for instance, by Swift et al. (1978) and Swift & Field (1981).

A more likely process responsible for the vertical growth of the ridges is related to sedimentation associated with the west-northwesterly divergence of an inlet jet. This is thought to occur when the latter encounters the westward flowing shoreface currents during the ebbing phase of a storm event. The WNW-decreasing mean grain size along the ridge trough and crest, a direction which is the opposite to that of the major storm and net tidal currents in the German Bight (E to ESE; Antia 1993b), supports this assertion.

Based on the above consideration, the observed vertical sequence of the ridge grain-size facies can be viewed as a natural consequence of the character of inlet sediments at a given point in time. The surficial ridge facies might thus represent the coarse-grained Pleistocene sediments which are presently exposed on the inlet channel bed. The subsurface facies, on the other hand, might represent the fine-grained Holocene counterpart which initially flooded the inlet channels.

Conclusions

This study of the vertical pattern of grain-size parameters of shoreface-ridge sediments in the German Bight leads to the following conclusions:

- (1) A two-fold grain-size facies (surficial and subsurface) can be distinguished in some of the ridge morphozones, based on the texture and colour of the sands.
- (2) In view of the deficiency of the surficial sands on the shoreface, their source of supply might be related to the tidal inlet channels.
- (3) The cross-ridge variations in the grain-size parameters of the surficial and subsurface ridge sediments are fairly comparable, leading one to suggest that the processes responsible for the generation and growth of the ridges must have been consistent over time.
- (4) Some morphozones of the studied ridges show an upward-coarsening grain-size pattern similar to that of their counterparts along the east coast of the American continent.
- (5) Ridge-generation models based solely on an *in-situ* scouring and deposition of the substrate sands, by whatever flow condition, are less appealing in the study area.

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