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RECENT SEDIMENTS IN THE SOUTHERN BIGHT OF THE NORTH SEA

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SUMMARY

The recent sediments of the southern bight of the North Sea were studied mainly as a possible model for the interpretation of fossil sand bodies. The area examined lies between England, Belgium and the Netherlands. It is an area of strong tidal currents.

A group of ridges were found to consist of sand and to rest on an essentially flat surface which is a continuation of the surrounding sea bottom. The ridges of the Well Bank area are asymmetric in cross section and are oriented parallel to the current direction. Sand seems to be transported obliquely over the gentle southwest slope of the ridges in a northerly direction towards the crest, whence it is deposited on their steeper northeast flank. This process gives rise to an internal cross-stratification which is visible on the sparker records. The ridges of the Well Bank area seem to be moving slowly northeastwards. Sparker records of the ridges formed by sand accumulation outside the Well Bank area revealed no internal structures and foreset directions observed in cores of them were found to be erratic and their asymmetry in cross section was found to be irregular. It is therefore impossible to deduce their internal structures from surface observations. It is certain, however, that they are all isolated sand bodies standing on a flat subsurface that is exposed outside their flanks.

The fact that the flood current does not follow the same path as the ebb current gives some of these ridges very complicated forms (e.g. Flemish Banks and Haisborough Sand).

In all cases, it can be stated that the sand of which these sand ridges consist is derived from the sea bottom and not directly from a river mouth. The sand in the ridges of the Well Bank area seems to have been derived from a glacial outwash fan formed in the area during the last glaciation. The material in the Outer Gabbard and probably the other ridges in the neighbourhood is derived from Tertiary sediments outcropping in that area. The sand in the Flemish Banks, the Hinder Banks, the Sandettie and the Falls is derived from Rhine sands deposited in the area during stages of lower sea level.

The Brown Ridge and the Zeeland Ridges were found to have been formed at least partly by erosion of older deposits.

Mega-ripples not associated with the sand ridges were found in great abundance in the area off the Dutch coast. They were all found to have their steepest slope towards the NNE. It is suggested that sand is transported towards the NNE in this area and that the fine fraction accumulates on the Texel Spur. This Texel Spur was found to be covered with extremely well-sorted fine sands, which were completely churned. There is evidence, though weak, that this Texel Spur sand is 10 meters thick.

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1. INTRODUCTION

1.1. Purpose of investigation

During marine transgressions that are not accompanied by strong tidal currents, only thin veneers of sand are formed. In the subsurface, these are of little value as oil reservoirs. Recent examples can be found in shelf areas in front of the Orinoco, Mississippi and Niger deltas (e.g. Nota 1958). Transport during such a transgression is mainly by wave action, which is always directed towards the shore. Consequently, the sand made available by marine erosion during the transgression is transported towards the shore, where it is deposited on coasttal barriers and in tidal channels.

In the case of the post- glacial transgression of the southern bight of the North Sea, however, strong tidal currents occurred offshore. Much of the sand made available by marine erosion was not transported towards the shore but was preserved at sea in often very big sand bodies. Most of these sand bodies consist of very well-sorted, clean sand and hence show good reservoir characteristics. An attempt was therefore made to find out more about their lithology, dimensions, genesis etc., so that this information might assist the interpretation and prediction of sandstone reservoirs.

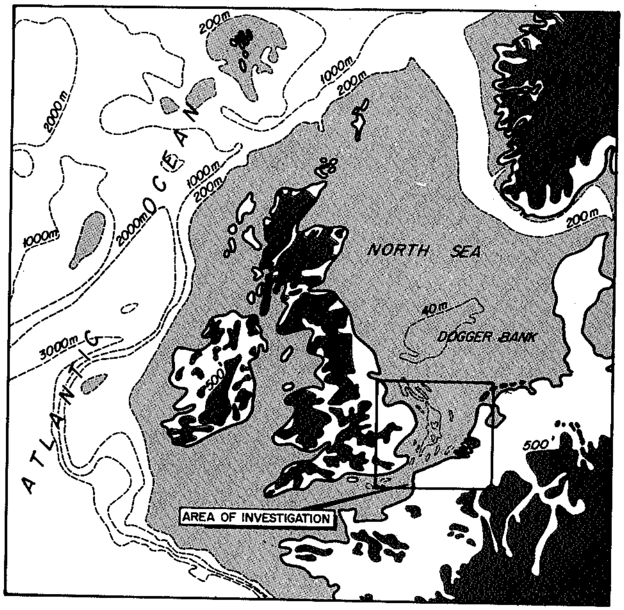

Fig. 1 - Situation map N.W. European shelf.

1.2. Physiography

The southern bight of the North Sea is the southernmost part of the North Sea and is bounded by the coasts of England, France, Belgium and the Netherlands (fig. 1).

1.2.1. Relief. An isobath map was constructed by contouring the depth notations which occur on the British Admiralty charts of the area. The result is given in enclosure 1. A simplified version occurs on figure 2.

The southern bight of the North Sea is rather shallow, its maximum depth being slightly over 50 m. The deepest part occurs in the English half, in a N-S trending elongated depression, the "Deep Water Channel", which leads to the Straits of Dover.

Towards the north a shallow zone protruding from the Humber estuary and the Wash bay to the east-northeast we call the Humber Spur. It meets another one, protruding from the island of Texel to the west, which we call Texel Spur. Humber Spur and Texel Spur separate the southern bight from the main part of the North Sea to the north.

At several localities in the southern bight of the North Sea elongated ridges occur, which may rise up to 40 m above the surrounding sea bottom. Maximum length is about 65 km (Falls) and the width reaches 5 km. In most cases these ridges are straight or nearly so (e.g. Well Bank), but complicated patterns occur as well (e.g. Haisborough Sand-Winterton Ridge).

1.2.2. Topographic names used. In the area investigated, the English, French, Dutch and German languages meet. The result is a great complexity of topographic names. Occasionally one name has different meanings in different languages. By Hoofden, for instance, Pratje & Schüler (1952) mean the southern bight of the North Sea, whereas Van Veen (1936) uses it to mean the Straits of Dover.

In this report all marine topographic names used are taken from the British Admiralty charts. To these were added the names Humber Spur, Texel Spur, Zeeland ridges and Well Bank area, to indicate certain units discussed below.

The word "ridge" is used for an elongated rise of the sea floor, either straight or curved, at least

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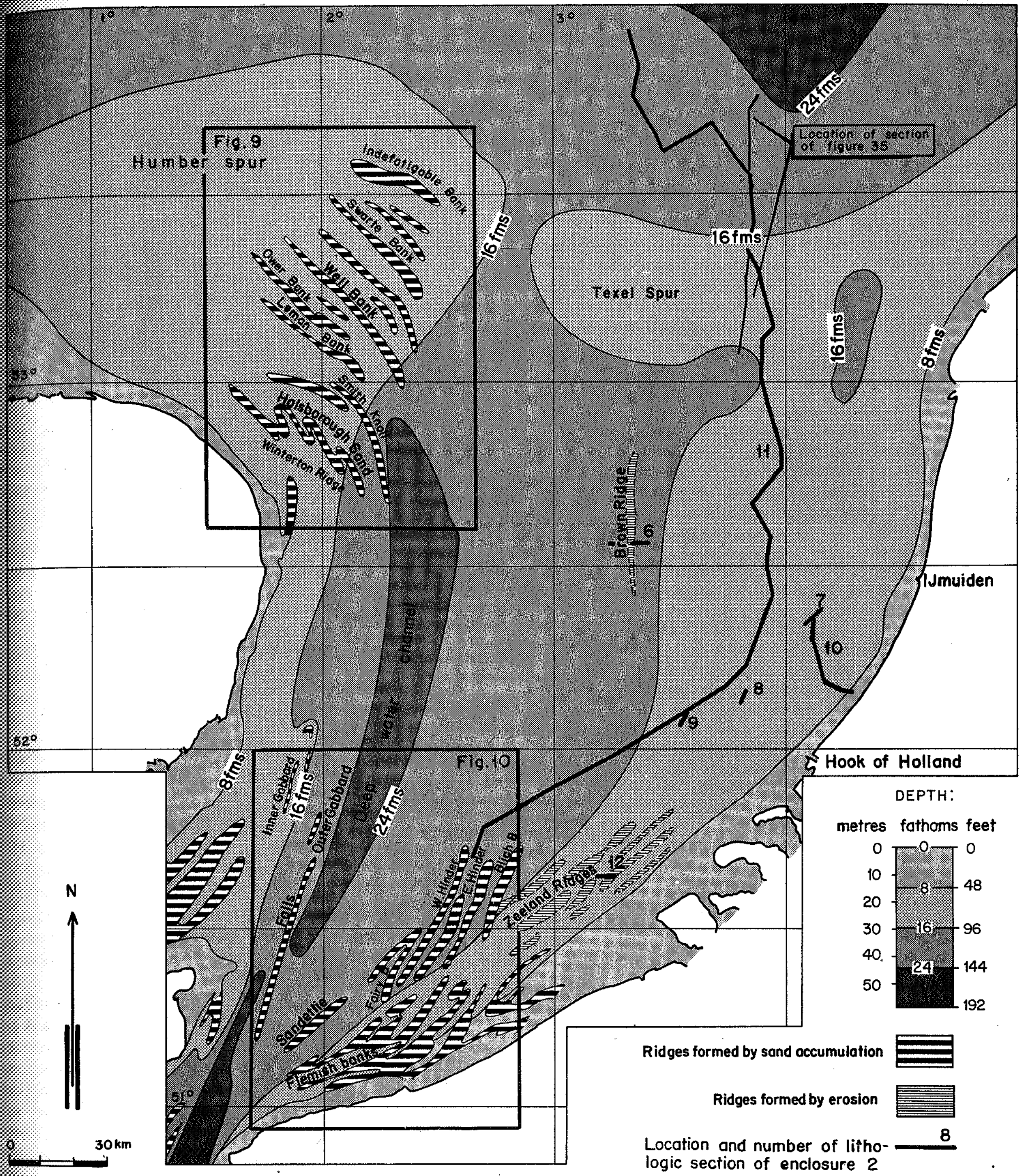
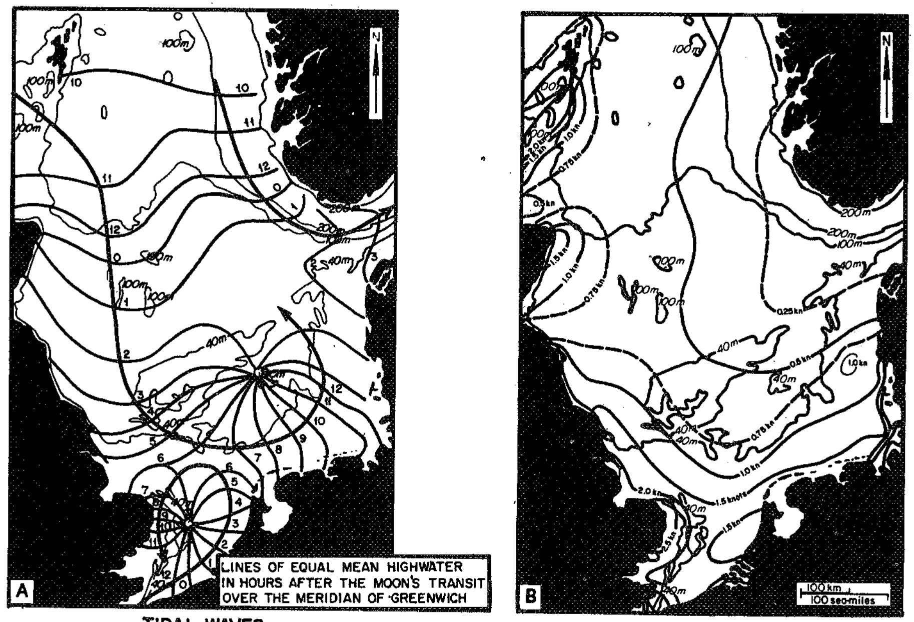


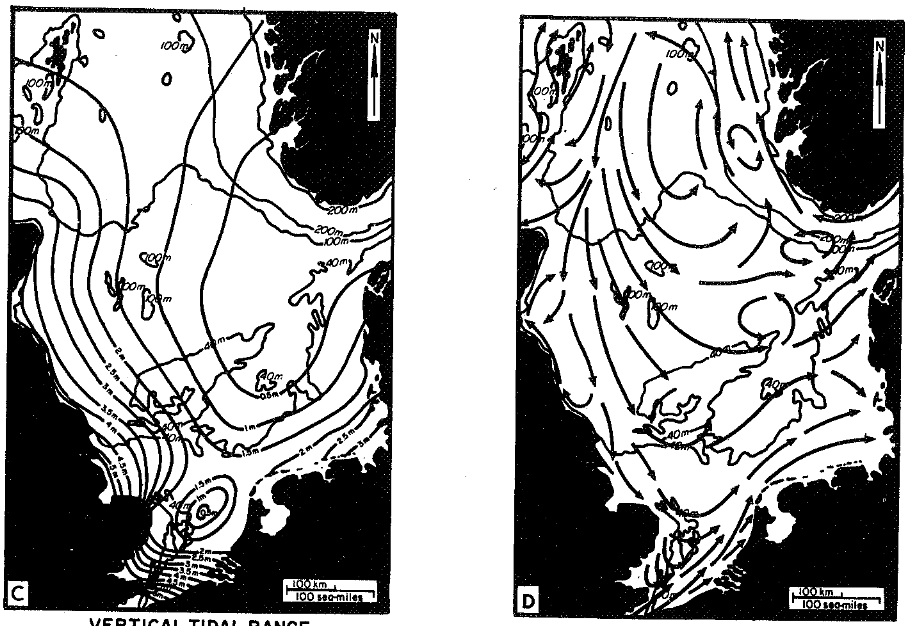
Fig. 2 - Sketch map of the bottom of the southern bight of the North Sea.

6 metres high, which stretches parallel to the direction of the tidal currents. (Synonyms used are: knoll, bank, rug.) It is thus distinct from a mega-ripple which, apart from usually being smaller, is orientated perpendicular to the tidal current directions (synonyms used are: sand wave, underwater dune, large sand ripple).



TIDAL WAVES

AVERAGE MAXIMUM TIDAL CURRENT

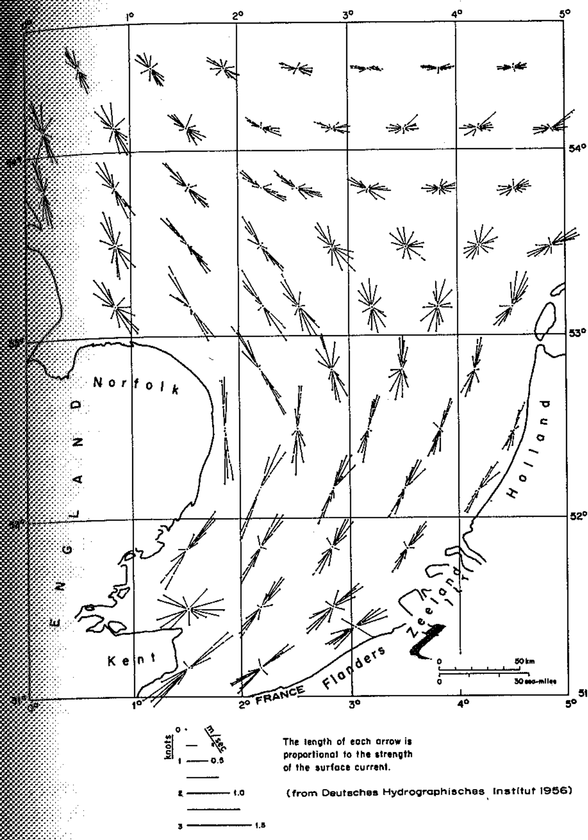


VERTICAL TIDAL RANGE

AVERAGE SURFACE CURRENTS

Fig. 3 - Generalities of tidal current system in the North Sea.

1.2.3. Hydrography. Three tidal waves enter the North Sea: one through the English Channel, one along the Scottish coast and the Shetland Islands and a third along the Norwegian coast (fig. 3A). Interference between these three tidal waves results in a complex tidal system in the North Sea. The strength of the currents is generally moderate (fig. 3B), but in places rises to over 2 knots (1 m/sec) under normal conditions (near the northern tip of Scotland, off the Norfolk coast and at the entrance of the English Channel). During storms far greater velocities occur. The normal tidal range varies



The length of each arrow is proportional to the strength of the surface current.

(from Deutsches Hydrographisches Institut 1956)

Fig. 4 - Direction and strength of the average tidal currents at the surface during one tidal cycle.

from 0 to 6.5 metres, and its distribution is irregular (fig. 3C). The rest currents resulting from the tidal movements are shown in figure 3D.

The direction and strength of the average tidal currents in the area investigated are given on figure 4. On this map it can be seen that the interference between the W-E running tidal wave from Scotland and the S-N moving Channel wave results in a peculiar pattern of circular tidal roses at 53°30'N and 4°E.

Many variations in this general hydrologic picture occur, owing to variations in the weather. For example, the patterns of tidal rest currents and of salinity distribution vary with periods of easterly or westerly winds. Detailed current observations from Texel Spur and the Broad Fourteen area by Deutsches Hydrographisches Institut (1958) clearly demonstrate the strong day-to-day variation of the tidal currents. During storms even greater variations are recorded, (e.g. Lawford, 1954).

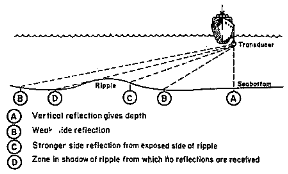
1.3. Methods of investigation

Two pilot surveys (in 1958 and 1962 by Van der Sluis) in the southern bight of the North Sea revealed that our existing sampling and observation techniques, which had served well enough for work off recent deltas, were not able to provide us with the information we wanted concerning the sandy sediments of the wave and current-swept bottom of this particular stretch of water. New sampling and observation techniques had to be used.

1.3.1. Ship. The actual fieldwork was carried out with the coaster "Sea Wyfe" in July 1963 and August 1964. This ship was equipped with DECCA, RADAR, and an echo sounder. An ASDIC apparatus and a Sparker outfit were added. Samples were taken with a Van Veen grab (Van Veen 1936), a specially developed sand corer and a water-jet sampling apparatus.

The less well-known of these instruments are briefly described below.

1.3.2. ASDIC. The use of ASDIC for geological investigations is discussed by Stride (1961). The



Ⓐ Vertical reflection gives depth
Ⓑ Weak side reflection
Ⓒ Stronger side reflection from exposed side of ripple
Ⓓ Zone in shadow of ripple from which no reflections are received

In the records reproduced here the transducer was directed perpendicular to the ship's long axis and slightly downwards. The Ⓑ reflections are weak in the case of sand and shale but strong if pebbles are encountered.

ⓐ Explanation of asdic recording.

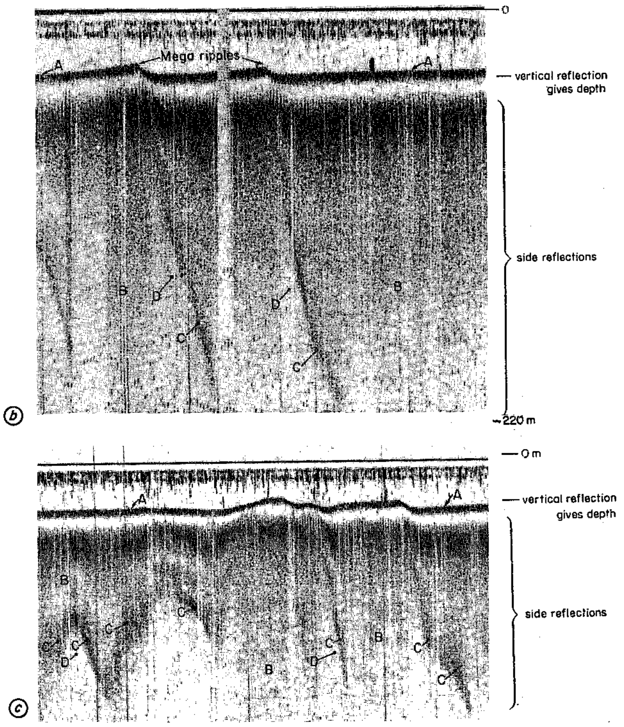
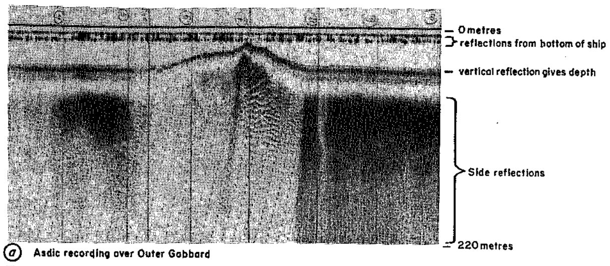
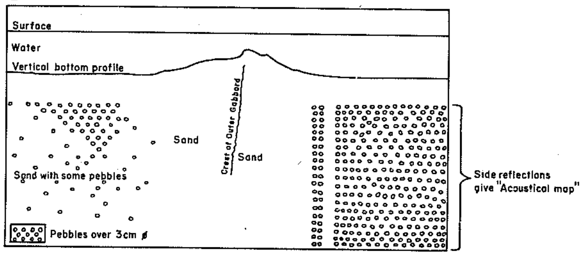


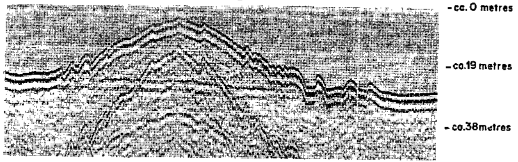
Fig. 5 - Asdic records of straight and curved ripples from Broad Fourteen area.



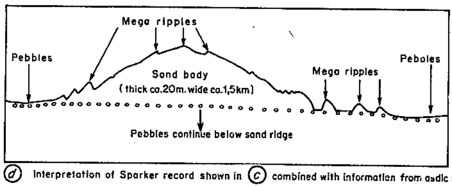
ⓐ Asdic recording over Outer Gabbard



ⓑ Interpretation of asdic record shown in ⓐ



ⓒ Sparker record over some shoal (different location)



ⓓ Interpretation of Sparker record shown in ⓒ combined with information from asdic records.

Fig. 6 - Asdic and Sparker records over Outer Gabbard and their interpretation.

"Sea Wyfe" was equipped with a simple ASDIC apparatus called Basdic made by Simrad in Norway. It consists of an echo sounder, the sound beam of which can be aimed in any direction. On most runs, it was directed perpendicular to the ship's long axis and arranged so as to scan a strip of the sea bottom parallel to the ship's course. Some examples of echoes received with this apparatus are given in figures 5 and 6. It was possible to measure the strike of mega-ripples and to distinguish between pebbly and sandy bottoms.

For measuring the strike of the mega-ripples two corrections had to be made. Firstly, the distances are measured through the water, whereas the distances over the sea floor are needed. Knowing the depth, correction can for the error involved be made if the sea floor is horizontal or nearly so. Secondly, the distances are measured perpendicular to the ship's long axis but, owing to the often strong tidal currents in the area investigated, this seldom turned out to be perpendicular to the ship's course. If the actual course of the ship is known from DECCA fixes, correction for the resultant error can also be made.

1.3.3. Sparker. A sparker apparatus designed by Shell Development Company, Exploration and Production Research Division (Houston, Texas, U.S.A.) was used. It is essentially a low-frequency, high-energy echo-sounding device capable of recording reflections from below the sea bottom. Photographs of records obtained with it are given in figures 6, 11 and 28.

1.3.4. Corer. For this survey Van den Bussche developed a coring apparatus that permits the collection of undisturbed cores from clean, unconsolidated water-filled sands (van den Bussche & Houbolt, 1964). A shockproof compass/clinometer is attached to the core sampler for measuring azimuth and inclination of the cores. Unfortunately this latter device was found to work unsatisfactorily on the 1963 trip. An improved version worked well on the trip in 1964 (Hbo station numbers higher than 155).

The corer was suspended from a specially made winch and mast assembly. For the benefit of future users of this instrument some photographs are enclosed which show how the corer was handled (fig. 7).

Photograph A. A core tube is connected to the corer, which is suspended on a pin passing through its centre of gravity. The pin is clamped to the railing of the ship. Part of the hoisting drum bearing the nylon rope is visible.

Photograph B. The compass is placed in the tail of the corer. Note the clamp welded on the railing.

Photograph C. The tripper is connected to the tail end.

Photograph D. The corer is hanging in the tripper (lower block), ready for dropping. A small hand-operated winch is used for manoeuvring the corer from the clamp. The latter is now open and is partly visible between the two people in the gangway. The nylon rope is guided through the top block. The winch is a diesel-driven pile-driving hoist, the original hoisting drum of which has been replaced by a specially designed very light one, running on roller bearings instead of the original sleeve bearings.

Photograph E. This is the moment the bottom is hit, shown by the slack nylon rope. The winch operator applies the brake to the fast-running spool.

Photograph F. The corer with fresh sample hanging upside down (one of the very few clay samples).

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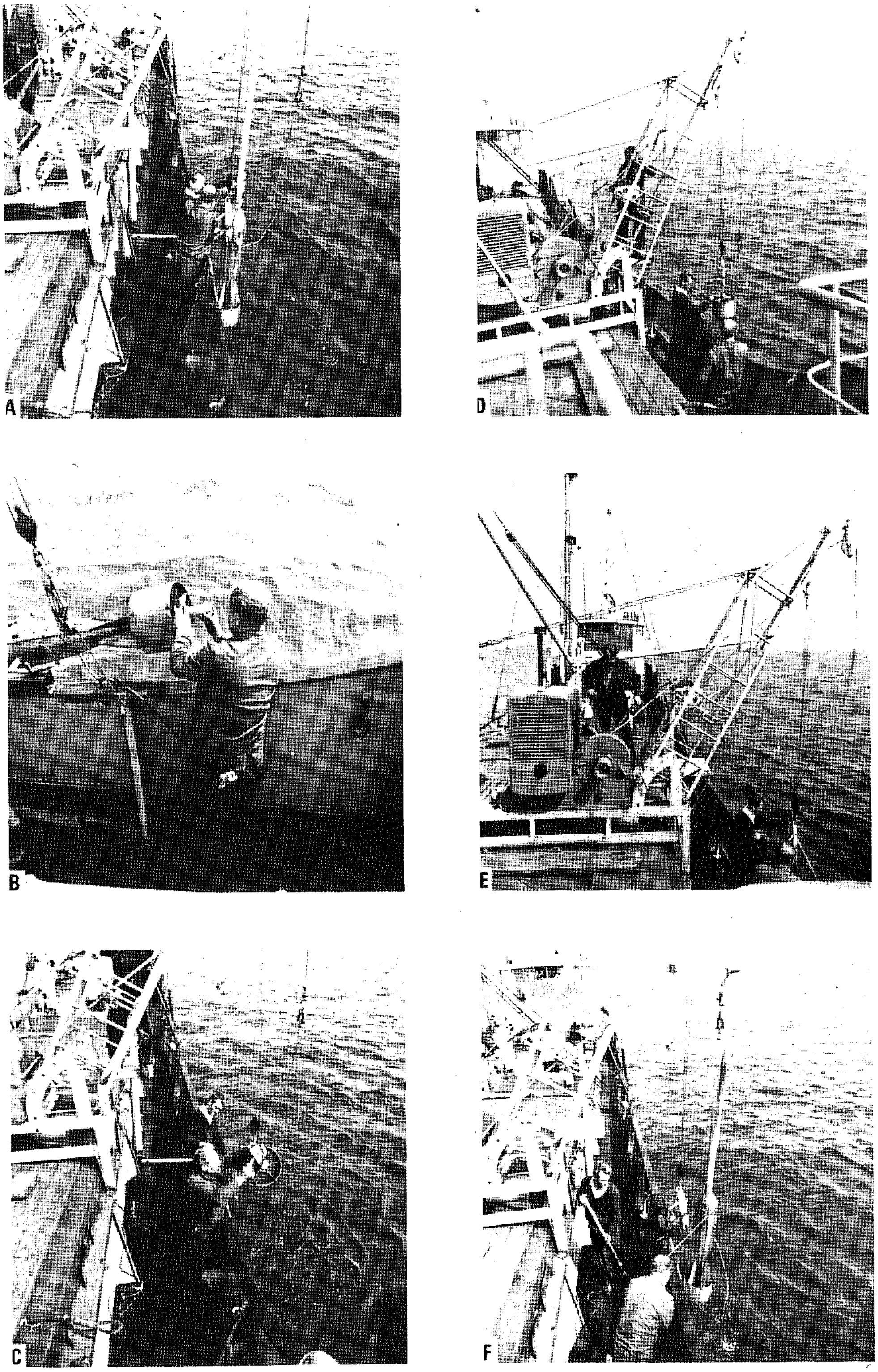

Fig. 7 - Photographs showing handling of coring apparatus.

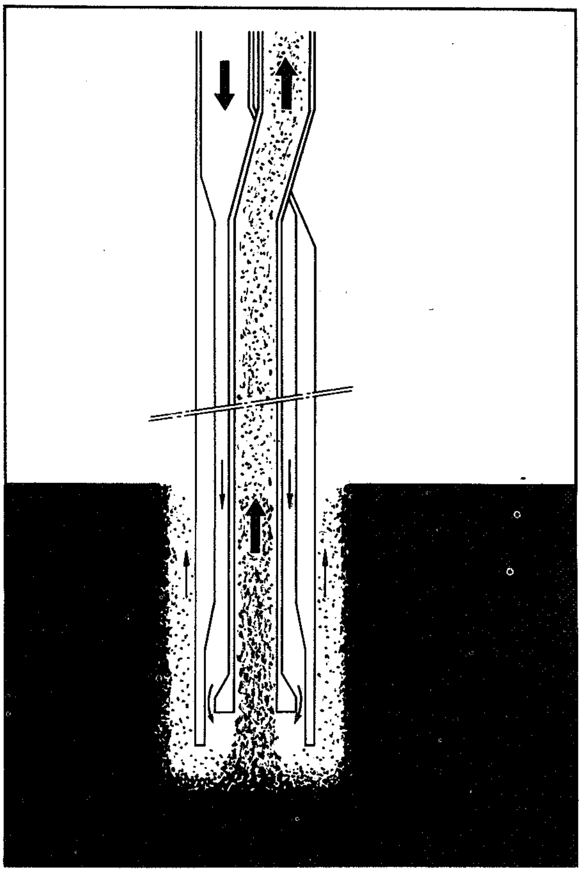

Fig. 8 - Jet sampler.

The cores were extruded in the laboratory and then slit in two. A lacquer peel was made of one half. The remaining half of the core was slit in two again perpendicular to the first slit. From this one a second lacquer peel was made. With the aid of these two oriented lacquer peels placed perpendicular to each other it was possible to establish the strike and dip of foreset planes.

1.3.5. Water-jet sampler. To obtain samples from greater depth below the sea bottom a water-jet sampler, also developed by our production-engineering section, was used (fig. 8). It consists of two co-axial tubes, connected to the ship by means of two fire hoses.

Water is pumped down through the outer tube and washes the sand away in front of the sampler. Most of the water goes up outside the tubes and so keeps the hole open. A small part returns to the ship via the inner tube, entraining a small quantity of sediment.

At best, this instrument usually yields only poor samples of any clean sands penetrated; but if clay layers are present, samples are brought up in the form of clay balls.

This simple instrument enables the thickness of the sand at the sea bottom to be ascertained. It works only in still water and a calm sea. Several instruments were lost owing to collapse of the hole when the instruments were at depth.

1.3.6. Grain-size analyses. The bulk of the grain-size analyses were made with the aid of a Van Veen settling tube (Van Veen, 1936) in which the grains are measured microscopically. The merits of this system are discussed by Houbolt (1957, p. 30).

Additional grain-size analyses were made with the sedimentation balance (Doeglas 1946). All cumulative grain-size-distribution curves given have been made with the aid of the sedimentation balance.

2. RIDGES FORMED BY SAND ACCUMULATION

2.1. Introduction

The ridges discussed in this chapter were found to consist of sand and to rest on an essentially flat surface which is at the same level as the

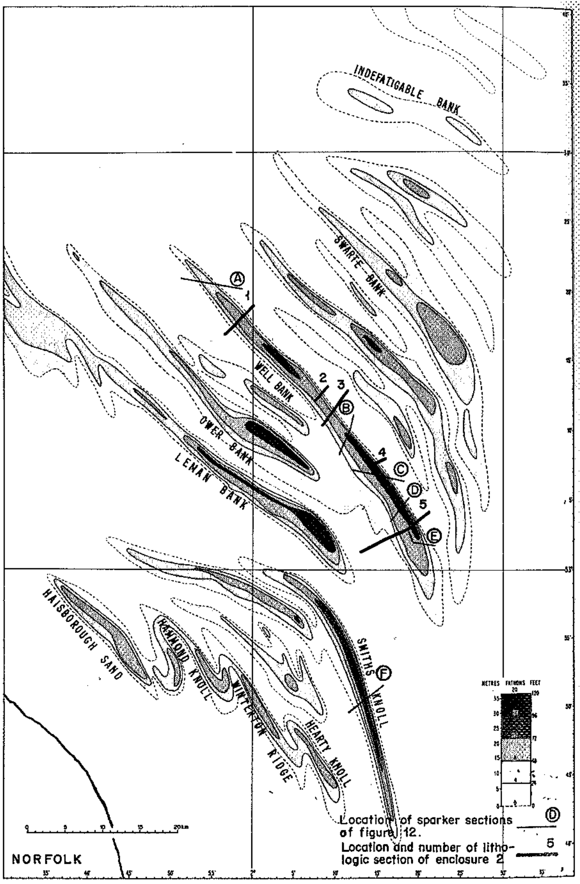

Fig. 9 - Approximate isopachs of sand ridges in Well Bank area.

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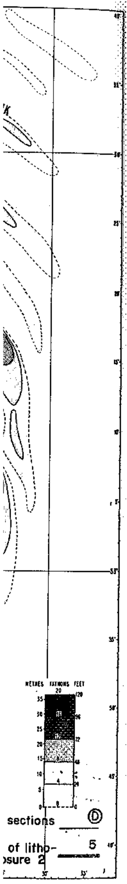

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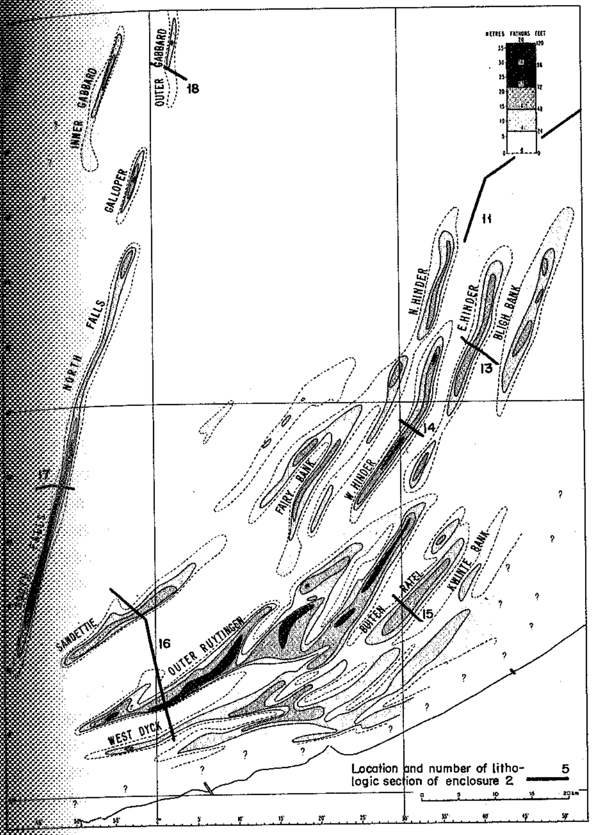

Fig. 10 - Approximate isopachs of sand ridges from Flemish Banks to Inner Gabbard.

surrounding sea bottom. They are thus isolated sand bodies standing on a flat sea floor, and it was possible to convert the isobath chart enclosure 1 into an isopach map showing the thickness of all the sand ridges known to belong to this type (figs. 9 and 10).

Several of these ridges and groups of ridges will be discussed separately below.

2.2. The sand ridges of the Well Bank area

The long straight ridges of the Well Bank area (figs. 2 and 9) lie south-east of a large gentle rise of the sea bottom, for which the name Humber Spur is introduced. In a northeastern direction they gradually become smaller until they disappear northeast of Indefatigable Bank. Towards the southeast they stop rather abruptly, giving way to the flat sea bottom of the central part of the area investigated. Towards the southwest the long straight sand ridges suddenly give way to the complicated, strongly curved forms of Haisborough Sand, Hammond Knoll and Winterton Ridge.

For convenience, the area of the straight sand ridges from Smith Knoll to Indefatigable Bank is called the Well Bank area.

2.2.1. Tidal currents. An outline of the average tidal current at the surface in the southern bight of the North Sea is given in figure 4. It can be seen that the ridges lie parallel to rather strong tidal currents.

2.2.2. Morphology. All ridges of the Well Bank area are clearly asymmetric in cross section. They all have steep northeastern slopes and much more gentle southwestern slopes.

Over the gentle southwest flank of the ridges, asymmetric mega-ripples, many as high as 6 m, were often found. These ripples strike roughly perpendicular to the crest of the ridges and tend to be oriented with their steep slope slightly towards the crest of the ridge in a northwestern direction (encl. 1). This is an indication that sand is transported in a northwestern direction over the gentle slope of the ridge towards the crest. It is thought to be due to spiral current action as described in section 2.10.

2.2.3. Sparker sections. Sparker sections over the Well Bank area nearly always show a distinct reflector at the base of the ridges. This reflecting horizon outcrops in the swales between

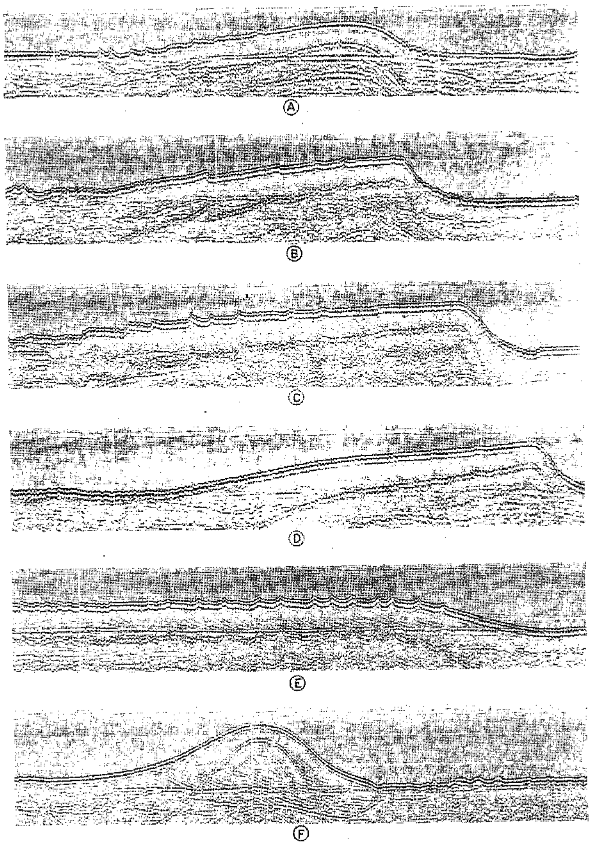

Fig. 11 - Sparker sections over Well Bank and Smith Knoll.

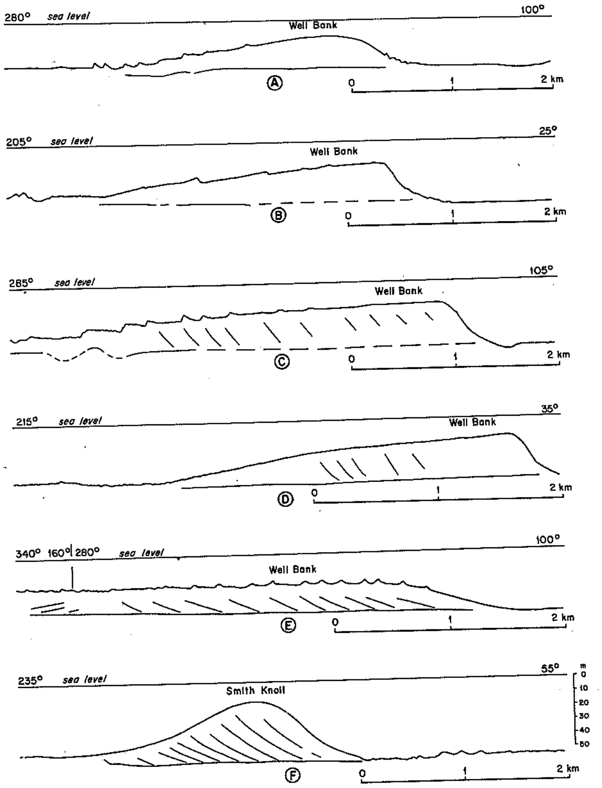

Fig. 12 - Interpretation of sparker sections over Well Bank and Smith Knoll.

the ridges (figs. 11 and 12). Clayey samples were often obtained here from below a thin cover of lag deposits (fig. 13). These clays were dated as Pleistocene on the bases of the pollen content (Stations Sl 70-Sl 73 det. W.H. Zagwijn, Pers. Comm.). Foraminifera from station Hbo 60 yielded a similar result (J. Brouwer, Pers. Comm.).

The water jet penetrated through the Swarte Bank to the level of the base reflection without yielding clayey material. It can therefore be said that the ridges consist of sand and overlie Pleistocene deposits. A foundation test hole on Ower Bank yielded similar results (subsec. 2.2.9.).

The sparker records also show internal cross bedding of the sand ridges parallel to the steep northeast flank, especially at the southeast end of the ridges (figs. 11 and 12). In the northwestern part of the ridges this internal cross-stratification is less distinct. Analogy with sand ripples suggests sand transport towards the northeast; sand would be moved up the gentle southwest flank of the ridge to the crest and then be deposited on the steep northeast flank.

2.2.4. Lithology. The sand of which the Well Bank is composed is very uniform in grain size. Median values range from 200 to 300 microns. The degree of sorting is very high (fig. 14). There does not seem to be a difference in grain size between sediments from the crest and those from the slopes (encl. 2, sec. 1-5). Carbonate particles, for the most part visibly of skeletal origin, occur in very small amounts in the same grain-size fractions. Some unbroken skeletal material occurs, especially in the coarsest fractions, and consists mainly of lamellibranch remains. The average insoluble residue in HC1 is 95%.

2.2.5. Foreset bedding. Short cores taken from the steep northeastern slope of the Well Bank show foreset bedding, often with many short clay laminations over the foreset laminae (fig. 13).

The dips in 12 of these cores were measured (fig. 15). About half of the measured dips fall into the northeast quadrant. This dip direction would be the same as that of the large foreset planes seen on the sparker records. The rest of the measured dips, however, fall into the southeast quadrant; these are more or less parallel to the sand ridge (this latter direction was not observed on the sparker records).

It seems that two processes take place here: one in which sand moves down from the crest and gives rise to the northeastward-dipping foreset planes and another in which sand is transported towards the southeast along and over the steep northeastern flank of the ridge, as indicated by the southeast foreset bedding.

Foreset directions on the gentle slope only were measured in station Hbo 174 (encl.2, sec. 2). The orientation here was found to be in opposite directions. No conclusions have been drawn from this single station.

2.2.6. Grain orientation. Grain orientation in the foreset bedding planes was measured by Winkelmolen. From all measurements taken together, there was found to be an average east-west orientation, that is 45^{0} to the strike of the sand ridges.

It was also found that the grain orientation in the foreset bedding planes dipping towards the northeast, i.e. perpendicular to the ridge, deviated from the dip direction. The grain orientation was found to be parallel to the dip on those foreset bedding planes which were dipping parallel to the strike of the sand ridge (fig. 17).

This can be explained as follows: Grains coming to rest on the steep slope of the sand rige are exposed to tidal currents running along this slope, whereas grains on the foreset plane of ripples migrating over this slope come to rest on a lee slope and are not exposed to currents.

2.2.7. Clay layers. In the middle and southeastern part of the Well Bank area, cores from the

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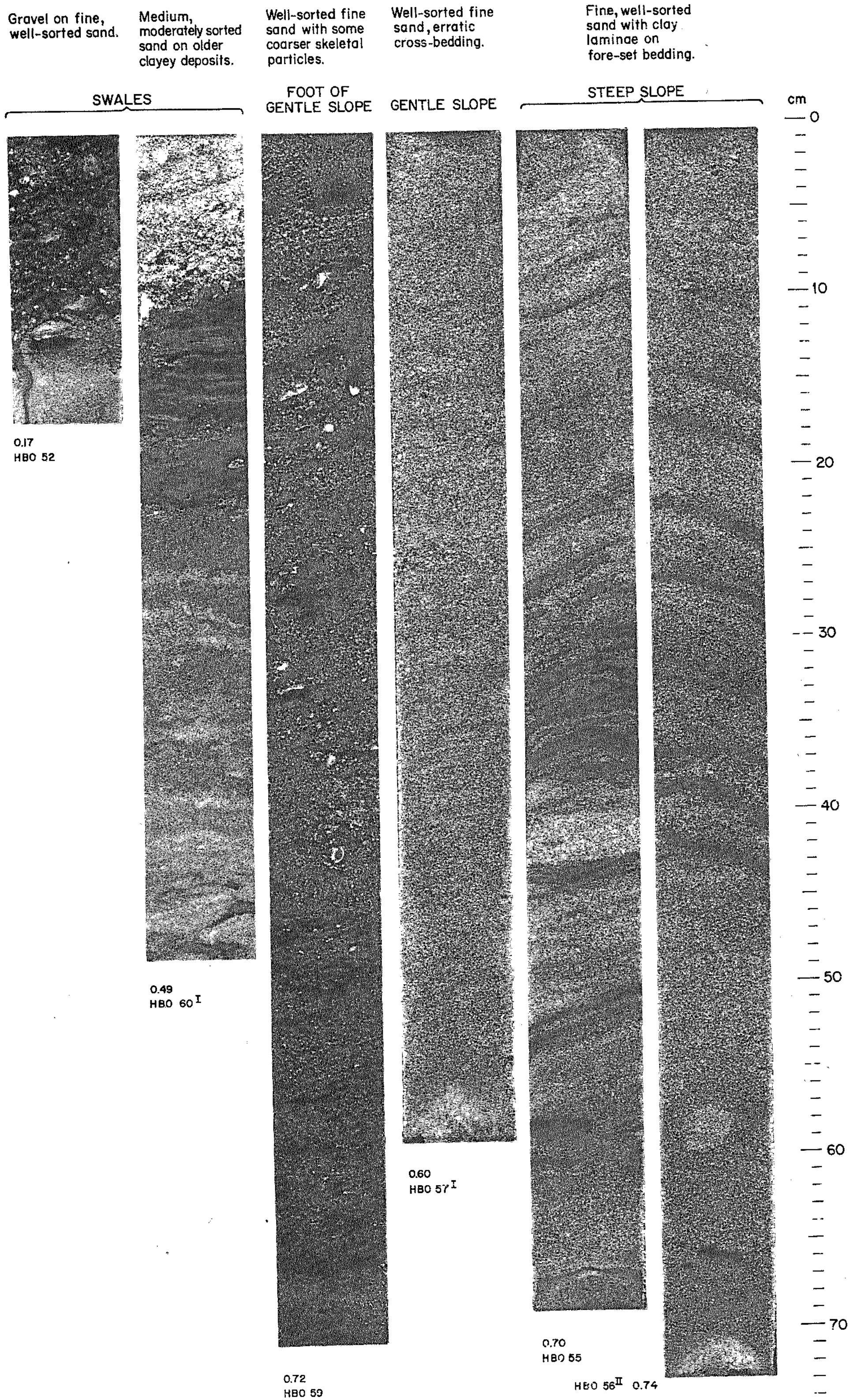

Fig. 13 - Cores from Well Bank.

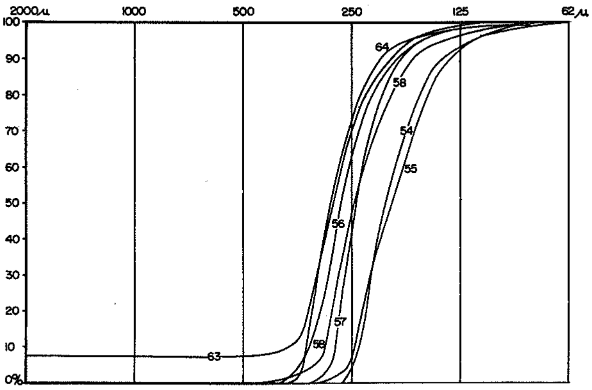

Fig. 14 - Grain-size-distribution curves of samples from Well Bank.

steep face showed many, often discontinuous, dark-blue to black, silty clay layers over the foreset laminae (fig. 13). Similar thin clayey laminae are described by Oomkens and Terwindt (1961) from the Haringvliet in the southern Netherlands. There they are thought to be deposited during the turn of the tide when for a short period the water is stationary. They are usually destroyed by the next tide but are occasionally preserved. In grab samples these clay layers showed up as weak, dark-blue to black, clay galls.

These typical silty clay drapes can be considered as an indication of tidal-current action. Their absence does not preclude such action, however. In the sand ridges of the North Sea the clay drapes have only been observed in the middle and south-eastern part of the ridges of the Well Bank area.

2.2.8. Lag deposits. In the swales between the ridges, coarse-grained lag deposits were found to overlie older often clayey strata (fig. 13). They consist of sand with some pebbles of various lithologies, coarse shells or large Sabellaria worm-tube agglomerates (Schäfer, 1962, p. 368). From this environment the anchor brought up an abandoned steel wire about 50 m long and an old telephone cable, this being a human addition to the lag deposit. Over this lag deposit, in the swales between the sand ridges, fields of mega-ripples occur which consist of fine to medium sand similar to that of the ridges.

2.2.9. Sequence. Although no vertical section was made through these ridges, it can be deduced that in vertical sequence such a sand ridge will show a well-sorted sand with distinct cross bedding and a few shells. Thin and often short, silty clay laminae will occasionally be found over the foreset bedding. There will be no vertical gradation in grain size but at the base a thin, coarser-grained lag deposit will separate the sand of the sand ridge from the underlying older deposits.

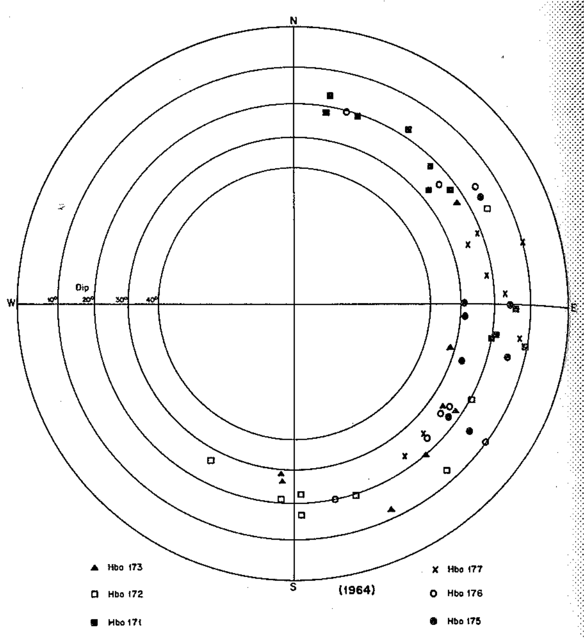

Fig. 15 - Cross-bedding dips from NE flank of Well Bank.

A foundation test boring on Ower Bank, by George Wimpey & Co. Ltd (1965) found "Medium dense becoming dense to very dense with depth, grey-brown fine to medium sand, with occasional seams of silt and traces of fine gravel" from the sea bottom to total depth at 47 feet below sea bottom. Figure 16 shows a sparker section over Ower Bank in the neighbourhood of this boring. It can be seen that it penetrated to a few metres above the base of the sand ridge.

Spot samples showed exactly the same type of sand as that encountered on the surface of the sand ridges in the neighbourhood. The "seams of silt" in Wimpey's core description are probably our silty clay laminae. The "traces of fine gravel" were not observed in the spot samples.

The spot samples did not show a vertical gradation in grain size.

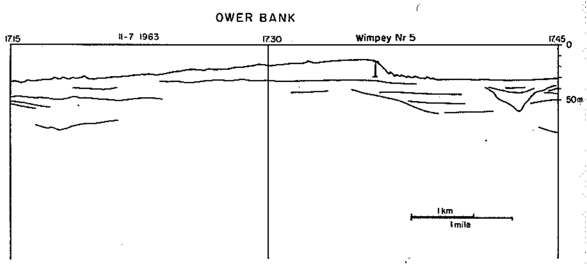

Fig. 16 - Sparker section over Ower Bank on which a foundation test boring is projected.

2.2.10. Sand movement along the Well Bank. The foregoing suggests the following sand movement along the Well Bank. Tidal currents along the gentle southwestern flank of the ridge transport sand obliquely towards the crest of the ridge. Insofar as this sand transport takes place in the form of mega-ripples it is visible on echo-sounding and ASDIC records. From the crest the sand is deposited on the steep slope and so gives rise to the northeast-dipping foreset bedding visible on the Sparker records and in the cores from the steep northeast slope. Along this slope sand is transported towards the southeast as indicated by the southeast-dipping foreset beds in the cores of this slope. The ripples which form this southeast-dipping foreset bedding were not observed in echo-sounding and ASDIC records.

Sand actually seems to go round the ridge (fig. 17). The entire ridge would seem to move slowly towards the northeast, perpendicular to its long axis and to the tidal currents.

The ridges are indeed now about one mile northeast of the positions indicated on the hydrographic charts which were compiled at the beginning of this century by ship to ship triangulation. This shift can also be explained, however, by the inaccuracy of the older maps.

2.2.11. Origin of the sand. The process described above is only capable of reworking sand already present in the sea into the shape of sand ridges. It is not capable of transporting large quantities of sand into the area. There are strong arguments for the contention that in the Well Bank area a glacial-outwash fan was formed during the last glacial period (Valentin, 1957). The sands of this glacial-outwash fan or sand plain were reworked into the present shape of sand ridges by the tidal currents during and after the Holocene transgression of the North Sea over the area.

2.3 The sand ridges of the Hinder Group

About 30 miles west of Walcheren a group of sand ridges occurs which consists of the North Hinder, East Hinder, West Hinder, Bligh Bank and Fairy Bank. For convenience they are grouped together as the Hinder Group of sand ridges. They are separated from the Flemish Banks by a channel-like depression. To the east they truncate the ridges of the Zeeland group (sec. 3.3). To the north and west they are bordered by a flat or almost flat sea bottom.

2.3.1. Morphology. The ridges of the Hinder Group are elongated, isolated ridges between 17 km

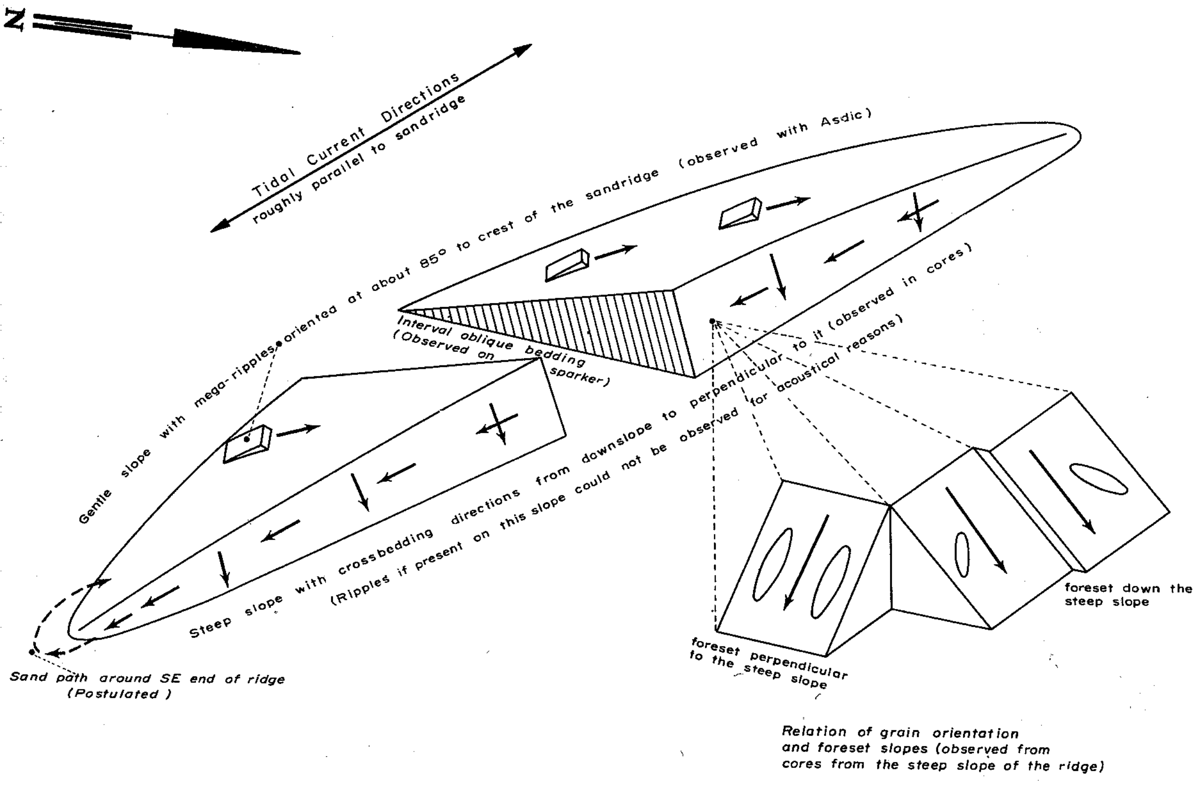

Fig. 17 - Schematic presentation of sedimentary features of Well Bank.

and 34 km long, which rise up to 30 m above the surrounding sea floor. In cross section they are usually asymmetrical. In most cases the eastern slope is the steeper one. Both on the ridges and in the swales mega-ripples were found to occur in great abundance. Almost all these ripples were found to be asymmetrical, mostly with the steeper slope towards the south (encl. 1). On the ridges the asymmetrical mega-ripples were mostly found to be oriented with their steep slopes at angles slightly less than 90° to the crests of the ridges.

From the fact that south-pointing asymmetric ripples predominate over north-pointing ones, it might be deduced that sand transport over the ridges was towards the south. Hence the ridges of the Hinder Group should move in a southerly direction. Comparison of detailed hydrographic measurements from 1929 and 1963, however, shows that the ridges are stationary (Veenstra 1964). It must be concluded, therefore, that north- and southward transport are roughly in equilibrium. Sparker sections over the Hinder ridges (encl. 2) showed a horizontal reflection at the base of the ridges at approximately the level of the surrounding swales.

2.3.2. Lithology. Surface samples from the ridges yielded well-sorted sands with median values between 300 and 400 microns. Small amounts of fine gravels (<4 mm) were occasionally found. They often contain a higher amount of shell fragments than is the case with the surface sands from the surrounding ridges (encl. 2, secs. 13 and 14).

The cores taken revealed mostly small-scale cross bedding, the orientation of which is not known. The colour of the cores from the Hinder Banks is somewhat closer to white and less yellowish-brown than those observed from other North Sea ridges.

Waterstaat (Dutch Ministry of Public Works) made a shallow boring on the West Hinder (Van Veen 1943, Pulsboring 71), in a water depth of about 11 m. This boring penetrated 7.70 m into the West Hinder sand ridge. At this locality the ridge is about 22 m thick. In the bored interval the $CaCO_3$-percentage dropped gradually from 49% at the surface to $\frac{1}{2}$% at the total depth of 7.70 m below sea bottom. Spaink (1963) concludes from the macrofauna of samples from this boring that this interval is of Holocene age and that it most probably has been laid down in a relatively short period.

2.3.3. Lag deposits. Veenstra (1964) who studied the gravels which occur in the swales between the sand ridges, concludes that they mainly consist of flint such as occurs in the Cretaceous of France and England along the southern North Sea and Channel coasts. Occasionally nummulites and sharks teeth are found. This coarse gravel was not rounded enough to be considered as beach gravel. Often organisms are attached to one side of the pebbles which indicates that they are not at present being transported.

Moreover, the current velocities recorded in this area are too weak to transport these pebbles. They must therefore have been transported in an earlier stage.

The sand between the pebbles does not differ much in grain size from the sands on the nearby ridges. There always seems to be a gap between the grain size of the sand and the size of the pebbles.

At station Hbo 103 (encl. 2, sec. 13) this gravelly lag deposit was found to be underlain by a stiff, dark bluish-grey clay. Unfortunately it did not contain any fauna, so its age is not known.

2.4. The Flemish Banks

Off the coast of Flanders a complex series of ridges occurs, commonly known as the Flemish Banks. They are separated from the Hinder Group by a narrow zone of deeper water. To the northeast they peter out in the relatively flat zone of Schooneveld. To the east and southeast they are bordered by a flat, relatively deep sea bottom.

2.4.1. Morphology. They consist of elongated ridges up to 30 m high. These ridges show a strong degree of parallelism but they are connected in a complicated pattern, especially off Dunkerque (figs. 2 and 10).

Van Veen (1936) attributes this complex morphology to a system of ebb and flood channels. Between the ridges one can distinguish between channels closed at their northeastern end, in which the flood current dominates, and channels closed at their southwestern end, in which the ebb current dominates. The closed end of an ebb channel forms a barrier to the flood current and the closed end of a flood channel forms a barrier to the ebb current. So ebb and flood currents take different channels.

In cross section the ridges of the Flemish Banks are often asymmetric. In the northeastern part the steepest slopes are dominantly to the northwest and in the southwestern part they are dominantly to be southeast.

Asymmetric mega-ripples were found in abundance on the Flemish Banks, but their orientation is not understood (encl. 1). They were also often encountered in the intermediate swales. Bastin (personal communication) mentioned that when diving over the Kwinte Bank he noticed a great complexity of ripples of all sizes. The smaller ones changed their asymmetry with the tides and at the peak of the tidal currents he saw large amounts of sand on the move.

The sand movement seemed quite sufficient to remove the whole Kwinte Bank within a few weeks (A. Bastin, personal communication). Nevertheless Kwinte Bank seems to have been present

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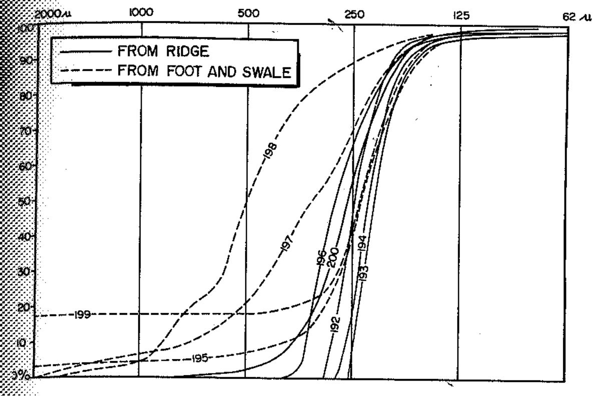

Fig. 18 - Grain-size-distribution curves of samples from Outer Ratel.

where it is now for at least some 300 years (subsec. 2.4.4.).

Sparker sections over the Flemish Banks showed a flat bottom surface which was exposed, or nearly so in the intermediate swales. Hence it was possible to draw approximate isopachs of these sand ridges (fig. 10). Towards the Flemish coast it was not possible to recognise this base horizon owing to the abundance of multiple bottom reflexions. Against the base level of the ridges reflexions from greater depth were found to be truncated.

2.4.2. Lithology. Samples were taken on Buiten Ratel, Outer Ruytingen and West Dyck (encl. 2, secs. 15 and 16). The surface samples showed a well-sorted sand with median diameters from 200-350 microns (figs. 18 and 19). $CaCO_3$ percentages ran up to 20%, but usually were low. It was found to consist mainly of skeletal particles and debris. Small pebbles were encountered now and then.

The cores mostly revealed small-scale (up to 25 cm) foreset bedding, but thicker cross-beds occurred (fig. 20). The cross-bed orientation varies greatly and is not understood. Churning of bedding was seen only occasionally.

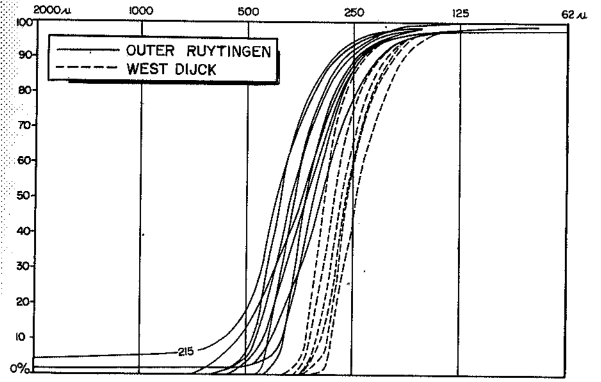

Fig. 19 - Grain-size-distribution curves of samples from Outer Ruytingen and West Dijck.

Along the Belgian coast clayey sediments were reported by Van Veen (1936) and Bastin (1964) (sec. 4.5).

2.4.3. Lag deposits. The lag deposits in the swales are characterised by an abundance of black chert pebbles and coarse skeletal particles. The sands encountered in them are often somewhat coarser than on the ridges. There seems to be a considerable gap between the sizes of the gravel and the sand.

At stations Hbo 195 (Buiten Ratel) and Hbo 218 (Outer Ruytingen) dense grey-bluish clays were encountered below the lag deposits. The one at station Hbo 218 is considered, on foraminiferal evidence, to be pre-Pliocene in age (J. Brouwer, personal communication).

2.4.4. Changes in historic times. Van Veen (1936) studied the changes in the bathymetry of the Flemish Banks from historic sources. He found that charts of the 16th century, though inaccurate, already mentioned many of the names in use now. A Dutch pilot book from 1632 mentions that the highest parts of the Flemish Banks off Dunkerque were exposed at spring tides. This is no longer the case.

Van Veen found that the situation recorded by charts issued after 1800 differed only slightly from that now prevailing. He concludes therefore that the configuration of the Flemish Banks has undergone only minor changes during the last 300 years.

2.5. Haisborough Sand - Hammond Knoll-Winterton ridge and Hearty Knoll

The above-mentioned series of ridges forms one curved "serpent"-shaped sand ridge south of the Well Bank area. A few sparker lines run over them showed that the surrounding flat sea bottom continues underneath these ridges. These ridges were not sampled.

Their complicated shape can be explained as a system of ebb and flood channels like that described by Van Veen (1936) with respect to the Flemish Banks (2.4). When isopached (fig. 9), this sand body looks like a subsurface geologist's nightmare.

2.6. Sandettie

At a distance of about 10 km west of the Flemish Banks there occurs a rather isolated sand ridge called Sandettie. It is 27 km long and rises 24 m above the surrounding sea floor. A small protrusion on its east flank can be interpreted as being due

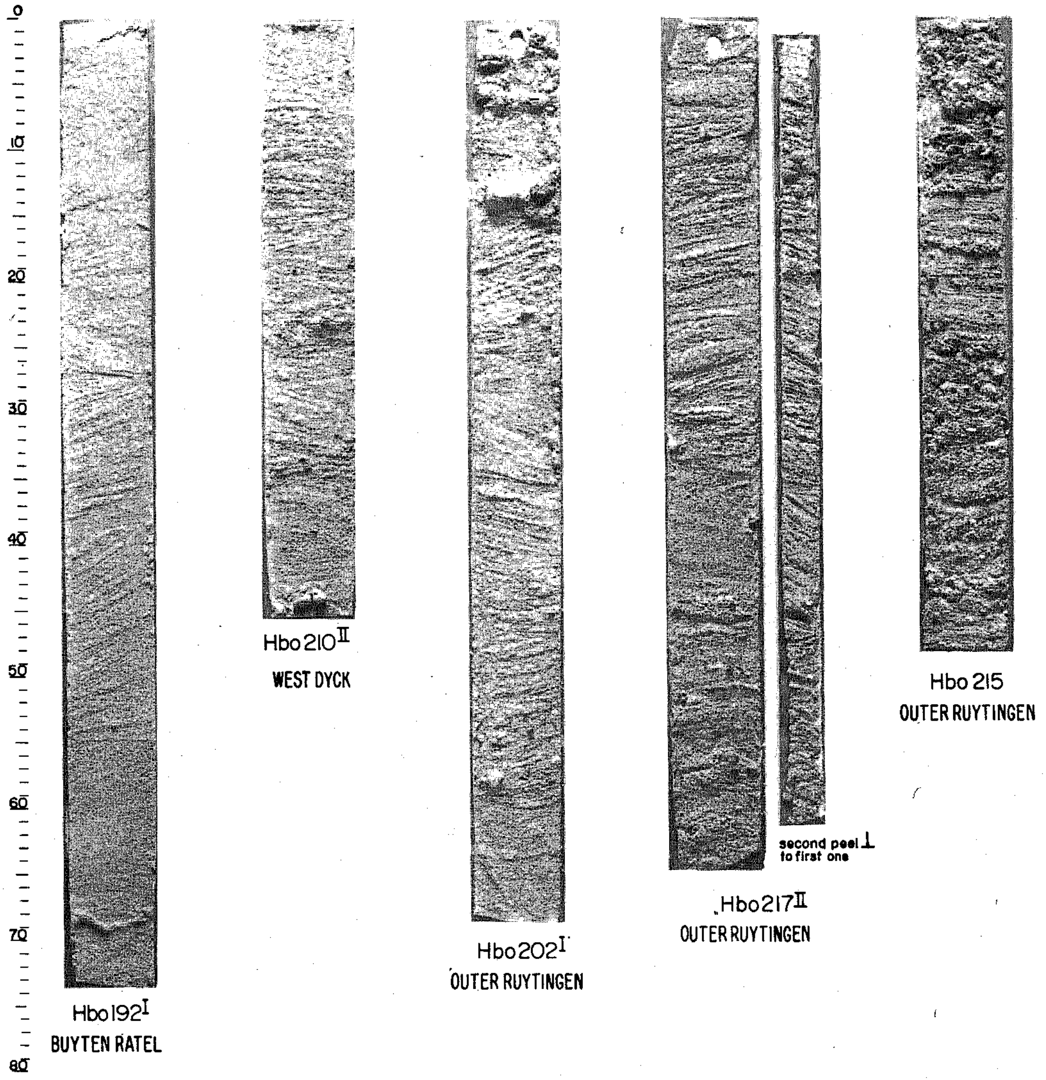

Fig. 20 - Lacquer peels of cores from Flemish Banks.

to an ebb channel. In cross section the Sandettie appears to be asymmetric, the southeastern slope being the steeper. On the gentle slope mega-ripples were observed striking roughly perpendicular to the crest of the ridge with a tendency to be oriented with their steeper slope at angles less than 90° to the crest. Along the steep slope of the ridge no ripples were observed.

Surface samples from the Sandettie yielded well-sorted sands with a median value of around 350 microns (fig. 21). The percentage of $CaCO_3$, mainly of skeletal origin, was low. Both small-scale and larger-scale cross bedding were observed. The orientation of these is not understood (encl. 2, sec. 16). The lag deposits surrounding the Sandettie were found to be similar to those found between the Flemish Banks. Just east of the Sandettie (station Hbo 221) Cretaceous chalk was found underneath the lag deposits.

2.7. The Falls

Off Kent and the Thames estuary a 65 km long, rather narrow sand ridge rises up to 35 m above the surrounding sea floor. It strikes at an angle of 40° to the nearby Sandettie Ridge. Generally the western flank is steeper than the eastern. On the eastern flank mega-ripples were observed with their steep slopes oriented to the south. On the

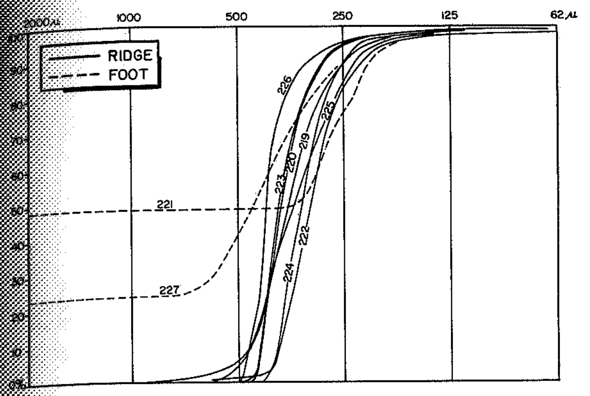

Fig. 21 - Grain-size-distribution curves of samples from Sandettie.

western flank only a few ripples were observed; they seem to point in a northerly direction.

The lithology of the sands encountered on this ridge is similar to that described from the Sandettie (encl. 2, sec. 17).

Van Veen (1936) explained the peculiar orientation of the Falls with respect to the nearby Sandettie by suggesting that Sandettie and Falls were a large ebb parabola the tip of which had been opened.

2.8. The origin of the sand making up the Hinder Banks, the Flemish Banks, the Sandettie and the Falls

According to Baak (1936) the sands of which these ridges are built up belong to the H and NH provinces (fig. 23). Kruit (1963) pointed out that both mineral suites are typical of Rhine-derived sediments. Yet at present the Rhine is not transporting an appreciable amount of sand into the North Sea (Van Veen 1936; Terwindt, De Jong & Van der Wilk, 1963). It has done so occasionally during the late Holocene (De Jong 1962; Pons, Jelgersma, Wiggers, De Jong 1963; De Jong 1967) but it is very unlikely that the vast amount of sand of the H and NH provinces has been brought into the North Sea during part of the Holocene only.

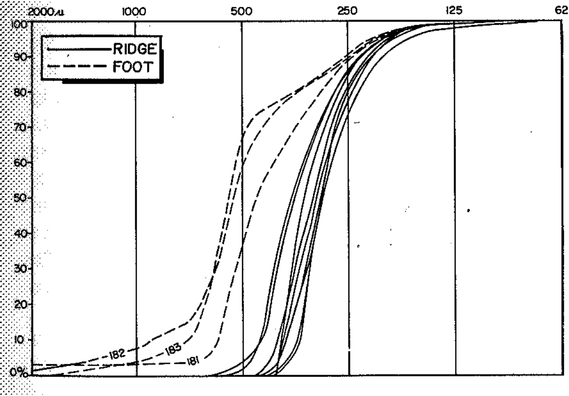

Fig. 22 - Grain-size-distribution curves of samples from the Falls.

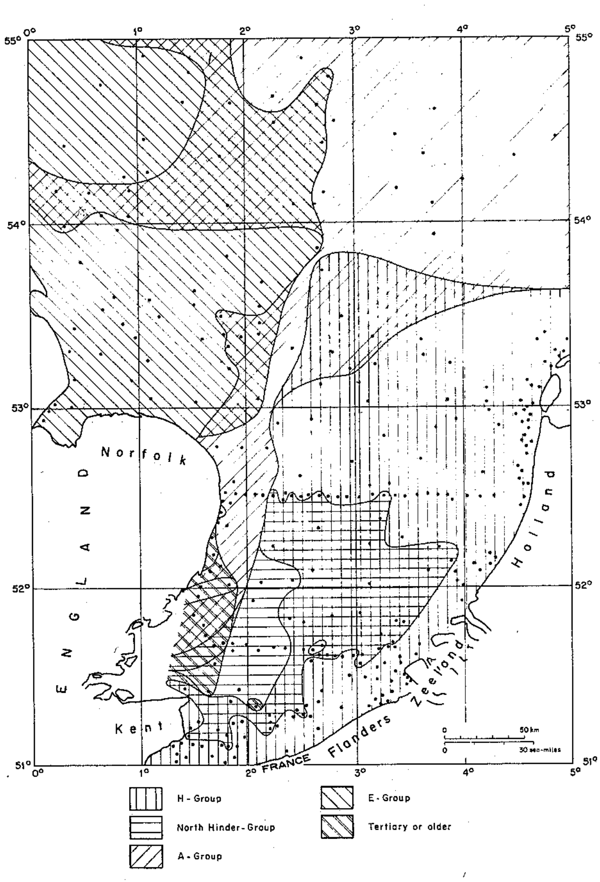

Fig. 23 - Heavy mineral associations (After Baak 1936).

During periods of lower sea level, such as the last glacial periods, the Rhine must have flowed southward through the area in which these sand ridges now occur, because the northern outlet around the Britisch islands was blocked by the ice sheet. It is very likely, therefore that, during and shortly after the last glacial period, the Rhine deposited sands in the area where these sand ridges now occur, and further south. During and after the post-glacial transgression of the North Sea over this area the tidal currents reworked part of these Rhine deposits into their present-day form of sand ridges.

As in the case of the other sand accumulation ridges, therefore, we may conclude that the sand of which the Hinder Banks, the Flemish Banks, the Sandettie and the Falls are built up was already present in the area before the marine transgression started and that it is not derived directly from the shore.

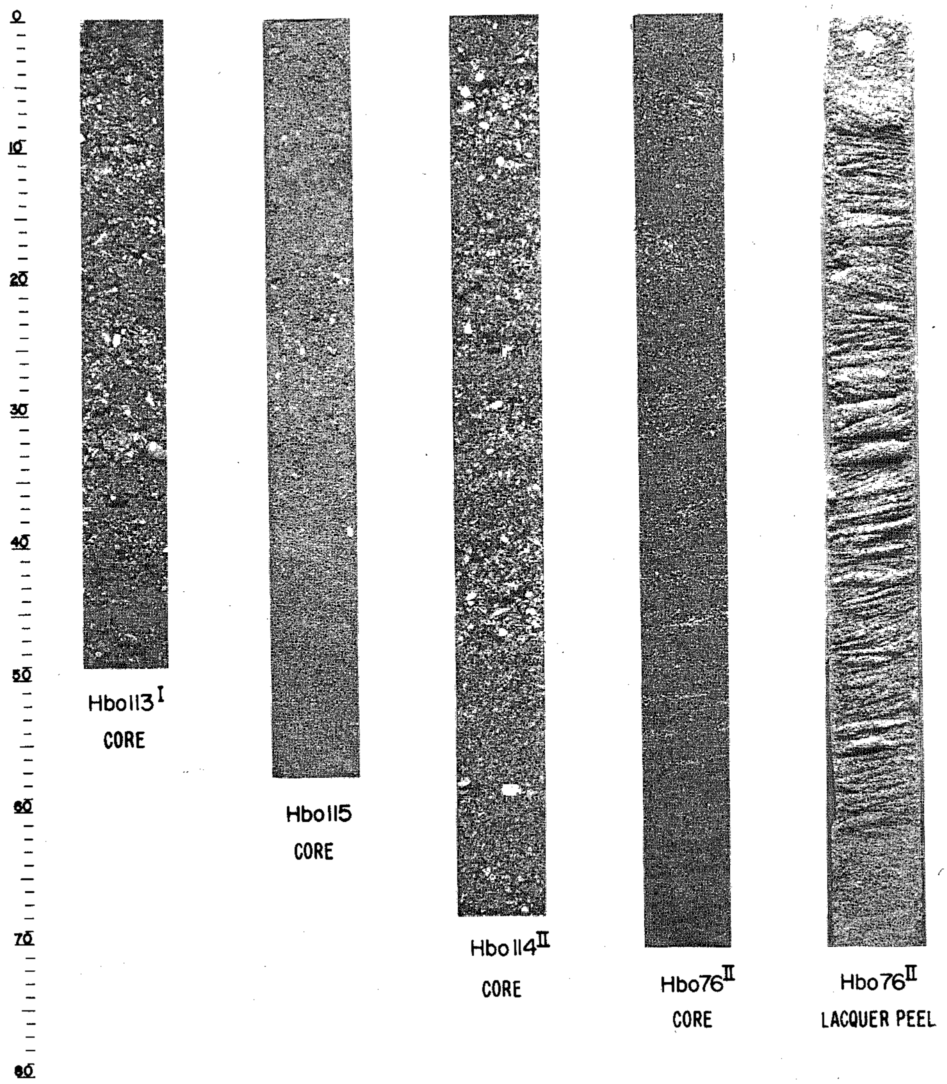

Fig. 24 - Cores and lacquer peel of samples from Outer Gabbard.

2.9. The Outer Gabbard

North of the Falls three smaller sand ridges occur, outside the Thames estuary: the Inner Gabbard, the Outer Gabbard and the Galloper. ASDIC and sparker sections over these ridges showed them to be isolated sand bodies standing on an essentially flat, gravel-covered surface which is exposed around the ridges. The asymmetry of these ridges is not very distinct; if visible, the steeper slope was found to be dipping to the west.

Mega-ripples occur on the flanks of these ridges. They mostly strike roughly perpendicular to the crest of the ridge, very often with foreset dips at angles of less than 90° to it. Figure 6 gives photographs of sparker and ASDIC recordings over the Outer Gabbard together with their interpretation.

Sampled sections were made over the Outer Gabbard. The samples were found to contain very high amounts of $CaCO_3$ (to over 50%) mainly in the form of debris of mollusc shells. Most of these skeletal particles are larger than the sand grains which surround them. These sands threfore make a rather unsorted impression (fig. 24). Grain-size analyses of samples from the Outer Gabbard are given in figures 25 and 26. These analyses were made with the sedimentation balance (Doeglas 1946). This instrument actually measures settling velocities and records them as diameters of quartz spheres with corresponding settling velocities. The actual dimensions of the carbonate particles are therefore greater than indicated.

Some small pebbles (up to 1 cm) were found in the grab and core samples. The cores show mainly small-scale cross bedding the orientation of which seems to be random.

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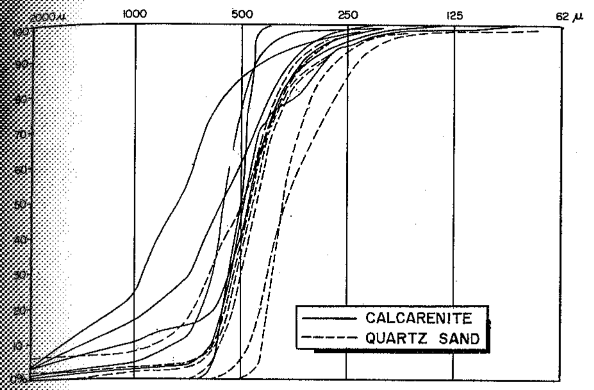

Fig. 25 - Grain-size distribution of sand from Outer Gabbard Sand Ridge.

mainly of flint, with coarse skeletal particles, was usually encountered. Occasionally sand rich in skeletal particles was found together with the lag deposit.

2.9.1. The origin of the sand of the Outer Gabbard.

Lagaaij (in prep.) studied the Bryozoa of several samples from the North Sea. In samples from the Outer Gabbard he found species which are typical of the Coralline Crag, a Pliocene formation which outcrops on the nearby English shore. Tesch and Reinhold (1946) constructed an outcrop area of the Pilocene over the southern bight of the North Sea which extends to the Wester Schelde estuary where it is known to outcrop again in the depest parts. The Outer Gabbard is situated practically on this outcrop zone. The Coralline Crag is known to be very rich in skeletal particles. Hence a large supply of coarse shell debris was available in the area in which the Outer Gabbard was formed.

The heavy-mineral assemblages in the Outer Gabbard area were found to be rich in zircon, garnet and rutile. Baak (fig. 23) considers this association to be derived from Tertiary sands.

Again we see that the material of which the accumulative type of ridge is built up is derived by erosion of the sea bed and is not derived from a nearby shore.

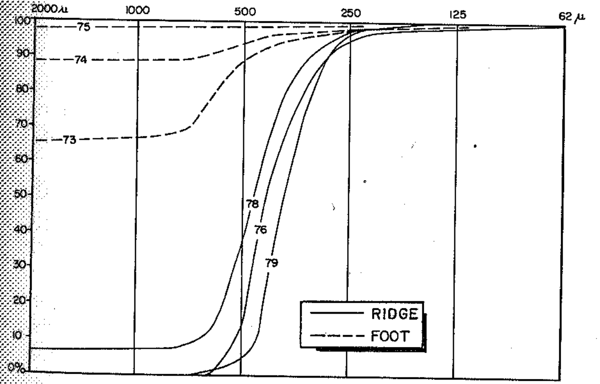

Fig. 26 - Grain-size-distribution of sand from Outer Gabbard.

2.10. The spiral current concept

The top parts of all the ridges discussed above reach well into the zone of wave action. On many of them dangerous seas occur during heavy weather. We may therefore safely assume that sand is transported downwards from the crest during storms. And yet several of these sand ridges are known to have been present in the area for at least 300 years (subsec. 2.4.4.). Hence, there must be a process by which sand is transported from the swales up to the ridges again, and by which the effect of erosion by storm waves is thus nullified.

The following hypothesis explains this upward transport of sand on the ridges by currents which essentially run parallel to them.

It was observed that the tidal currents are stronger over the swales than over the ridges. To compensate for these differences in velocity the water will flow in two long spirals in such a way that the water over the bottom is directed outward from the swale towards the crest of the ridge (fig. 27). The following four observations support this view:

1. The meeting of two masses of water with different current velocities and directions is usually revealed at the surface of the sea by current rips. Two types of current rip are observed. One type shows up as long foam lines and often contains concentrations of drift-wood and other floating objects. Here the surface currents obviously converge. Such current rips were always found over the swales and never over the ridges. The other type of current rip only shows up as a difference in wave height and length and never shows a concentration of floating material. Such rips are explained as areas of diverging surface currents. They were frequently encountered over or near the crests of the ridges. Both phenomena fit the hypothesis of the spiralling tidal currents in figure 27. Over the ridges the water tends to rise and diverge at the surface, whereas the foam line type of current rip with converging surface currents occurs in the zone where the water spirals down again.

2. On tidal flats in Zeeland it was observed that at shallow places in wide flat gullies, the foreset direction of the asymmetric sand ripples is slightly towards the crest of the shoal. This would indicate that the bottom current which is

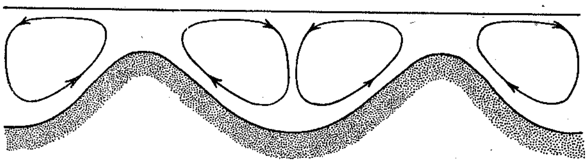

Fig. 27 - Cross section over a system of ridges and swales showing assumed spiral currents.

responsible for these ripples has a slight inclination towards the crest of the shoal, which fits the hypothesis of spiral currents.

3. A similar phenomenon was just distinguishable on some ASDIC records made of the North Sea ridges. Mega-ripples on the flanks of the ridges have their foreset dips directed slightly (ca. 5°) toward the crest of the sand ridge (encl. 1 and fig. 6). These observations were very close to the limit of accuracy.

4. Casey (1935) generated 14 spiral currents of the same dimension and intensity and with alternating sense of rotation in a wide flume. Between these spiral currents 6 furrows were formed. This seems to be a model experiment that demonstrates the spiral current concept given above. Unfortunately, Casey mentions this phenomenon without pursuing the problem any further.

In the case of tidal currents, the direction of the current is reversed four times each day. The resultant of the ebb and flood currents along the strike of the ridges is either very small or zero. The component over the bottom towards the crest of the ridge, however, is not reversed but keeps the same direction. It is believed that these spiral currents are capable of transporting sand towards the crest of the sand ridges whilst the sum total of the sand transport along the strike of the sand ridge is very small or zero

It should be possible to prove or disprove the occurrence of spiral currents and their influence on the formation of sand ridges by direct current measurements.

If the spiral currents on each side of the ridge are equally strong a symmetric ridge can be expected. Near the Channel such ridges do occur, often with mega-ripples pointing towards the crest on both sides (e.g. Outer Gabbard, fig. 6).

As regards asymmetric sand ridges it is believed that the spiral current on one side is dominant. This would be the case on the ridges of the Well Bank area.

2.11. Conclusions

At the base of a marine transgression rather large, thick and elongated sand bodies can be formed if, following this transgression, strong tidal currents have occurred.

These sand bodies will consist of clean, well-sorted sand, without a vertical gradation in grain size and will be overlain by clayey marine sediments if the transgression continues. Hence they will form excellent reservoirs for oil.

To illustrate this point: The volume of Well Bank measured from figure 9 is about $2.4 \times 10^9 m^3$. Assuming a porosity of 30 % and an ultimate recovery of 20 % this would mean that Well Bank filled with oil would be able to produce about $150 \times 10^6 m^3$. This is quite a considerable figure for a single sand ridge. Unfortunately, however, the ridges studied are filled with sea water only.

The sand of which these sand bodies are built is derived from the sea bottom by marine erosion, mainly by tidal currents. In the Well Bank area the sand was present as a glacial-outwash fan when the transgression started. In the southern half of the area the sand came from deltaic and fluviatile Rhine sediments which were deposited there during the lower sea level stages of the foregoing glacial periods. The Outer Gabbard, about 40 % of which consists of shell fragments, comprises a large quantity of skeletal particles from the Coralline Crag which outcrops in the neighbourhood.

The sedimentary structures of these sand ridges are characterised by the occurrence of often large-scale cross bedding, the orientation of which is complex. In the case of Well Bank this foreset pattern has been unraveled.

3. RIDGES FORMED BY EROSION OF OLDER DEPOSITS

3.1. Introduction

In this chapter ridges are discussed from which evidence was found that older deposits occur in them at a level above the surrounding sea floor. They hence must have been, at least partly, carved out from older strata and are not formed by sand accumulation only.

3.2. Brown Ridge

At approximately 52°30'N and 3°20'E a single N-S trending elongated ridge occurs, called Brown Ridge. East and west of this ridge, small depressions occur which strike parallel to it. On the flanks of this ridge abundant mega-ripples are present, the steep slopes of which point towards the north along the western flank and towards the south on the eastern flank. In both cases the dip of almost all the steep slopes is slightly inclined towards the crest of the ridge (encl. 1).

One could conclude from this that sand is moving towards the south along the eastern flank and towards the north along the western flank. Sand seems thus to move around the ridge.

On both the eastern and the western sides of the ridge lie elongated depressions parallel to the ridge. In these depressions mega-ripples were frequently encountered, dominantly with steep slopes pointing to the north. Between these ripples a not very coarse lag deposit was found, which only in one case showed up as a strong ASDIC reflection.

Sparker sections always showed a reflection below Brown Ridge about at the level of both rim

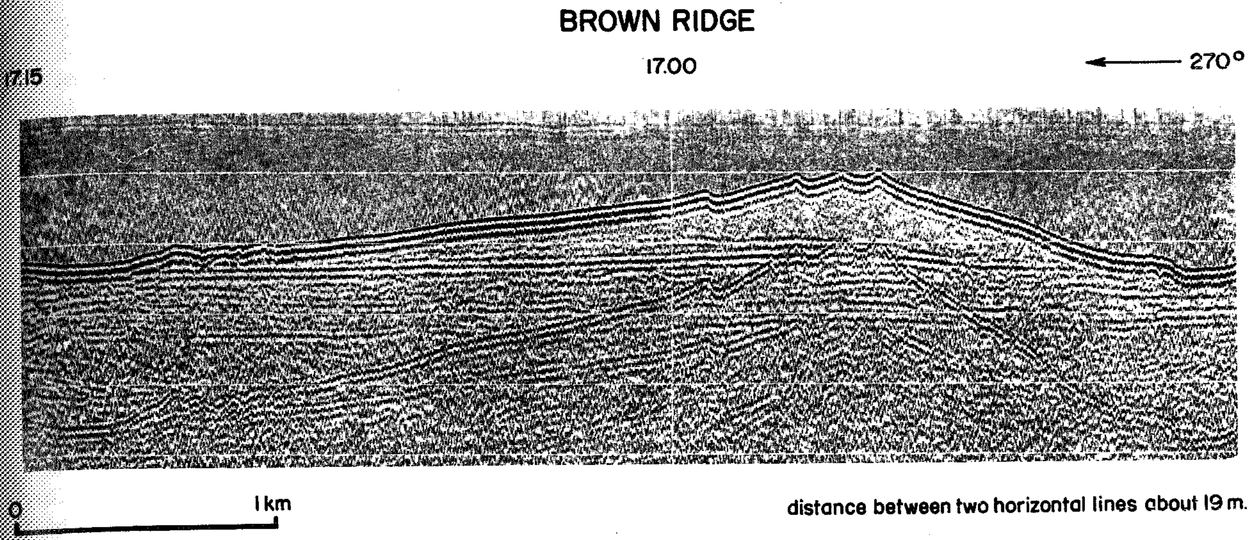

Fig. 28 - Sparker section over Brown Ridge.

depressions (fig. 28).

Some cores and water jet samples taken in the rim depressions yielded clayey deposits below a thin lag deposit. Based on the pollen content Zagwijn (1963) considers them to be of Eemian age (last Interglacial).

To our great surprise a water jet sample also brought up a clay sample from a few metres below the crest of Brown Ridge (station Hbo 12, encl. 2, sec. 6). A second water jet boring at short distance (same station number) gave exactly the same results. Van Raadshooven studied the Foraminifera and Ostracoda of these samples and reported the presence of an autochthonous brackish water fauna. This excludes deposition in the present-day North Sea and hence Brown Ridge must be an erosional remnant. It seems to have only a thin cover of recent sand.

One must accept that tidal currents are capable of forming ridges by eroding older deposits as well as by accumulating sand. Possibly the process of spiral currents described in paragraph 2.10 could achieve this.

3.3. The ridges of the Zeeland Group

Under this name are taken together the SW-NE striking ridges which occur off the Dutch province Zeeland (fig. 2). In the southwest they are cut off by the SSW-NNE striking ridges of the Hinder Group. They were studied briefly. A few sparker lines were sailed over them and one section was sampled over Middel Bank.

Echo sounding and ASDIC recording showed the presence of many mega-ripples on and between the Zeeland ridges (encl. 1). There seems to be a dominance of northward-pointing asymmetric ripples, which is in accordance with the tidal rest current, which is to the north here (fig. 3D).

Gravelly lag deposits did not show up on the ASDIC records from the swales. Only in station Hbo 232 was the lag deposit sampled. It was found to contain some gravel and coarse skeletal particles in low concentrations.

A series of sparker sections taken over these ridges yielded structures which differed greatly from those observed on most other North Sea ridges. These latter ridges are isolated sand bodies standing on a flat surface (chap. 2). In the case of the Zeeland ridges, the reflecting horizons from below were found to reach inside the ridges (e.g. encl. 2, sec. 12). No flat base has been observed. From this it must be concluded that these ridges are, to a large extent, erosion forms rather than sand-accumulation forms.

Baak (1936) pointed out that the Zeeland ridges line up remarkably well with a series of beach ridges which occur in the province of Holland (the so-called "oude duinlandschap". He concluded therefore that the Zeeland ridges were drowned extensions of these beach ridges. This hypothesis is not supported by our recent sparker survey which shows markers, from below, to rise within the ridges.

On one section over Middel Bank (encl. 2, sec. 12) cores were taken. At stations Hbo 229 and 232 bluish-grey sand and clayey sand were found below a thin cover of the yellowish-brown sand, that is normally encountered on the North Sea bottom (fig. 29). Similar bluish-grey coloured sediments were not found in any of the other sand ridges studied. The cores from the upper part of Middel Bank (stations Hbo 228, 230 and 231) showed the normal type of yellowish-brown mostly cross-bedded sand.

From the sparker reflections one can deduce the cross section through Middel Bank given in figure 30. The yellowish-brown sand overlies the bluish-grey sediments, which are exposed, or only covered by

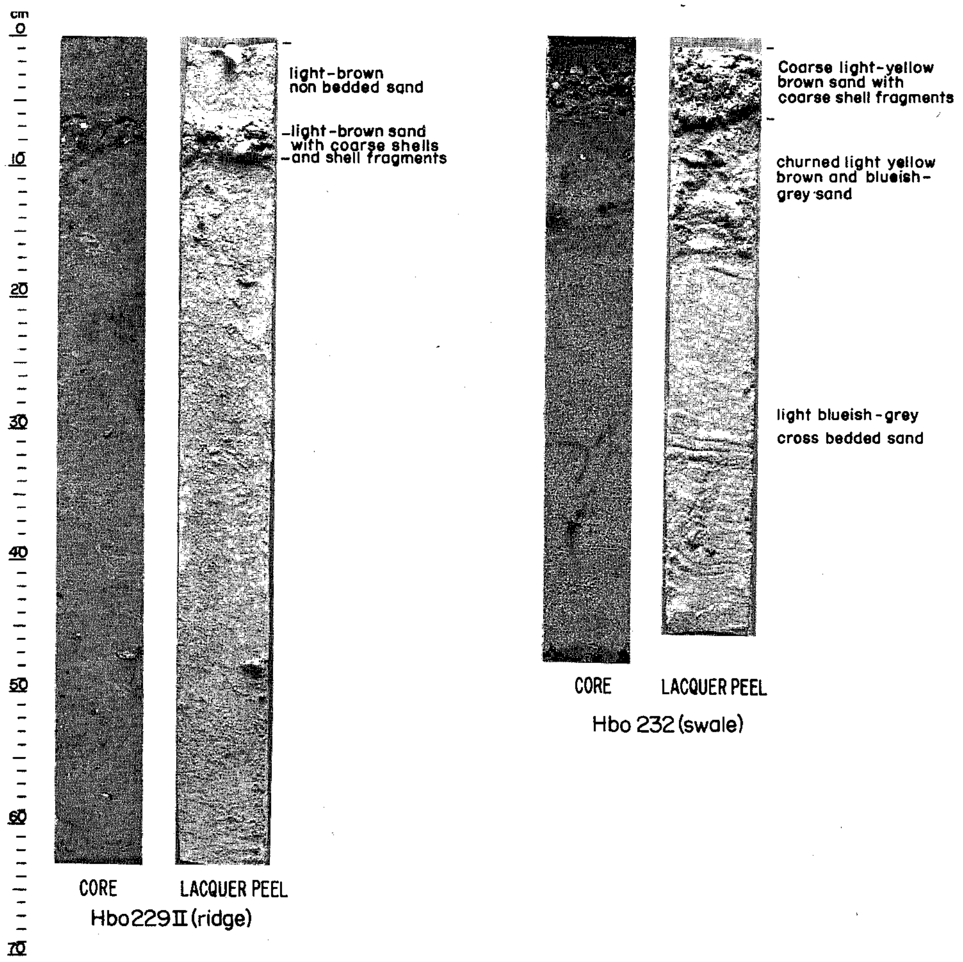

Fig. 29 - Cores and lacquer peels from cores on and near Middel Bank.

a thin lag deposit, on the flanks of the ridge. Unfortunately, the microfauna of the samples obtained from the bluish-grey zone did not yield any information about their age.

Van Straaten (1954) studied such colourations in the Waddenzee. He distinguished three zones, the colouring of which was due to different stages of authigenic iron:

a. The hydroxide zone (L) corresponds to the zone of oxidation. The sediments are brownish or yellowish grey. The colour is due to the presence of ferri-hydroxides. This is the case with most of the North Sea sands.

b. The monosulphiric zone (M) occurs below the L zone. The sediment here is in an anaerobic condition. This zone is characterised by a more or less intensely black colour. An important part of the iron is in a monosulphuric state.

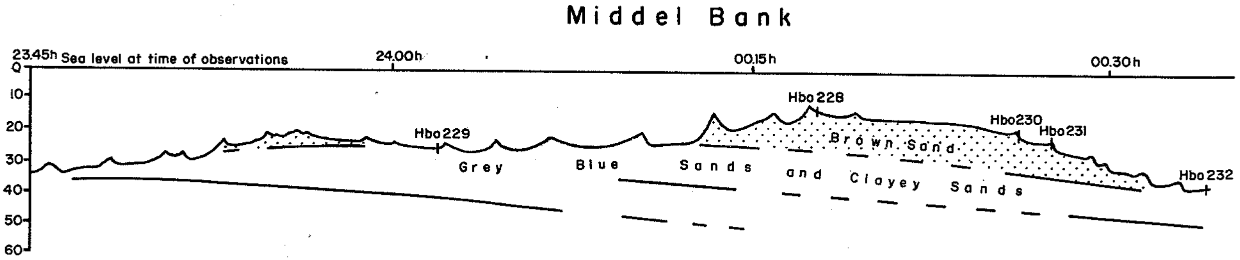

Fig. 30 - Deduced cross section through Middel Bank.

c. The bisulphuric or pyrite zone (P) is found below the M zone. Colours are more or less light (bluish) grey. The iron is almost exclusively present as pyrite. The bluish-grey sediments encountered in the cores of stations 229 and 232 are in this stage.

The succession in which the above zones are given is the normal sequence encountered in many bottom profiles according to Van Straaten. Transitions from L to M and from M to L proceed quickly. Transitions from M to P may take from 50 to 200 years. Transitions from P to L may occur but go very slowly. Transitions from L to P bypassing the M stage are not on record. Van Straaten believes that the intermediate M stage always occurs.

In the profiles described from Middel Bank the yellowish-brown upper sands, which are in the L stage, directly overlie the bluish-grey sediments (P-stage). The intermediate M stage was not observed. This is an indication that the contact between the yellowish-brown sands and the underlying bluish-grey sediments is erosional. And hence that the bluish-grey sands are fossil. Which is a second indication that the Zeeland ridges are at least in part erosion forms.

Waterstaat (Dutch Ministry of Public Works) drilled a shallow boring on the southeastern flank of Thornton Ridge, one of the Zeeland ridges, in a water depth of 12.50 m (van Veen 1943). Spaink (1964) examined the macrofauna from this boring. At about 10 m below the sea bottom he found that the sand was very poor in specimens (which he attributed to a stratigraphic change). Above and below this level he found richer faunas. Above this level he found fewer warm-water species than below it. Spaink cannot decide whether this change reflects a change in climate within the Holocene or an Eemian (last interglacial)/Holocene contact.

In our sparker sections over Thornton Ridge a reflector at about the same depth below the surface can be observed. This horizon was found to truncate reflections rising up from below. Our sparker profiles did not go through the location of the Waterstaat boring, but it must be considered possible that the zone reflecting a change in climate observed in this boring is this sparker horizon.

Though not a proof, the above is a third argument in favour of the view that at least part of the relief of the Zeeland ridges is due to erosion of older deposits.

A fourth argument to support this view can be found in the truncation of the Zeeland ridges by those of the Hinder Group, which suggests that the Zeeland ridges are older than those of the Hinder Group.

Considering the above four arguments it must be

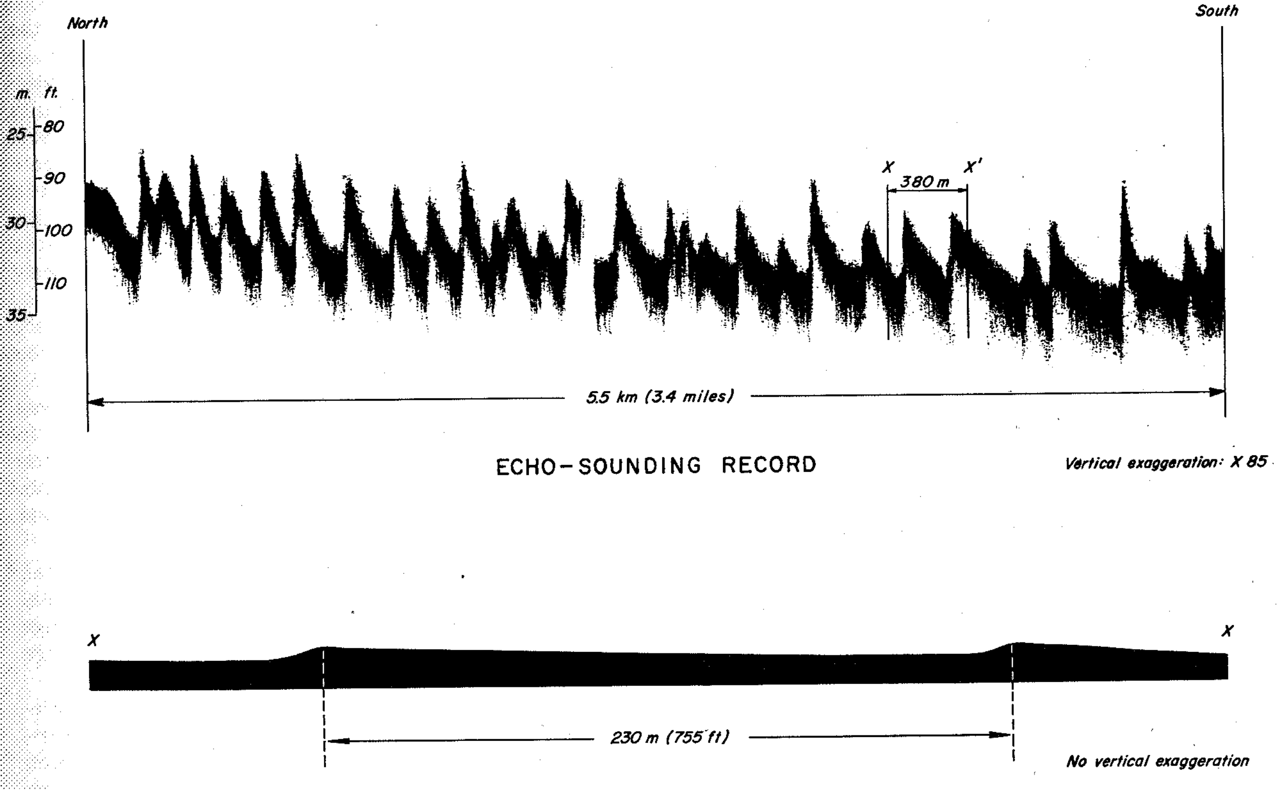

Fig. 31 - Mega-ripples West of IJmuiden.

considered very likely that at least the lower parts of the Zeeland ridges consist of older sediments. The upper parts are most probably recent.

The conclusion to be drawn from this is that the Zeeland ridges are nearly stationary. If they had moved more than their width, the lower, fossil, part would have been reworked. There are indeed no data on record which point to a significant displacement of the Zeeland ridges (van Veen 1936). The naval historian Warnsinck remarked to van Veen that modern hydrographic charts are more useful for the study of the naval battles on the Vlakte van Schooneveld in the 17th century, than the charts the combatants had to sail by. Which is a remarkable argument for the stability of the sea bottom in this particular region.

3.4. Conclusions

It must be concluded that tidal currents (perhaps in the spiral form described in section 2.10) can scour out ridges from older material as well as build them up. Brown Ridge (sec. 3.1) is an example of a ridge which seems to be formed largely by erosion. It seems that in the Zeeland ridges both erosion and accumulation are responsible.

4. THE AREA OFF THE DUTCH COAST

4.1. The mega-ripple field off the Dutch coast

A very wide zone off the Dutch coast is almost completely covered by mega-ripples with heights of as much as 9 m (encl. 1 and fig. 31). Towards the north these mega-ripples disappear at about 53°N (Anon. 1967). They are separated from the coast of Holland by a ripple-free zone about 20 km wide (sec. 4.4). To the south the mega-ripples continue over the Zeeland and Hinder ridges. In the west they become less abundant near the Deep Water Channel.

Stride (1959) and several others before him have paid attention to these large-scale ripples. They are almost all asymmetric, their steepest slopes facing to the north and northeast (encl. 1). This is in accordance with the rest current of the tide (fig. 3D). In the area about 25 km north of the Hinder Group their asymmetry was found to alternate between north and south and about 10 km north of the Hinder Group they were found to have their steep slopes predominantly to the south. Just northwest of Thornton Ridge a similar phenomenon was observed (encl. 1).

On very quiet days, the tidal currents bouncing upward against the ripples give rise to an anastomosing pattern of rippled zones at the surface of the sea, alternating with patches of smooth water (van Veen 1936). We did not succeed in photographing this phenomenon. Seen on the ASDIC records the ripple crests were found to be straight or nearly so. Only in a zone east of Brown Ridge were mega-ripples with strongly curved crests found (fig. 5C).

The sands encountered were always very well sorted and clean. Over the whole area there is a gradual decrease in median grain size towards the north (encl. 2, sec. 11). The sands contain less than 5% $CaCO_3$, most of which occurs in the form of shell debris. A small quantity of whole shells occurs. Especially off the coast of Holland large quantities of the sea urchin *Echinocardium cordatum* were found. The sedimentary structures from the cores obtained from this area often consisted of borings by this animal. Cross-bedding was very often spoilt by its boring activity.

Echinocardium cordatum feeds at about 20 cm below the sea bottom. It goes down through a straight vertical shaft and then moves around horizontally at distances of up to 60 cm from the lower end of the shaft. It moves by eating the sediment and extruding it as a textureless mass as well as by pushing the sand backwards with its spines. The result is a peculiar quarter-moon-shaped sand texture (fig. 32, Schäfer 1962 p. 349, Reineck 1963).

The thickness of the sand in this area is not known. The sparker did not reveal subsurface reflections and the corer penetrated the sand only near Brown Ridge (sec. 3.2.).

At about 28 km northwest of Hoek van Holland the Dutch navy repeated precision echosounding at regular intervals for $2\frac{1}{2}$ years (Langeraar 1966).

Langeraar states that comparison of the results of these surveys shows that not a single movement of the different crests exceeds the level of significance (ca. 60 m) during this time interval. "There are, however, a number of smaller shifts in the position of the crests which, though none of them is significantly large, all - or at least the great majority of them - point in a NNE direction".

He therefore concludes "with some confidence", that these mega-ripples indeed move slowly to the northnortheast.

In roughly the same area we took a line of cores across a mega-ripple. The results are given in enclosure 2, section 8. The cores in front of the steep slope showed unbedded sands with sea urchin trails. On the ripple itself foreset-bedded sands were encountered.

At a location 36 km westnorthwest of Hoek van Holland cores from a mega-ripple were taken. These showed an abundance of sea urchin churnings which had disturbed the foreset bedding to a large extent (encl. 2, sec. 9).

The cores taken over a mega-ripple 35 km southwest of IJmuiden showed less churning and better-preserved foreset bedding, the orientation of which was measured (encl. 2, sec. 7). On the gentle slope small-scale foreset bedding was found, some of

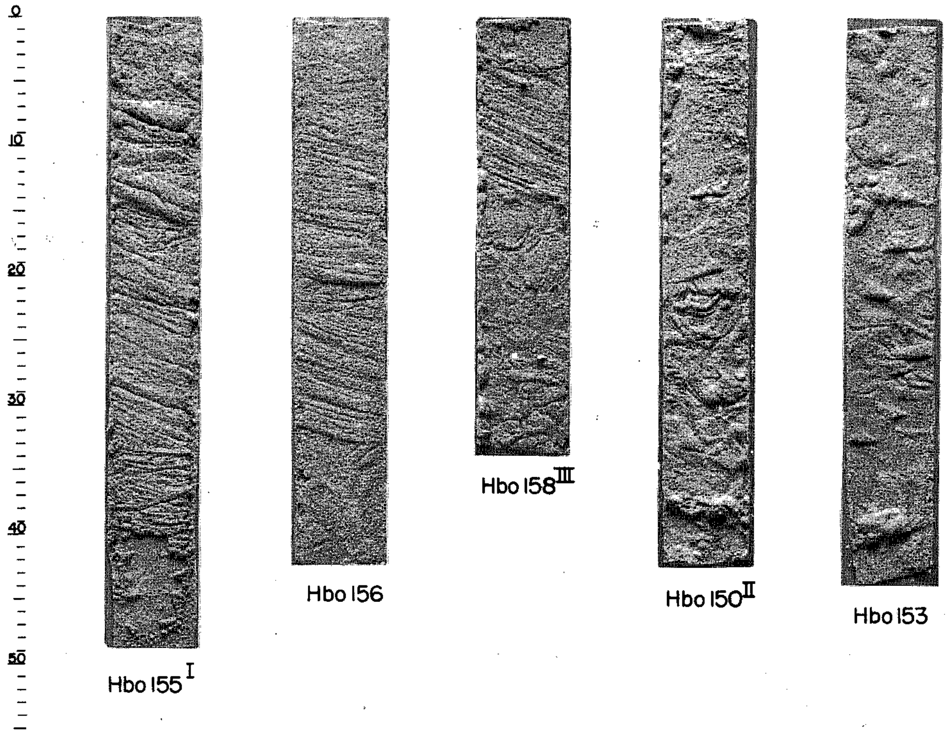

Fig. 32 - Lacquer peels from cores from Broad Fourteen area.

which was dipping roughly parallel to the strike of the ripple. In front of the steep slope great variations in dip were found. The core from the steep slope showed one foreset-bedding direction over the whole length of the core, which was about 30° to the dip of the steep slope of the ripple.

4.1.1. Conclusions. In view of the above we may conclude that:

1. Off the coast of Holland a large area is almost completely covered with asymmetric mega-ripples up to 10 m high, with a wavelength of several hundreds of metres.
2. They are all asymmetric towards the north.
3. Repeated detailed echo soundings at one location suggest that they move slowly to the north.
4. It is not yet known whether they move regularly or under special conditions only (e.g. storm tides).
5. Their sedimentary structure seems to consist of large-scale cross-bedding frequently destroyed by boring animals, especially sea urchins.
6. The occurrence of small-scale ripples in cores from the gentle slope indicates that small ripples occur on the mega-ripples. On echo-sounding records, however, these were never observed.
7. From the above, one may conclude that sand is transported to the north over a wide zone off the Dutch coast.
8. Apart from the area near Brown Ridge, where the sand was penetrated (sec. 3.2.) nothing is known about the thickness of the sand in this area.

4.2. Mega-ripples not associated with ridges elsewhere

In figure 33 the directions of the dips of the foreset slopes of asymmetric ripples over the area investigated are summarised. It can be seen that in the area off the Dutch coast to the Deep Water Channel and Texel Spur, north of the line running from a few miles north of the Hinder Group towards the Outer Gabbard, the dips are predominantly northward. Along the English coast, however, there is a dominance in the oppposite direction. Similar results were obtained by Stride (1959, 1961 and 1963). It is stressed that this pattern does not hold for ripples observed on the flanks of ridges. Only ripples on the flat sea beds away from the ridges are considered here.

There is a reasonable correlation between the above foreset directions and the rest currents of the tide as given in figure 3D. It seems likely therefore that the pattern shown actually reflects sand transport directions.

Bryozoan studies by Lagaaij (in prep.) support this view. The Pliocene Bryozoa from formations which outcrop at the North Sea bottom from the Schelde mouth to Norfolk (Tesch and Reinhold 1946) were found to be transported towards the north along the eastern side and towards the south along the western side of the area investiaged.

No south-bound ripples were sampled.

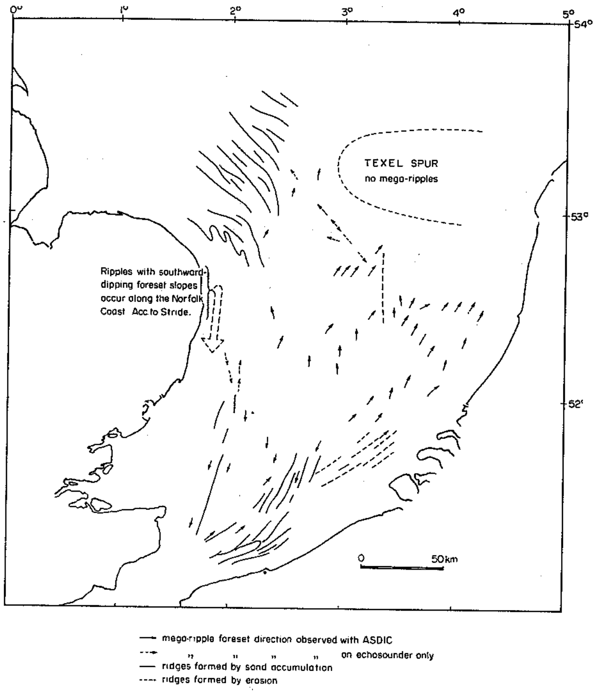

Fig. 33 - Main trend of mega-ripple foreset direction outside the ridges.

4.3. Texel Spur

North of about 53^{O}N the mega-ripples discussed in section 4.1. disappear (Stride 1965 & Anon. 1967). Here the sea bottom seems smooth on echo-sounding records and shows a gentle spurlike elevation about 12 metres high between 53^{O}30'N and 3^{O} and 4^{O}E. This rise we call the "Texel Spur" (fig. 2).

The Texel Spur is separated from the coast of Holland by a slight depression trending north-south, which is called "Vlieland rif". The bottom of Vlieland rif is rich in boulders and hence according to Pratje (1951) is a washed-out moraine. Northwards, the Texel Spur slopes down into a deeper area, called "Auster" Ground, which is covered mainly by extremely fine sands and silts (von Völpel 1959).

The Texel Spur is separated from the Well Bank area by a north-south trending deeper zone. It is believed that the spill-over channel of the ice-dammed lake between the Texel Spur and the Dogger Bank in the Weichselian (last glacial period) occurred here. Some parts of the sparker record in this zone could be interpreted as a filled-in channel which had migrated slightly and through which this overflow may have taken place.

The area of transition to the mega-ripple fields in the south is described by Anon (1967).

Texel Spur is covered with very fine sands, extremely well sorted (fig. 34) and completely homogenised. The thickness of this sand is now known from cores, nor could it be established with the water-jet sampler because in this area there is no slack in the tidal currents. Sparker sections over the Texel Spur support the view that this sand is up to 10 m thick (fig. 35a). If this is correct the Texel Spur sand would be a sand body with good reservoir properties since, owing to the very high degree of sorting, porosity and permeability would be satisfactory. Its extent, 70 km by 30 km is quite impressive. The thickness assumed above, however, can only be proved or disproved by expensive marine drilling.

4.4. Hypothesis of the sand transport off the coast of Holland and the genesis of Texel Spur sand

For this hypothesis the thickness and extent of the Texel Spur sand assumed above are considered to be correct.

4.4.1. Mega-ripples. The mega-ripples off the Dutch coast are nearly all asymmetric and, with exception of the ripples on the west flank of Brown Ridge, they have their steep slopes facing in northerly directions. This indicates that these mega-ripples are moving to the north. This would mean that, off the Dutch coast, sand is transported in the direction of the Texel Spur.

4.4.2. Grain size. As one passes from the sands of the Hinder Group to those of the Texel Spur there is a very gradual decrease in the grain size (500-150 micron). North of the Texel Spur we find rather abruptly either finer-grained sands and silts or poorly sorted coarser sands (encl. 2, sec. 11).

4.4.3. Heavy minerals. The heavy minerals from the southern North Sea were studied by Baak (1936) (fig. 23). One of the provinces distinguished is characterised by the occurrence of saussurite and augite. Both minerals are characteristic of

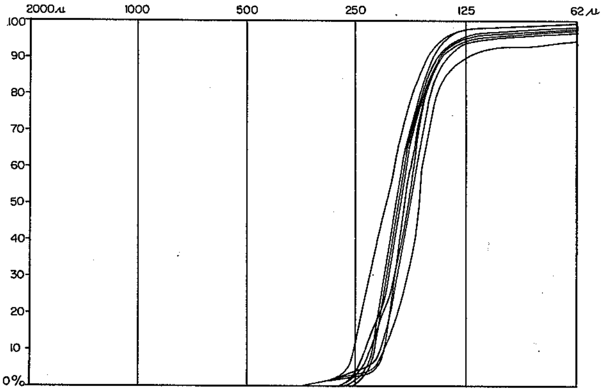

Fig. 34 - Grain-size distribution of surface samples from Texel Spur.

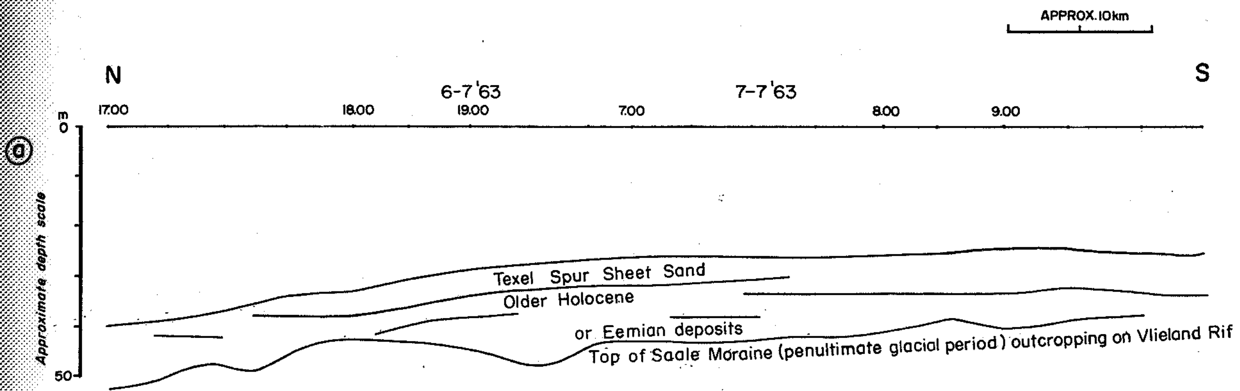

Fig. 35a - Tentative interpretation of sparker section over Texel Spur.

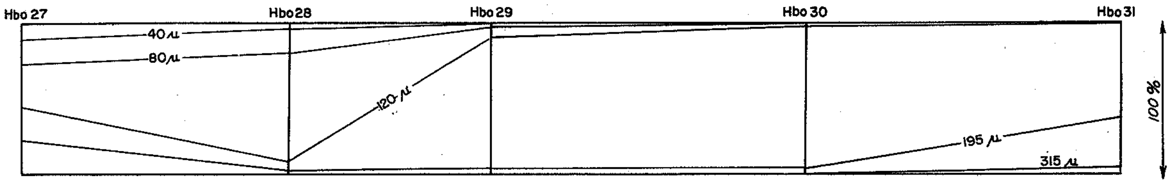

Fig. 35b - Grain-size distribution of surface samples on above section.

sands supplied by the Rhine (van Andel, 1950, Kruit, 1963). This "H" province occurs over the greater part of the southern bight of the North Sea along the Dutch coast to about the northern boundary of the Texel Spur. North of it occurs the so-called "A" province, characterised by the minerals garnet, epidote and hornblende which are of northern, i.e. Scandinavian, origin, having been brought south by the Pleistocene ice sheets.

Besides a change in grain size, therefore, there is also a mineralogical change roughly north of the Texel Spur.

4.4.4. Tidal currents. Off the Dutch coast the tidal currents run north and south (fig. 4). The northward currents are on the average slightly stronger (fig. 3D).

North of the Texel Spur, however, the tidal currents run east and west. Between the north-south and east-west tidal currents a transition zone occurs with weaker currents in all directions.

The Texel Spur is in the southern half of this transition zone.

4.4.5. Conclusions. The asymmetry of the mega-ripples south of the Texel Spur suggests sand transport towards the north. This can be explained by the fact that the northward tide is slightly stronger than the southward tide. The gradual decrease in grain size which occurs in this area is in agreement with this conclusion and correlates also with the very slight decrease in strength of the tidal currents to the north.

Sand transported towards the north in this way will finally arrive on the Texel Spur where, owing to the rotating and weak tidal currents, it will most probably be deposited. The heavy mineral provinces of Baak (1936) and the rather abrupt change in grain size support this hypothesis.

4.5. The muddy sand sediments off the Dutch shore

4.5.1. Near Scheveningen. Van Straaten (1965) mentions the occurrence of a zone of muddy sediments at the foot of the barrier along the provinces of South- and North Holland. Seaward these fine-grained sediments grade into the sands of the mega-ripple area discussed in paragraph 4.1. Some cores were taken along a section running from the shore to the first occurrence of mega-ripples (encl. 2, sec. 10). For a discussion of this rather strange phenomenon we refer to van Straaten (1965).

4.5.2. Near the entrance of the Wester Schelde. From the French/Belgian border to the island of Walcheren muddy bottom sediments occur along the coasts of Flanders and Zeeland. Off the Schelde entrance the sea water is more muddy than elsewhere. It is here that the zone of muddy sediments reaches the greatest distance from the shore (van Veen 1936, Bastin 1964). This mud is thought to be derived from Tertiary strata which are exposed in the estuary of the Wester Schelde. (The Ooster Schelde in which no Tertiary is exposed has clear sea water.) To this it may be added that according to our sparker sections many Tertiary outcrops should occur off the Schelde entrance as well. It is not yet precisely understood why this mud is being redeposited in the same area instead of being deposited elsewhere. Bastin (1964) is at present studying the sediments in this area in great detail.

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