DEPARTMENT OF MINERALS AND ENERGY

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

 RECORD 1974/78

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Abbreviated title: Baltic Sea offshore sand bar field.

ABSTRACT

In the breaker zone in southeastern Gelting Bay, east of Flensburg in north Germany, a field of up to 20 parallel relatively small-scale offshore sand bars has developed. The bars, which consist of fine to medium grained sand derived from till, are flat and asymmetrical and their steeper sides generally face the shore. Crests are as much as 1000 m long; wavelengths vary from 7 m inshore to 70 offshore, and heights correspondingly from 5 to 70 cm. The bars are formed by waves driven by northwesterly winds, and are probably destroyed during severe storms and rebuilt as they wane.

INTRODUCTION

A sand bar field in Gelting Bay in the western Baltic Sea was investigated as part of a study (Exon, 1971) at the Geologisches-Paläontologisches Institut of the University of Kiel, under the guidance of Professor E. Seibold. The general setting of the area was described in Exon (1972), but the bar field was not.

Gelting Bay (Fig. 1) is a triangular inlet which lies at the outer end of Flensburg Fjord, faces north, and has a maximum water depth of 22 m. It is floored with and surrounded by glacial till and was shaped by the Baltic Ice Sheet during the last glaciation.

The sea entered the area about 8000 years ago, when the water level was about 20 m below the present level (see Exon, 1972). In the next 2000 years the sea rose to within 5 m of its present level, and for the past 2500 years has been within one metre of the present level. Wave action modified the glacial landforms, and the eroded till was sorted into sand, silt, and clay fractions which were deposited as belts in the bay, the coarsest fractions nearest the shore.

Southeastern Gelting Bay is unique in the Western Baltic Sea in that it forms a trap for the large waves associated with the frequent northwesterly gales which are most common in winter, but is virtually unaffected by waves coming from other directions. Fetch from the sector 270° - 340° is 10 to 20 km, whereas in other directions it is less than 6 km. These very regular waves (not interfered with by groundswell) break along a line parallel to the gently curving northeasterly-trending coastline on the eastern side of the bay.

Essentially this situation has prevailed for the last 6000 years (Exon, 1972) and a broad wave-cut platform has developed in water shallower than 8 m on the southern and eastern coasts of the bay. There is no efficient outlet by means of longshore currents from the bay, so sand provided by erosion of the till has either accumulated on the platform in water shallower than 2 m, or has been transported into deeper water offshore. More sand has been carried toward the area from the sandy Birckmack (Fig. 3) by means of longshore currents, but most of this has remained in the sandpits west of Gut Beveroe and northeast of the bar field.

Water less than 2 m deep extends offshore from 250 to 600 m in the east and south, but only from 100 to 200 m in the west. In this shallow water, waves have formed asymmetrical offshore bars. In the west there are one, two, or three bars on the relatively narrow platform (Exon, 1971), whereas in the east up to 20 shore-parallel sand bars are found*. The sand bar field is 4 km long and up to 500 m wide.

In Gelting Bay the maximum tidal range is about 30 cm and tidal currents are unimportant. During westerly storms the water level can fall a metre in the Western Baltic whereas during normal easterly storms the water level can rise a metre. Wave action during easterly storms erodes the offshore bars along the west coast of Gelting Bay and the cliffs behind them; at such times the till can be laid bare in wide areas (Kannenberg, 1951). Waves driven by northwesterly storms similarly attack the east coast, but much of their energy is dissipated on the broad sand bar field.

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* <u>Footnote</u>: Offshore bars have been widely described and discussed and Reineck (1970) provided a summary and literature review. Wave-formed bars in the practically tideless Baltic Sea arc fairly well known (e.g. Werner, 1963; Brand, 1955), but normally not more than 3 bars are found. To distinguish the unique occurrence at Gelting Bay the terms "sandwave" and "sandwave field" were used by Exon (1971, 1972), but the distinction is rather artificial and the terms "sand bar" and "sand bar field" will now be used.

FIELD WORK AND LABORATORY METHODS

To document changes in the bar field during the last 30 years sets of aerial photographs were examined. A 1969 photograph (original scale 1:3000) of a typical area shows the general form and size of the bars (Fig. 2).

Maps drawn from aerial photographs flown in 1964 and 1969 (Fig. 3) show little change in the general distribution of sand bars, although most individual bars could not be identified in both sets of photographs. There has been little change in the distribution of the sand bars since 1936, when the first aerial photographs were taken. Glacial erratic boulders project through the sand bars in places, and most of them had not moved between 1964 and 1969.

In 1970 three profiles normal to the coast and across the sand bars were measured with the aid of a diver. It was possible to walk out from the beach or use a rubber boat and, using steel-tipped rods with flags and a long rope marked in metres, to measure the water depth at intervals of 2 or 2.5 m. Water level changes over the few hours needed to measure a normal 200 to 300 m profile are unimportant in periods of calm weather, and no corrections were applied.

The profiles were continued out from the beach to beyond the sand bars, where the underlying till was revealed (generally in 1.5 to 2 m of water). Surface samples or push-box cores were taken at regular intervals on selected bars. In two profiles the sand thickness was measured at regular intervals, either by digging to the till surface or by use of a water-jet lance. Water was forced through the lance by a pump mounted on a rubber boat, and rapidly penetrated the loose sand of the sand bars. The more compact till slowed the lance, which allowed the sand thickness to be measured either directly on the lance or by lowering a scale into the hole.

Polymer relief casts of sand bar cores were made to determine the internal structure (see Exon, 1972, for technique). Grainsize analyses of surface samples, and from top and bottom of cores, were made using a sediment balance. A computer program developed by Dr E. Walger converted the data into sediment grainsize parameters.

GENERAL FEATURES OF THE SAND BARS AND CONTROLS ON THEIR FORMATION

As the general distribution of the bar field has varied little in the past thirty years, the forces creating the sand bars have evidently not changed, although the bars themselves have moved. The bars are very sensitive to disturbance by inflow of fresh water from small streams, or waves refracted from man-made structures, as is shown by the gaps in, or drastic reduction of, the field south of the old dyke wall off Gelting Noor (inlet), off the groynes southwest of Quisnis Peninsula, off the Wackerballig jetty, and off the little stream in the far south (Fig. 3). The field is limited to the north by the Gut Beveroe sandspits, and disappears on the sheltered southerly coast because little sand has accumulated there. Wavelengths increase from the shore outwards, and tend to be longer in the more exposed northerly areas than in the southwest (15 to 50 m in the northeast, and 10 to 30 m southwest of Wackerballig jetty). Furthermore the axial length of individual sand bars is as much as 1000 m in the northeast, but seldom exceeds 200 m in the southwest.

In the more exposed areas of the western Baltic Sea, the frequent reworking of the sand bars by sizeable waves means that biotic cover cannot establish itself. Under these conditions the shape of individual bars is very regular (e.g. Brand, 1955). However, on the eastern shore of Gelting Bay wave action is quite limited during the warmer months, a period when growth of sea grass and seaweed is at a maximum. Sea grass and Mytilus communities have established themselves on the seaward flanks of many of the sand bars, and have tended to stabilize them. During winter storms shoreward sand movement on the less densely covered parts of the bars occurs, and this has destroyed the natural regular shape of many of the waves (see Fig. 4). Field observations show that sand is commonly scoured away above and below Mytilus banks.

The sand bars are eroded by longshore currents caused by wind drag or the escape of piled-up water from the bay. This effect is greatest inshore, and there the bars are very low, or glacial till may even be exposed. Small scour channels perpendicular to the shore are cut through many bar crests south of Gelting Noor. These channels (generally <5 m wide and 10-20 cm deep) are presumably cut by outflowing bottom currents when wind drives the surface water directly onshore. They are readily recognizable on aerial photographs (e.g. Fig.2) where they have eroded dark areas of sea grass and Mytilus and exposed the light sand beneath. In November 1969 channel cross-sections, although normal to the shore, tended to be strongly asymmetrical, with erosion concentrated on the northeast side where Mytilus banks were being undercut. Presumably the outflowing undercurrents had first cut the channels normal to the shore, but later outflow had a more northerly direction, causing lateral cutting in the existing channels.

Profiles B & C (Fig. 4) show that in general the shape of the underlying till surface and that of the sand bars are independent. Where the bars are best developed the sand body averages 60 cm in thickness. From the three sections and other data Exon (1972) estimated that about 500 000 cubic metres of sand lie on the southeasterly platform.

The shapes of the sand bars in the profiles were measured, and the parameters wavelength, wave height, ripple index (length/height), and symmetry (horizontal distance from crest to shoreward trough/wave length) were plotted against the distance of the bar crest from the shore. Wavelength was also plotted against bar height. All these graphs are shown in Figure 5. Overall, wavelengths vary from 7 to 70 m, heights from 4 to 55 cm, ripple indexes from 80 to 370, and symmetry from 0.3 to 0.63 (symmetry values < 0.5 indicate asymmetry with steep side shoreward; values > 0.5 steep side seaward). In detail the various graphs with these sand bar shape data show:

a) Wavelength and bar height both increase with distance from shore, but height increases more rapidly than length inshore, and length more rapidly offshore.

b) The ripple index is greatest (i.e. the bars are flattest) inshore, reaches a minimum in the middle distances, and decreases somewhat offshore.

c) The bars of Profile C tend to be asymmetrical in the seaward direction (steep side seaward) near shore, and strongly asymmetrical in the shoreward direction further offshore. The bars of Profile A are very irregular, but generally also show decreasing symmetry values (change from steep side seaward to steep side shoreward) with distance from shore.

When frequency of occurrence is plotted against wavelength and against bar height, there is a marked difference in the patterns. The wavelengths give a unimodal curve, with three-quarters of lengths lying between 12 and 33 m and one third between 15 and 20 m. Bar heights show no clear maximum but frequency decreases steadily with height. Thus 15% of the bars are less than 5 cm high and 10% between 25 and 30 cm.

Grainsize moment data obtained from surface samples and pushbox cores on five sand bars have been plotted against bar shape in Figure 6, and show:

a) The sand is well sorted.

b) Although grainsize is related to bar shape for most sand bars, this relationship varies from bar to bar. However, in most cases the coarsest sand is in the troughs.

c) Curves for subsurface samples at Wackerballig in summer (bar 10515) and autumn (bar 10423) appear to be out of phase with the surface curves, which suggests slow migration of the sand bars with time.

Plots of skewness against mean grainsize (Fig. 7) show that data points for each bar sampled lie in separate fields. Plots of skewness against standard deviation (Fig. 7) show a greater spread of points and the various bars are not as distinct. Plots of standard deviation against grainsize (Fig. 7) also allow the various bars to be distinguished. The Wackerballig offshore samples (10514), with coarse grains and appropriately high standard deviation, are just as distinctive as in the skewness plots.

Relief casts were made from pushbox cores 15 to 30 cm long taken across sand bars 10423 and 10515 (Wackerballig onshore: the same bar at different times of the year) and are illustrated in Figure 8. These show that day-to-day migration of the bars takes place by means of small-scale ripple migration in units mostly less than 5 cm thick. The structure is complex, crossbedding units dip both onshore and offshore, and some laminae are parallel to the bar surface. In this particular area wave action was not hampered by Mytilus or sea grass cover.

In cores from sand bar 10423 taken in autumn 1969, fresh structure was visible to depths of 5 to 10 cm on the seaward side, but only to 1 or 2 cm on the leeward side, showing that reworking was strongest on the seaward slope. The underlying 20 cm of sediment was bioturbated, showing that the bar had been dormant earlier. Structure is commonly preserved at the bottom of the cores, suggesting that bioturbation does not reach more than 20 to 25 cm below the surface. The abundance of sea grass fragments in the troughs shows that broken off stems settle there preferentially. The cores from sand bar 10515, taken in summer 1970 on the same bar in much the same position, contain very little fresh structure. The bar had been essentially inactive for some time, and burrowing crustaceans and worms had thoroughly mixed the sediment.

Wave action and its effects

Walden (1960) plotted wave data for the lightship "Flensburg" ("F.S. Flensburg" in Fig. 1) which lay several kilometres north of Gelting Bay, for the six years 1949 to 1954, and the data gathered over this relatively long period can be regarded as fairly representative. The exposure of the lightship to waves from the sector 270° - 340° is much the same as that of southeast Gelting Bay, and wave heights and periods in both areas must be similar at the same time. The wind and waves came from this quadrant on 31% of days. The distribution of readings for various sized waves interpreted for southeast Gelting Bay, i.e. excluding waves which could not reach this side of the bay, is tabulated below (Table 1). The most common appreciable waves are around 0.5 m high, but waves to 1 m high can be expected several times a year, and still larger waves must be reckoned with.

From Walden's (1960) wave height and period data it is possible to calculate the theoretical maximum current velocities developed in various water depths for various wave sizes (see Table 2). These values cannot be regarded as accurate, but do give an indication of velocity relationships.

Table 1: Waves in Gelting Bay

	From all directions	Only produced by northwest winds			
Wave height (m)	< 0.25	0.5 (0.25-0.75)	1 (0.75-1.25)	1.5 (1.25-1.75)	2 (1.75-2.25)
% of readings	73	22.8	3.5	0.9	0.4

Table 2: Effect of waves in outer Flensburg Fjord

(1) Wave height H (m)	(2) Period T (secs)	(3) Wave velocity v (m/sec)	(4) Wave length λ (m)	(5) Base of erosion $\frac{\lambda}{2}$ (m)	(6) Water depth h (m)	(7) Maximum horizontal bottom velocity (cm/sec)
0.5	2.3	3.7	6-9	4	2	20
					3	12
					4	6
1.0	3	4.8	15	7-8	2	70
					8	10
1.5	4	6.4	28	13	8	32
					14	9
2.0	6	9.6	60	30	8	64
					12	40
					20	12
					30	1

(1) and (2) measured on lightship "Flensburg" (Walden, 1960).

(3) Velocity = 1.6T (Bascom, 1959)

(4) $\lambda = vT$

(5) Feels bottom at $\frac{\lambda}{2}$ where orbital velocity is 4% that at surface (Bascom, 1959)

(6) Water depth assumed to calculate (7)

(7) Maximum horizontal bottom velocity = $0.4V \left(\frac{H}{h} - 0.062\right)^{0.72}$ (Johnsen, 1961).

The well-known curves of Hjulström (1935) show that velocities of 15 cm/second can erode fine and medium sand, and velocities of 30 cm/second fine gravel. Thus the larger waves are capable of eroding glacial till down to water depths of 10 or more metres. The clay is swept away in suspension and the sand (50% of the solids in the till - Exon, 1972) is transported along the bottom by various currents, and in the shallower water is swept inshore by breaking waves. Sand accumulates in water shallower than 2 m, where wave energies are lower.

Western Baltic Sea sand bars are normally (e.g. near Heiligenhafen - Brand, 1955) strongly asymmetrical, with steeper lee slopes. The strong reworking caused by turbulence at the foot of the lee slope means that only coarser material can remain there, and finer material accumulates higher on the bars. The bars have a wavelength of 50 to 75 m and a height of 1 to 1.5 m. The crest of the outermost bar is as much as 2 m below sea level. The deeper internal structure of the bars, which are generally a metre or more thick, is unknown, but pushbox cores (Werner, 1963; Newton, 1969) have shown that the uppermost 30 cm is commonly characterized by small-scale ripple lamination and bioturbation. These features develop during periods of relative calm.

In the less exposed Gelting Bay the outermost sand bars may be as long (70 m) as the bars in the open sea, but they are usually flatter (60-70 cm) as a result of longer periods of relative calm during which modification by small-scale ripple migration is possible. The nearer the shore the shorter and lower are the bars. The original wavelengths have been preserved, but the heights of the bars have been extensively modified by small-scale ripple migration of sand from the crests to the trough, and vary much less than wavelength does with distance from shore.

Figure 5 shows that the sand bars were steepest and most asymmetrical in the middle distance at the time they were measured. This suggests that rebuilding of the bars had been most active in these areas, and thus that most waves had been breaking there. Water depths over the crests were between 60 and 80 cm, suggesting that waves a little over 0.5 m high were involved (waves break in water where the depth is 1.3 times their height - Bascom, 1959). These were probably the very common 0.5 m high open sea waves (Table 1) somewhat shortened and heightened by bottom drag.

DISCUSSION

The formation of such an extensive field of highly regular wave-formed sand bars as that in Gelting Bay (similarly extensive fields have not, to my knowledge, been previously described), seems to depend on two things.

Firstly, the Baltic Sea is virtually tideless, and thus no matter what the tide, waves of similar size and orientation must attack much the same part of the sea bed. Secondly, effective waves come from virtually one direction only, the northwest, which also happens to be perpendicular to the shore line, so that little refraction occurs and wave energy is evenly distributed along the shore. Thus exceedingly regular bar fields could develop which, once they had formed, were not attacked by waves coming from different directions.

The outstanding problem with these sand bars remains their genesis - either by gradual growth by small-scale ripple migration, or suddenly during major storms. The author favours formation during storms, and envisages their development as follows:

The postglacial sea level rise slowed several thousand years ago, and thereafter wave action cut a broad platform on which sand, derived from the till which was being eroded, accumulated. Once enough sand had accumulated a bar formed. The breaking of waves on the bar caused scouring on the lee side, but as the waves reformed they deposited their sand load, forming a second bar shoreward of the first. Gradual erosion of the till surface behind the bars, and massive erosion caused by particularly wild storms when the bars were destroyed and the whole platform attacked, caused the platform to widen. As it widened more and more bars could be built up. Because much energy was expended on the outer bars less wave energy was available to form the inner bars and hence the size of the sand bars diminishes inshore.

It is suggested that even now during major storms the entire sand mass is reworked, and only as the storms wane, and wave sizes diminish, do the sand bars again form. Such storms may occur only once or twice a century. Vicro-corer investigations could show if the lower parts of the bars consist of large scale cross-beds, which would indicate that the bars were, in fact, formed during one storm and modified thereafter by ripple migration.

It is unlikely that such features would be preserved in the geologic record. This would require sudden protection from wave action (tectonic movements, development of a protecting sandspit), and deposition of silt or mud on the bars.

If they were found in the record they would be difficult to distinguish from normal large scale current ripples. With their ripple index of around 100, they are flatter than most such ripples, but still fall within the possible field (see Fig. 4.10 in Allen, 1968). If outcrop were very good, and the position of the palaeocoastline were known, the fact that the large scale ripples would parallel the shore and diminish in size shoreward, and that they would show cross lamination oriented both shoreward and seaward, would be diagnostic of a sand bar field.

ACKNOWLEDGEMENTS

This work was carried out at the suggestion of Professor E. Seibold, during a two year stay at the University of Kiel. Drs R. Newton, F. Werner, and M. Sarnthein gave advice and practical assistance in the field and the laboratory. Student divers B. Flemming and R. Fritsche helped with the field work, and Frl. W. Rehder with the laboratory work. Dr E. Walger advised on the grainsize work and provided a suitable computer program. I wish to thank all these colleagues for their unstinted help and encouragement.

REFERENCES

ALLEN, J.R.L., 1968 - Current ripples. North-Holland Publishing Company, Amsterdam. 433 pp.

BASCOM, W., 1959 - Ocean Waves; in Scientific American August 1959.

BRAND, G., 1955 - Sedimentpetrographische Untersuchungen zum Erkennen der Sandwanderungsvorgänge am Strand, im Flachwasser und dem daran anschliessenden Seegebiet. Meyniana, 4, 84-111.

EXON, N.F., 1971 - Holocene sedimentation in and near the outer Flensburg Fjord (westernmost Baltic Sea). Doctoral Dissertation, Geologisches Institut der Universität Kiel (unpubl.).

EXON, N.F., 1972 - Sedimentation in the outer Flensburg Fjord area (Baltic Sea) since the last glaciation. Meyniana, 22, 5-62.

HJULSTROM, F., 1935 - Studies of the morphological activity of rivers as illustrated by the River Fyris. Bull. geol. Inst. Uppsala, 25, 221-527.

JOHNSEN, R., 1961 - Wechselbeziehungen zwischen der Welle und dem strandnahen Unterwasserhang. Veröffentl. Forschungsanstalt Schiffart, Wasser-Grundbau 9, 1-102.

KANNENBERG, E.G., 1951 - Die Steilufer der schleswig-holsteinischer Ostseekuste. Schr. Geogr. Inst. Kiel 14(1).

NEWTON, R.S., 1969 - Internal structure of wave-formed ripple marks in the nearshore zone. Sedimentology, 11, 275-292.

REINECK, H.E., 1970 - Marine Sandkörper, rezent und fossil. Geol. Rdsch., 60(1), 302-320.

WALDEN, D.H., 1960 - Der Seegang bei den Feuerschiffen "Flensburg", "Kiel", und "Fehmarnbelt". Deutscher Wetterdienst, Seewetteramt Einzelveröffentlichungen Nr. 26.

WERNER, F., 1963 - Uber den inneren Aufbau von Stradwallen an einem Kustenabschnitt der Eckernförder Bucht. Meyniana, 13, 108-121.

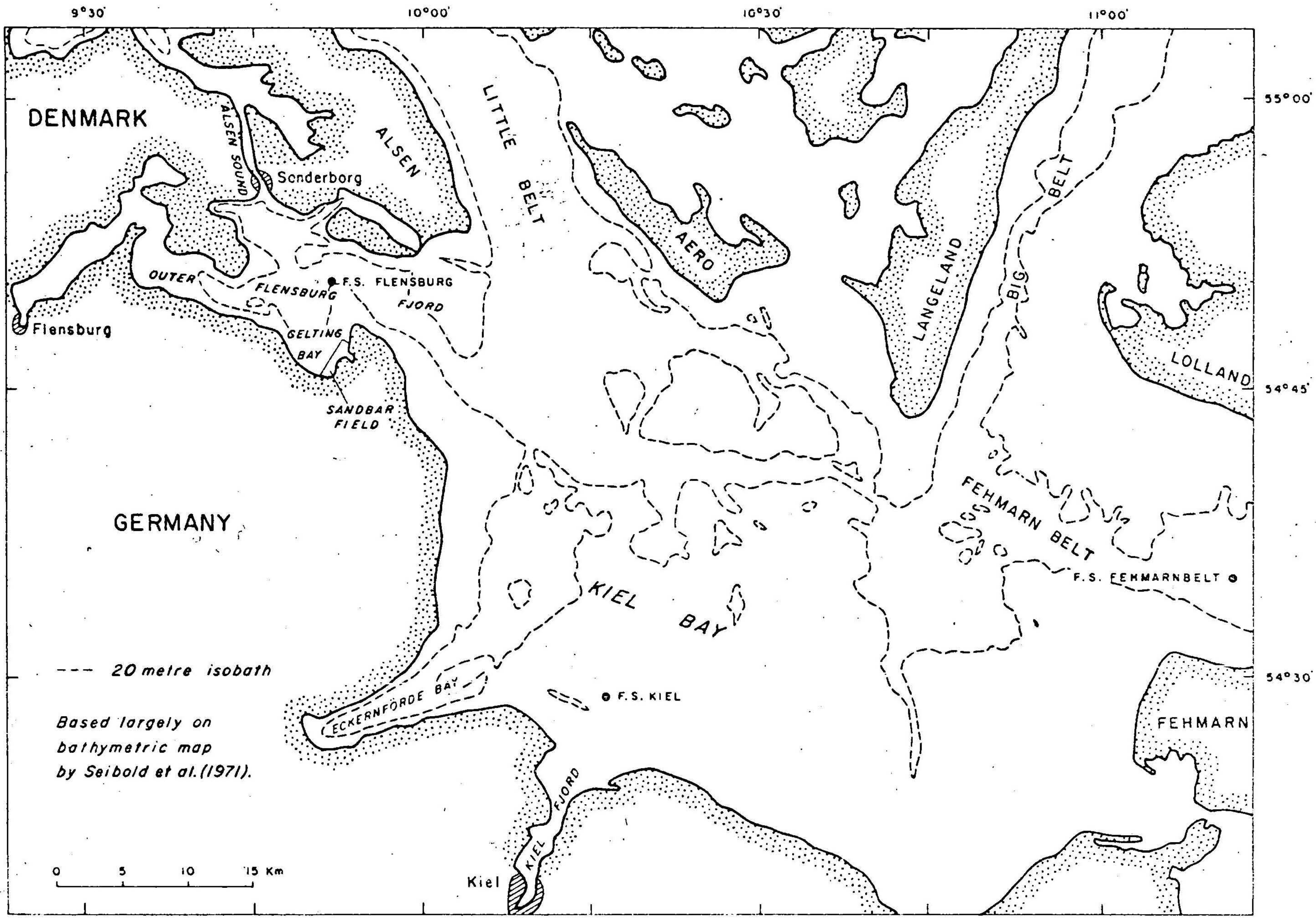

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Fig. 1 Regional setting within the Belt Sea.

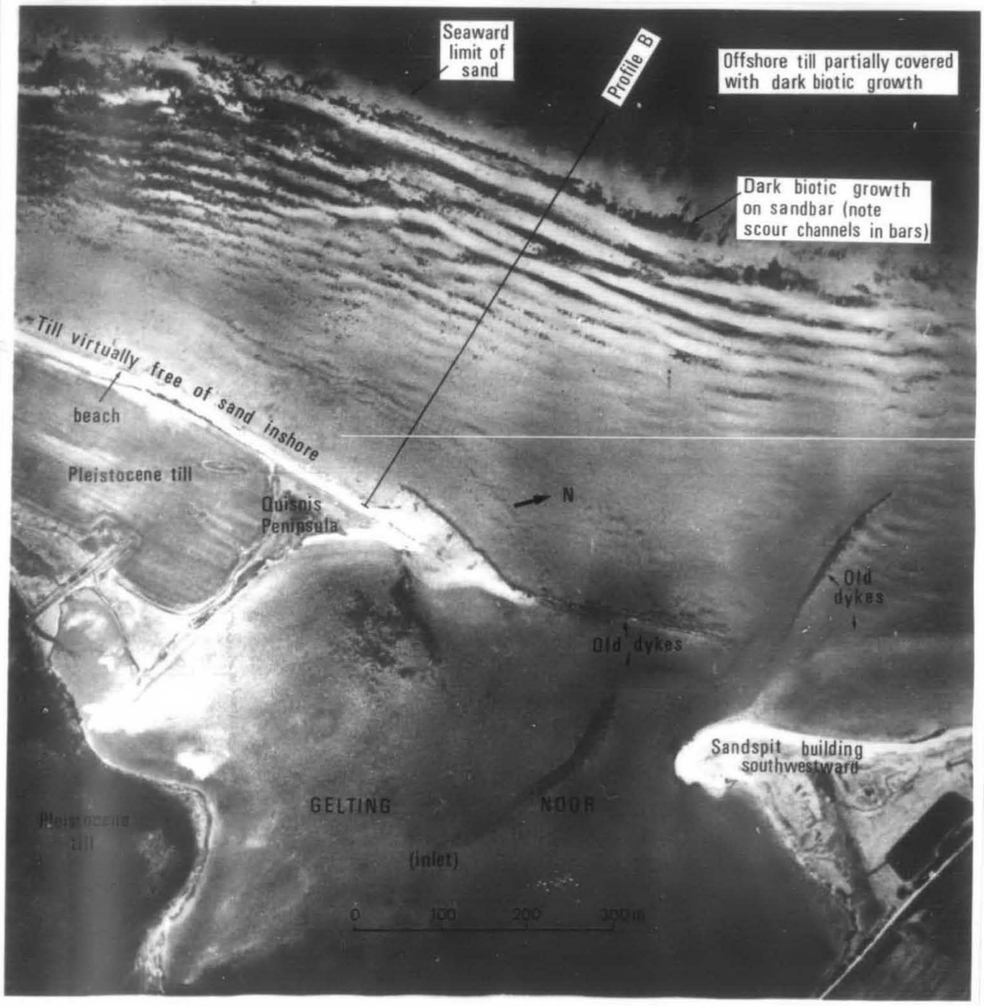

Fig. 2: Aerial photograph of part of the sand bar field

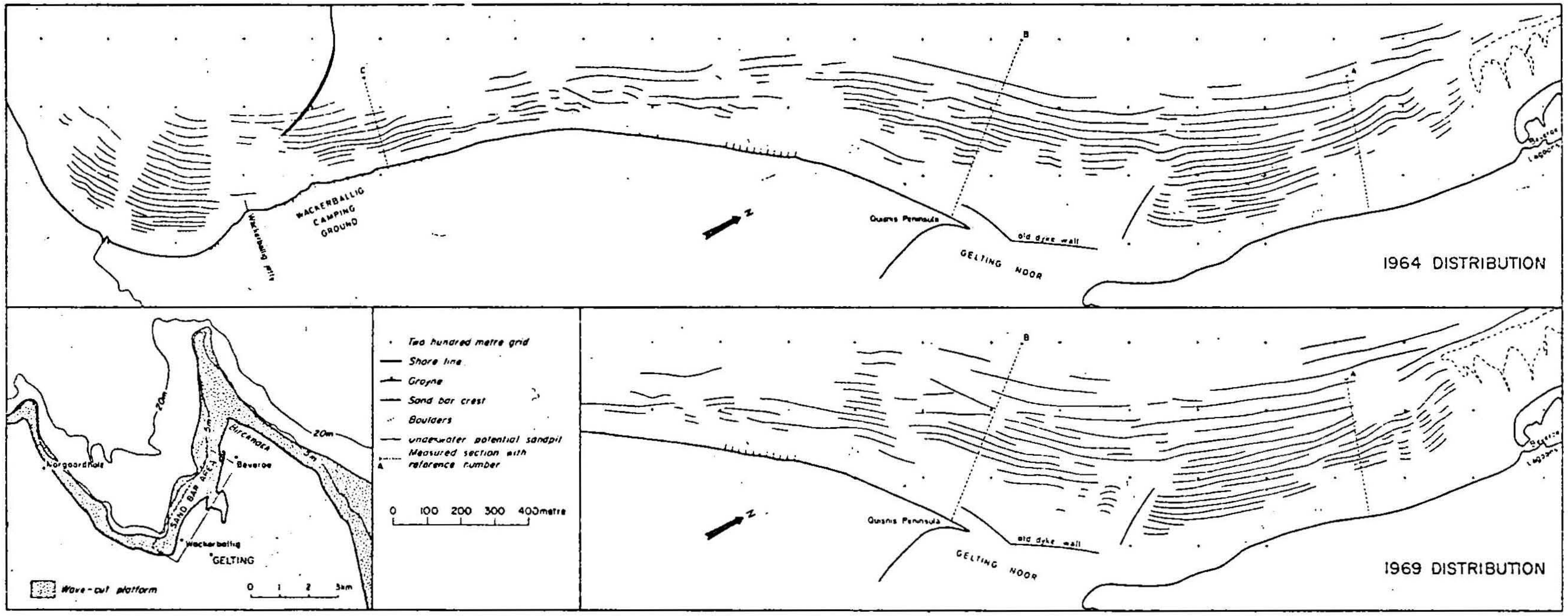

FIG. 3 THE SAND BARS OF EASTERN GELTING BAY
INTERPRETED FROM VERTICAL AIRPHOTOGRAHS AT AN APPROXIMATE SCALE OF 1:3000

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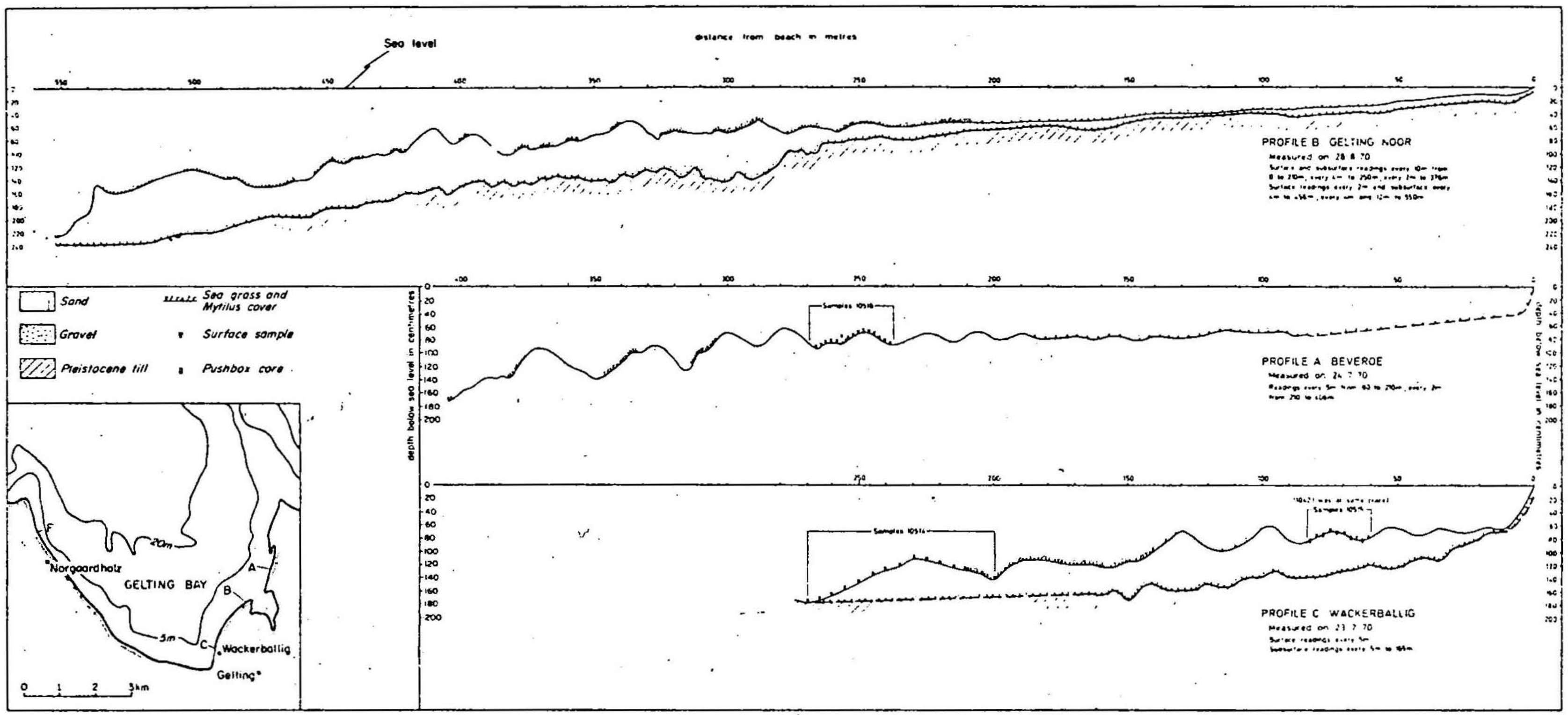

FIG. 4 PROFILES ACROSS THE SAND BARS ON EASTERN SHORE OF GELTING BAY

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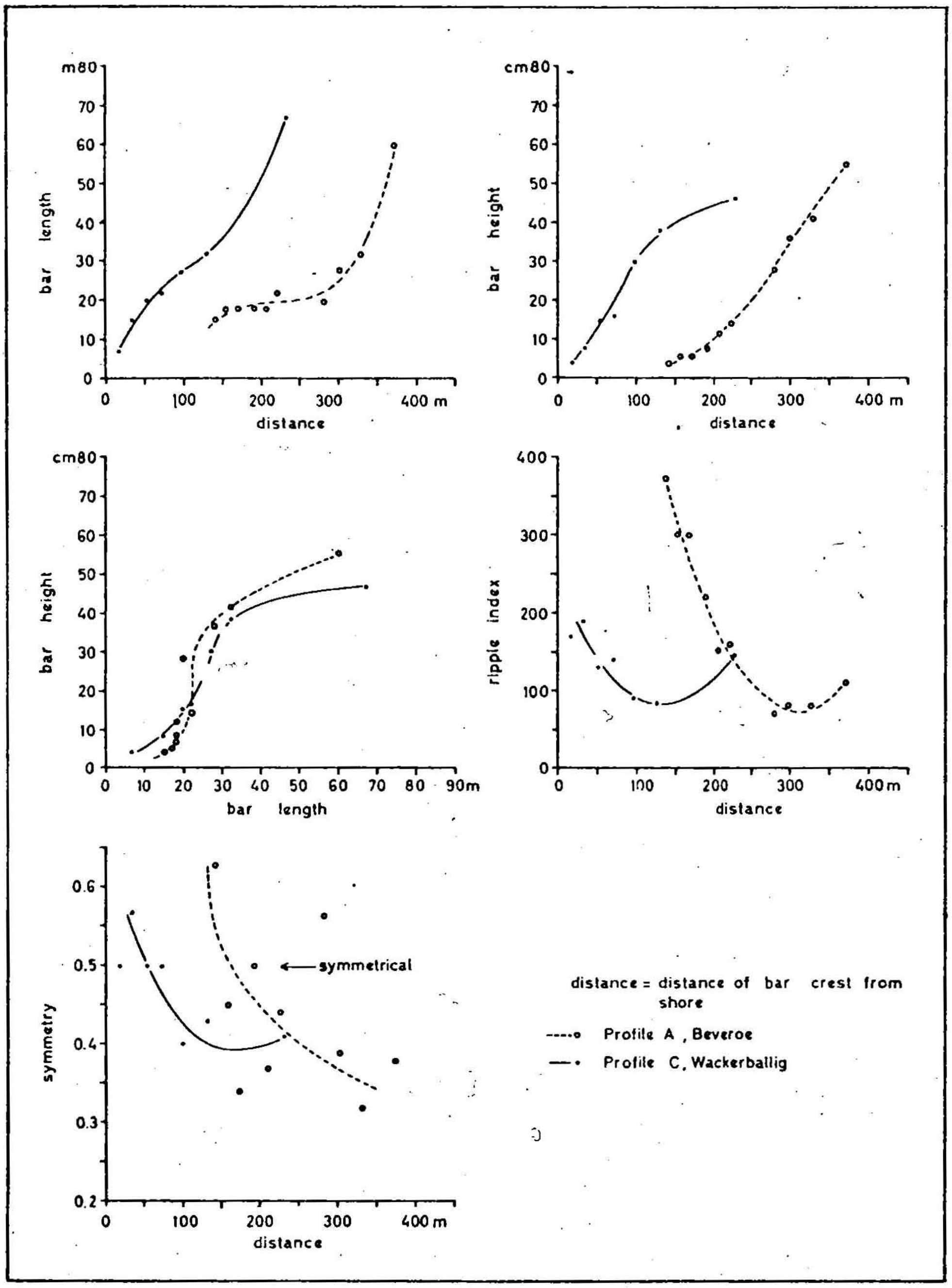

FIG.5 SAND BAR SHAPE DATA RELATED TO DISTANCE FROM SHORE.

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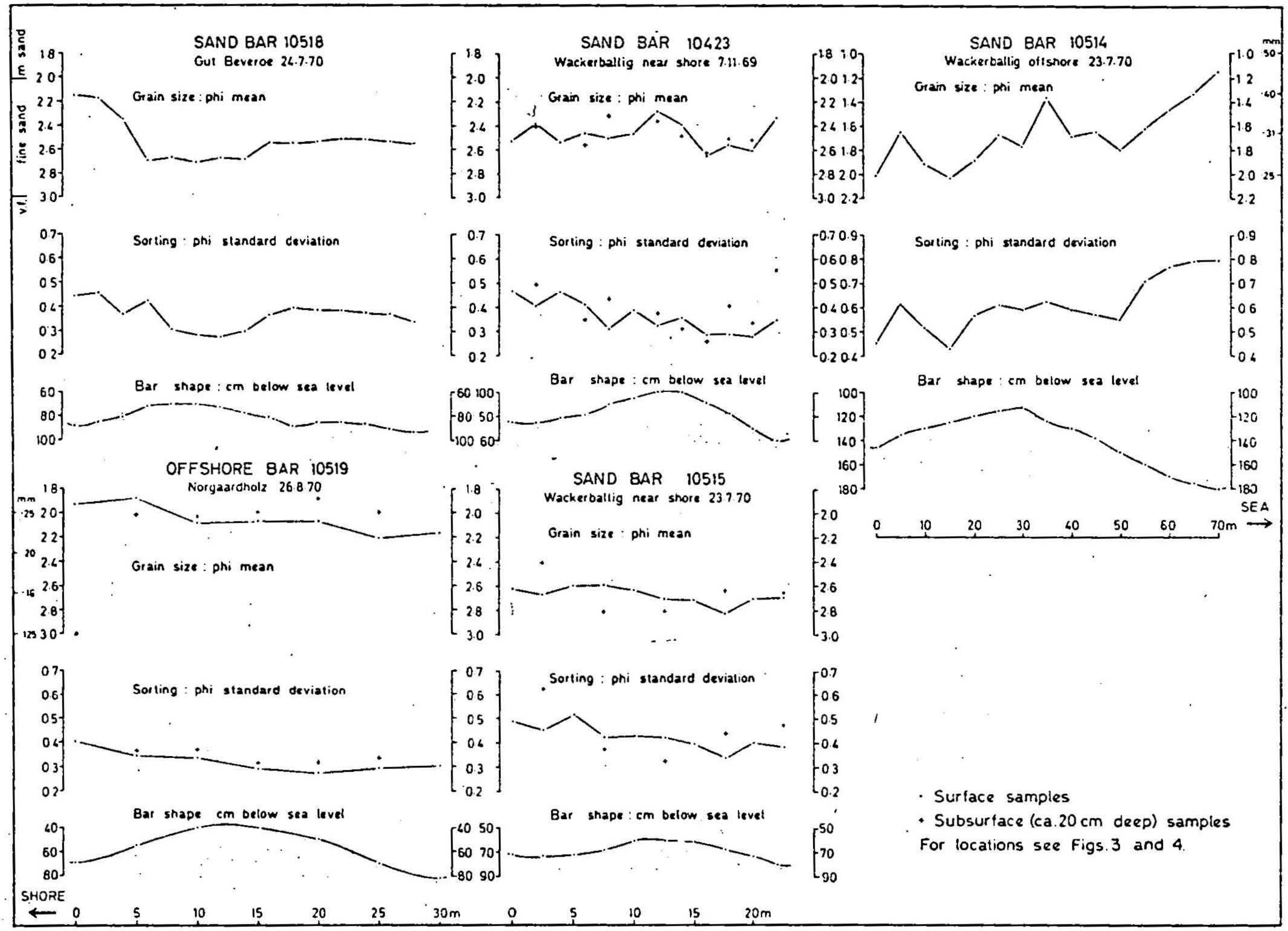

FIG. 6 CHANGES IN GRAIN SIZE DISTRIBUTION ACROSS OFFSHORE BARS.

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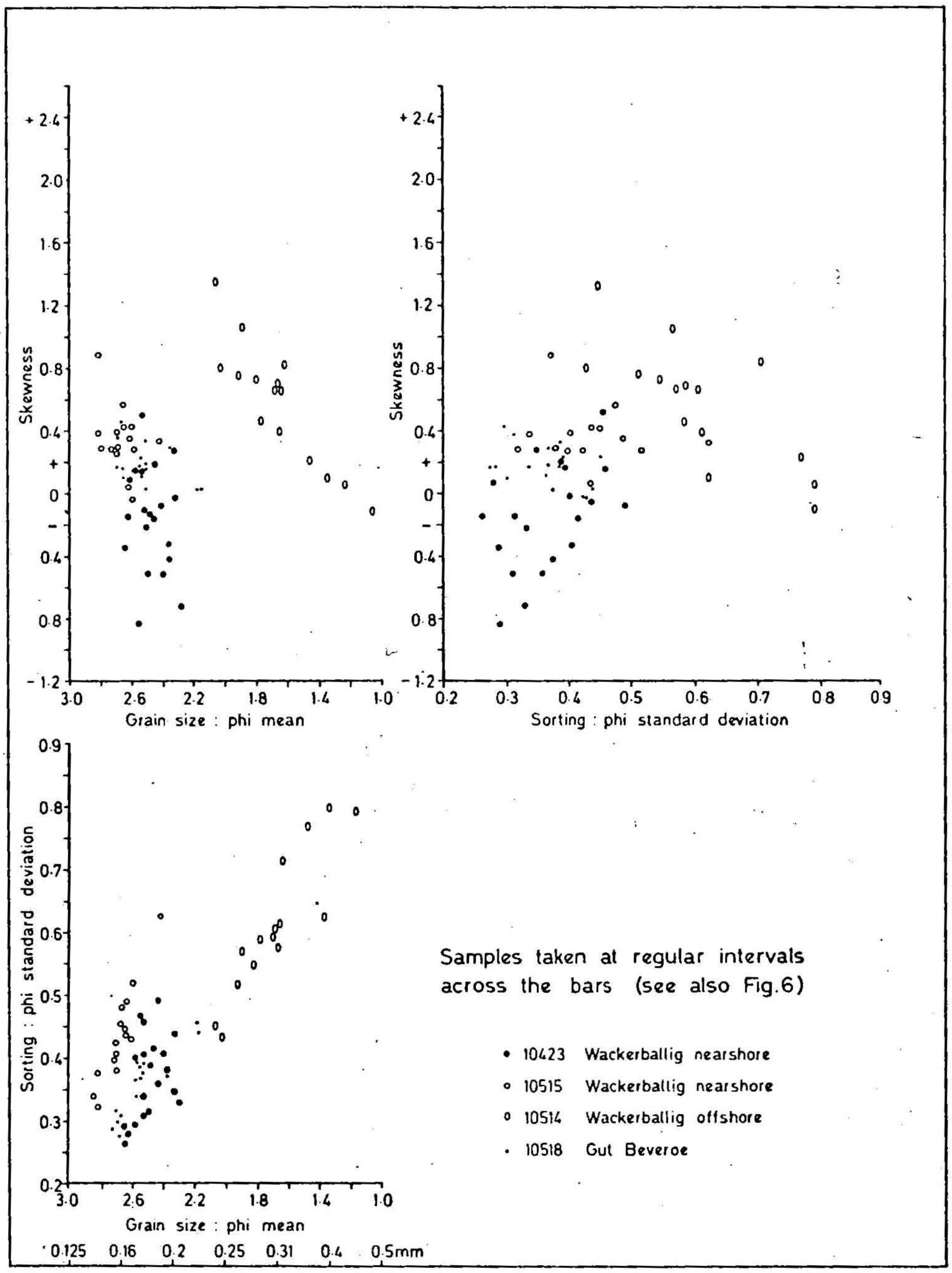

FIG. 7 GRAIN SIZE CHARACTER OF THE SAND BARS SAMPLED

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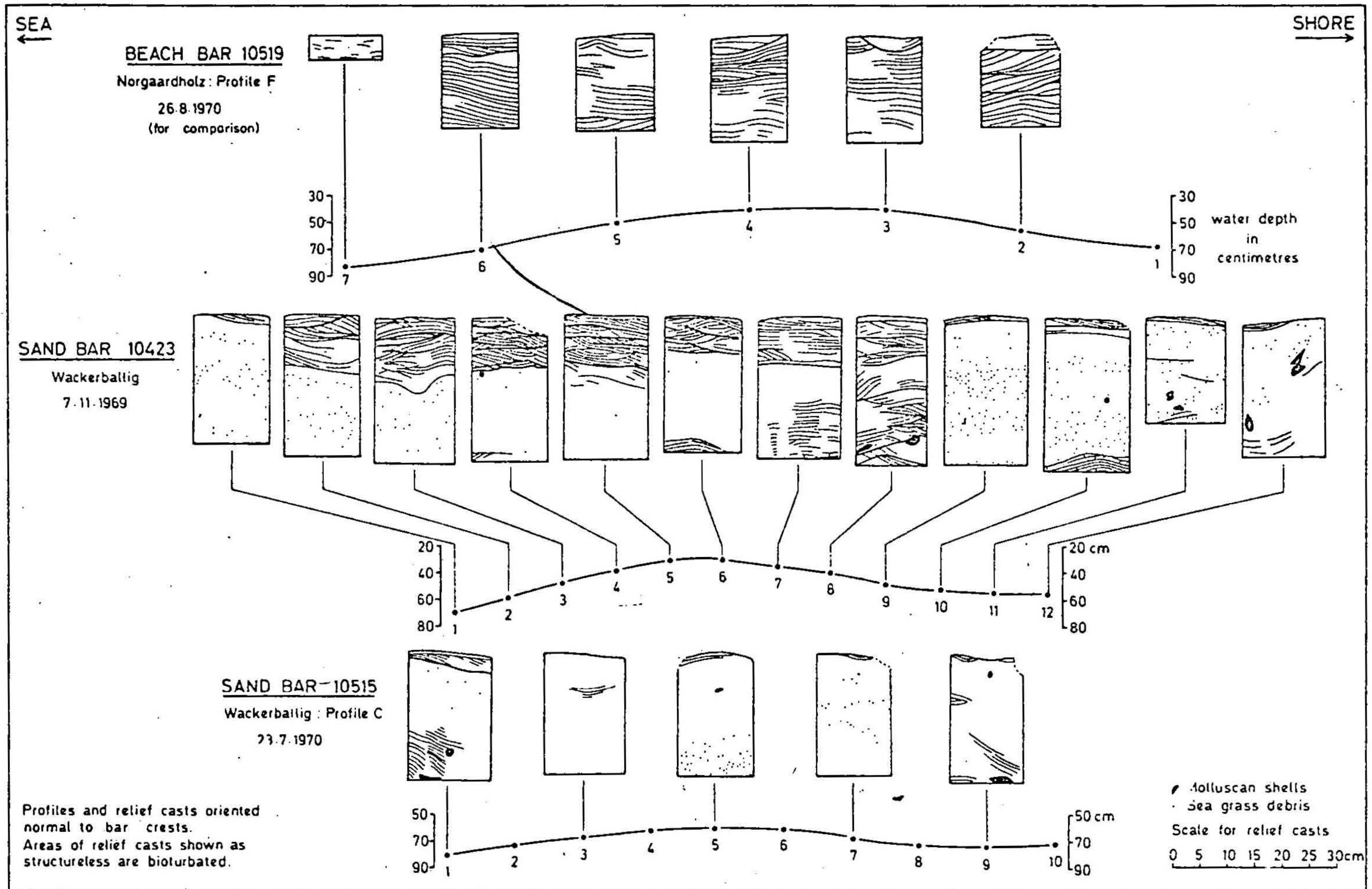

FIG. 8 INTERNAL STRUCTURES OF SAND BARS FROM RELIEF CASTS OF PUSHBOX CORES.

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