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MIGRATION OF LARGE-SCALE BEDFORMS AND PRESERVATION OF CROSSBEDDED SETS IN HIGHLY ACCRETIONAL PARTS OF TIDAL CHANNELS IN THE OOSTERSCHELDE, SW NETHERLANDS[1]

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ABSTRACT

J. H. Van den Berg 1982 Migration of large-scale bedforms and preservation of crossbedded sets in highly accretional parts of tidal channels in the Oosterschelde, SW Netherlands – Geol. Mijnbouw 61: 253-263.

Recent large-scale crossbedded sands have been studied in two construction pits of the 'Delta Project' in the Oosterschelde, The Netherlands. The deposits form long crested megaripples of about two metres high at a depth of 4 to 17 metres below Mean Sea Level.

Crossbedded sets have been analysed for stand-still phases of megaripple migration during the subordinate tide (pause planes). An average lee side accretion rate of the dunes was calculated from the cyclic neap to neap tide change in thickness of the sand layers between successive pause planes.

Information on the morphodynamics of the environment of deposition and the rate of accumulation of the discussed units was acquired through some particular sedimentary structures and through the study of series of hydrographic charts of the area. The latter information also strongly suggests a wide occurence of alike sedimentary units in the subsurface of shoals of the Oosterschelde mouth and outer delta. Finally the thickness and the number of the sets in relation to sandwave migration and rate of accumulation is discussed.

INTRODUCTION

Deep pits, dug at several locations in the tidal inlets of the SW Netherlands for the foundation of sluices and other heavy constructions, enable a detailed study of subrecent tidal deposits, laid down at depths as much as 15 m below Mean Sea Level. OOMKENS & TERWINDT (1960) and TERWINDT (1971) have described several lithologically and structurally different units which can also be recognised in cores, and these authors have related them to conditions of flow. In a recent paper the latter author described 7 lithofacies of assemblages of sedimentary structures and lithology, all reflecting a particular process or subenvironment (TERWINDT, 1981).

A paper by VISSER (1980) focused attention on the recognition of ebb/flood and spring/neap cycles in x-bedded[3] sets; the occurrence of seasonal bedding in an abandoned channel fill has been reported by VAN DEN BERG (1981b).

The present paper is devoted to the origin of some unidirectionally x-stratified intervals built up in tabular sets with great set heights (up to 2.5 m) exposed in the 'Philipsdam' and 'Schaar' pits in the Oosterschelde tidal basin, SW Netherlands (for location, see Fig. 1).

THE PHILIPSDAM EXPOSURE

This exposure was situated in the southwestern part of the 'Philipsdam' pit at a depth of 3 to 9.5 m below Mean Sea Level.

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[3]x-bedding in this paper refers to cross-stratification produced by migrating megaripples, while x-lamination is used for crossstratification produced by small scale ripples.

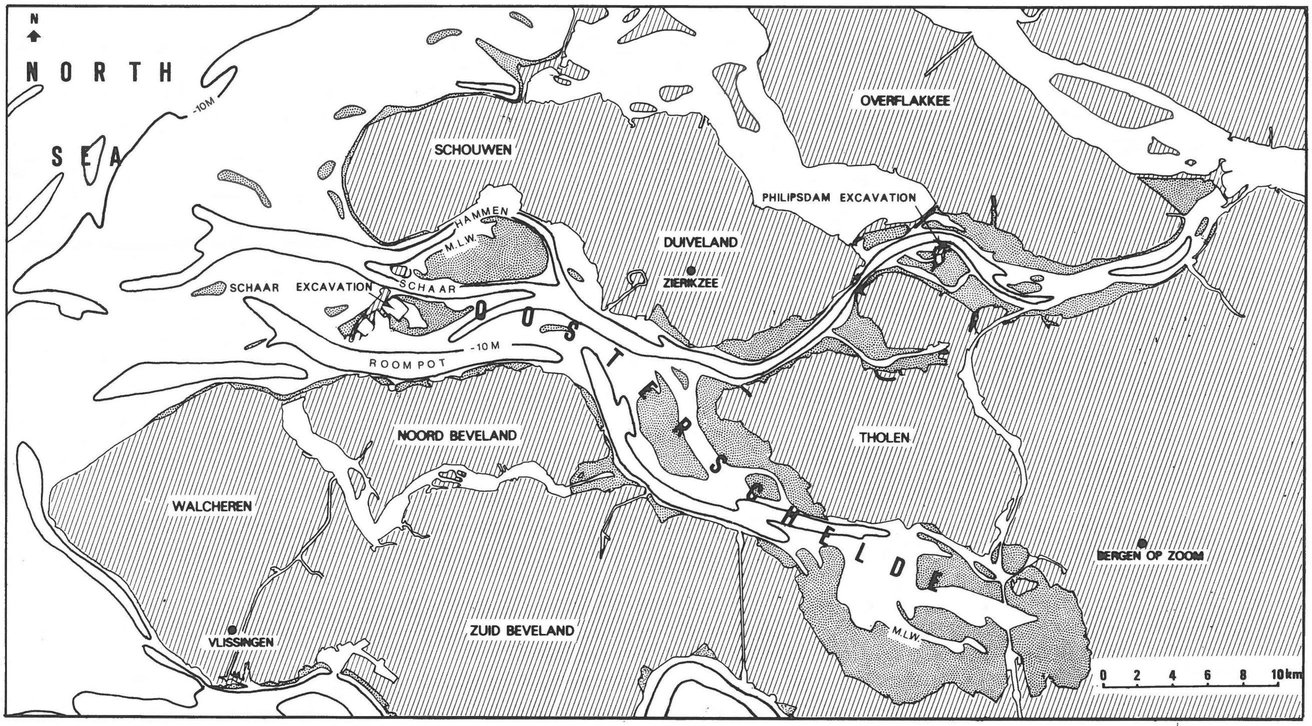

Fig. 1
Location of studied outcrops.

Hydrographic background

The depositional history of the exposure is well-documented by a series of sounding charts made by the 'Rijkswaterstaat' (the Governmental Board for Roads, Waterways and Harbours) of which annual editions are available from 1959 onwards. In the early years of this series of soundings the exposure was located at the southern bank of the Krammer channel (Fig. 2).

Originally the Krammer channel was part of a complicated net of tidal inlets east of the island of Schouwen-Duiveland. With the construction of a dam accross this area (1962-1964) an artificial tidal watershed was established. As a consequence, the ebb discharge of the Krammer channel increased by about 25% (VAN DEN BERG, 1981a), initiating a rapid process of channel bending and deepening. Between 1965 and 1975 erosional retreat of the outer bank of the channel amounted locally to more than 600 m. Simultaneously considerable amounts of sand were deposited on the southern inner bend. The pattern and rate of accretion in this area were strongly influenced by the formation of a secondary flood channel, which in its most active stage – between the soundings of 1964 and 1965 – even resulted in some erosion in its thalweg zone. At the site of the exposure this channel cut down to a depth of 9 m below M.S.L. After 1965 the flood channel silted up rapidly, and in 1973 it was abandoned because of the formation of a sill in its western connection with the Krammer main channel (Fig. 2). The exposure is a longitudinal section located in the midst of the channel fill. The process of silting up in this area in the course of some years, as revealed by sounding charts, is visualized by a transverse section of the channel fill (Fig. 3).

General description of the exposed sequence and its relation to hydrographic changes

The median grainsize of the deposit varies between 150 and 200 μm. The coarsest fraction consists of small to boulder sized peat fragments derived from Holocene peat layers (Holland Peat) which locally are exposed in channel banks. At about 9.0 m below M.S.L. the base of the channel fill is marked by a lag deposit consisting of somewhat coarser sand with many bivalve shells, shell debris and some artefacts like brick-bats. Sedimentary structures of the channel fill consist of easterly directed tabular x-bedding, passing upwards into an x-laminated unit (Fig. 4).

It is clear that this easterly directed x-bedding reflects the direction of the dominant flood current. The upward transition to an x-laminated unit expresses the decrease in current intensity, related to the gradual channel abandonment. The directions of the x-bedding correspond with the directions of the tidal currents, as inferred from sounding charts. In the following section the lower x-bedded interval will be dealt with in more detail.

The coset of x-bedding

According to the classification of inshore tidal deposits by TERWINDT (1981) the lower x-bedded interval belongs to the lithofacies STRO CUR (strong currents) representing '. . . a period of intensive transport in the form of megaripples . . .'. The lower 2.5 m of the coset was deposited in the period between the soundings of 1965 and 1966. The upper part was formed during the following two years (see Fig. 3). During deposition of this sequence, neap, mean and spring tidal ranges have been resp. 2.5, 3.1 and 3.5 m. The straight set boundaries in the exposed longitudinal section suggest deposition by straight long-crested bedforms. However, small sections perpendicular to the same outcrop revealed trough-shaped x-bedding. So lower set boundaries approach cylindrical forms and sets must have been produced by sinuous to cuspate bedforms. In order to produce the cylindrical set boundaries, scour pits in front of the crestlines must have migrated downstream regularly together with the ripple bedforms.

The inferred ripple morphology corresponds with the ripple crest pattern visible at the bank of the channel on a contemporaneous aerial photograph (Fig. 6). The unidirectional foresets to the east are in agreement with the predominance of the flood current as expressed by channel geometry

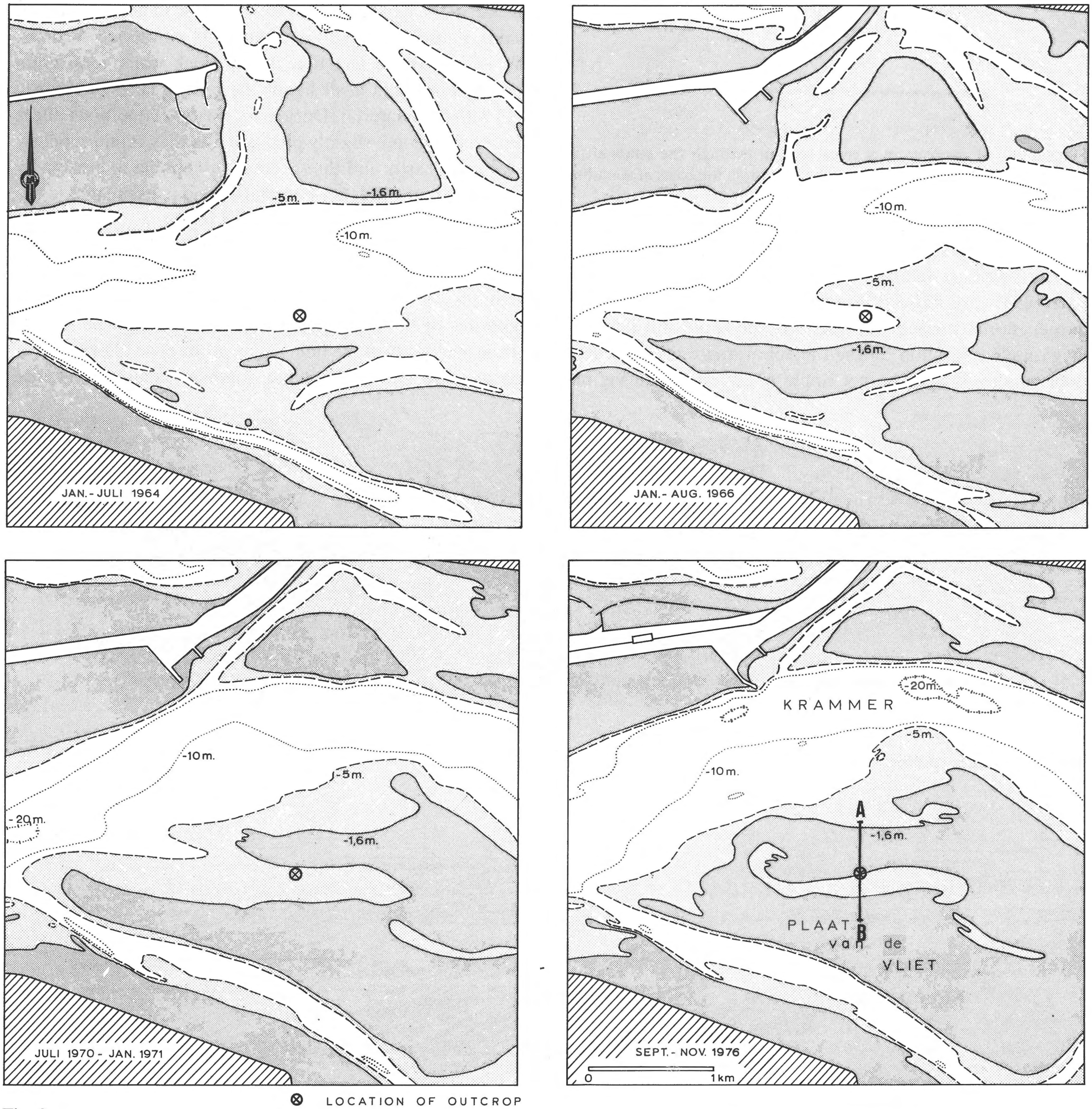

Fig. 2
Hydrography of the Krammer channel and adjacent shoals 1964-1976. A – B = cross section in Fig. 3.

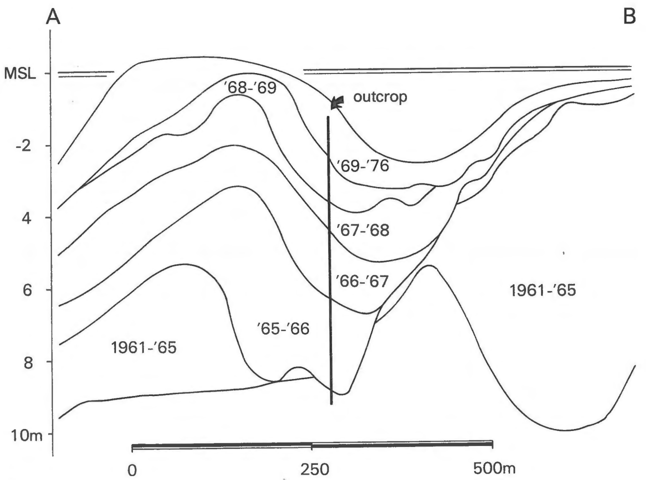

Fig. 3
Chronology of deposits in a cross section through the channel fill exposed in the Philipsdam pit, reconstructed on the basis of sounding charts (A – B in Fig. 2).

and megaripple asymmetry. Within the foresets the cyclic tidal current reversal has resulted in the generation of 'tidal bundles' that are laterally enclosed between 'pause planes'. Such planes are defined by TERWINDT (1981) as erosional or non-erosional surfaces representing the stand-still phase of megaripple migration during the subordinate tide. In fact a tidal bundle reflects the net ripple progradation during one tidal cycle. Pause planes may be draped by one or two thin mud laminae representing slack water. Usually most of the slack water drape deposited on the ripple front directly after the dominant tide, is eroded. Only a mud drape laid down after the subordinate tide is preserved. In toesets some evidence could be found for the preservation of both high and low slack water periods which VISSER (1980) calls 'mud layer couplets', enclosing veneers of sand deposited by the subordinate current.

In wet sections pause planes could hardly be traced if non-erosional and not covered by a mud drape, which often is the case in the exposure. However, in case of absence of mud drapes, pause planes still became visible in drying sections. This is due to the fact that during slack water sand grain interstices in a thin layer below the pause planes, are partly filled with fine material. During dry weather conditions, these thin layers become slightly protrusive as they retain capillary water more easily and thus are less susceptible to erosion by dessication and wind. Set boundaries and pause planes in the exposed x-bedded sets are indicated in Fig. 5.

Bundles of sand vary in thickness from a few mm to more than 50 cm. The series of bundles in one set often show cyclic variations in thickness. This is (may be) attributed to properties of the tide (VISSER & DE BOER, 1982): periods of diurnal inequality of the tide, which produce an alternation of high and low velocities of the dominant tidal current, are

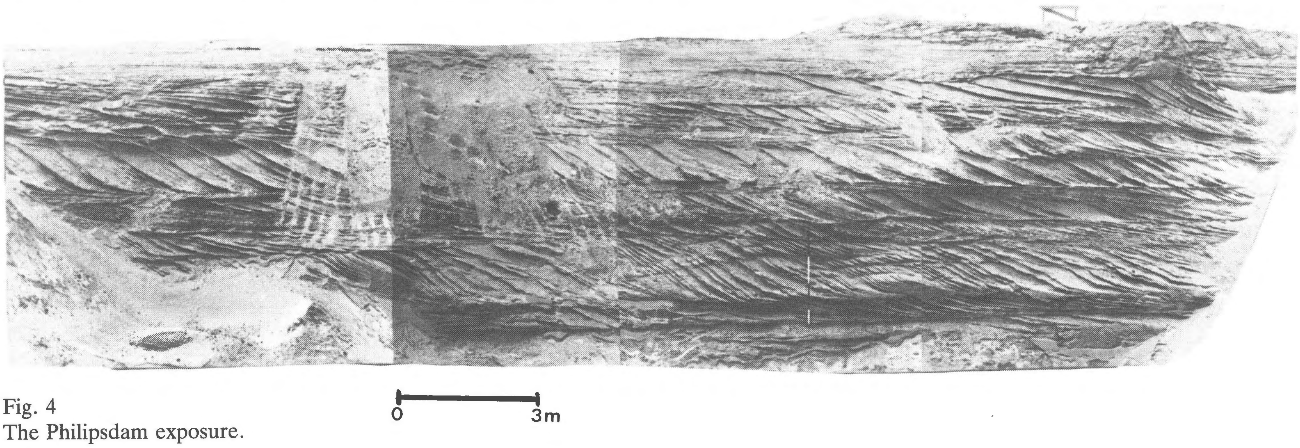

Fig. 4
The Philipsdam exposure.

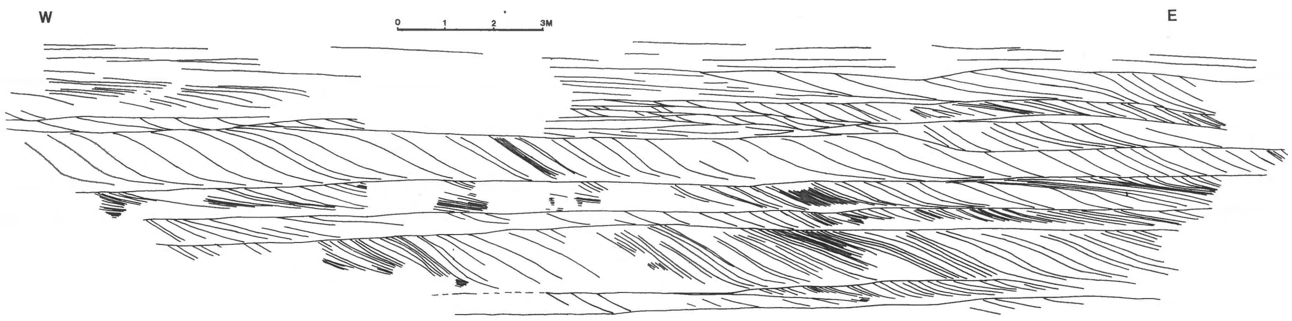

Fig. 5
Set boundaries and pause planes in the Philipsdam exposure.

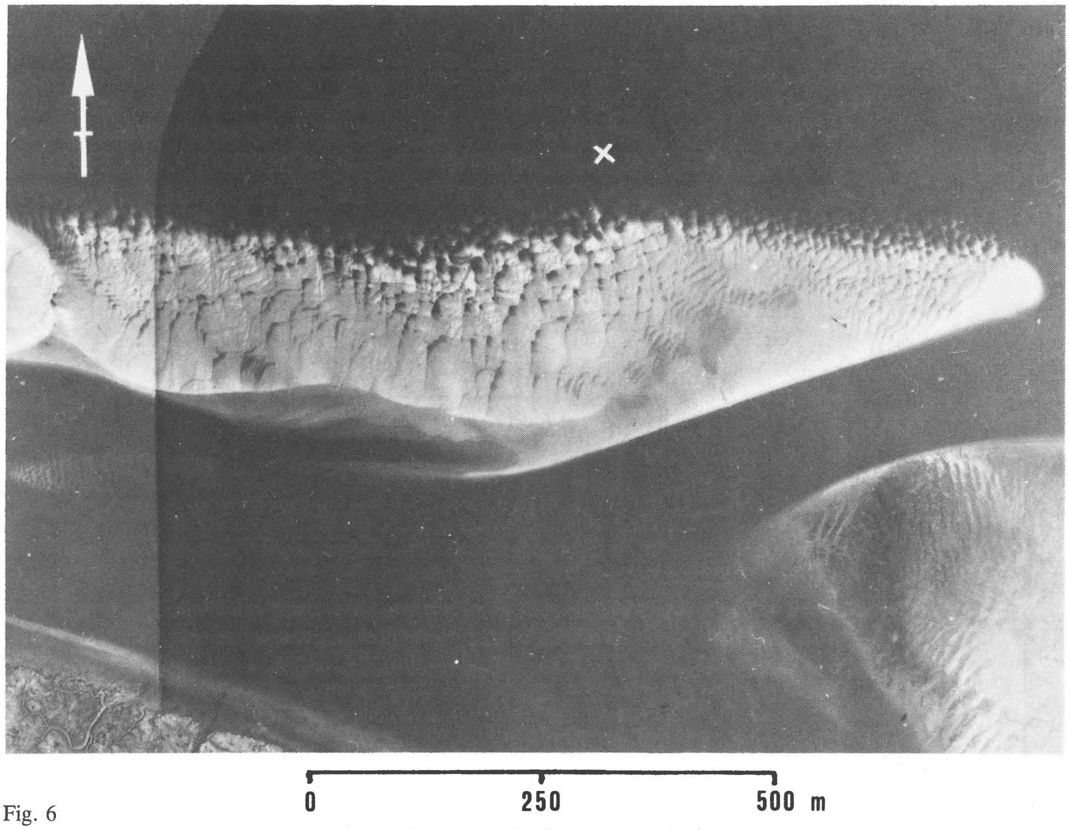

Fig. 6
Aerial photograph of the Krammer channel on May 12, 1966 at low tide (location of studied outcrop indicated by X).

reflected in series of alternating thick and thin bundles (Fig. 7). The 28 to 29 days neap – spring tide cycle, as described by VISSER (1980) is very clear; series of thin bundles are produced in the days around neap tide, whereas relatively thick bundles are generated around spring tide (see Fig. 5). Apart from the cyclic change in bundle thickness the neap to neap tide sequence of bundles manifests itself in a number of sedimentary features, summed up by TERWINDT (1981).

Several of these may be noted here briefly: thick toesets corresponding with thin bundles of the days around neap tide; erosive pause planes – especially in the upper part of sets – generated by stronger subordinate currents in the zone of thick bundles produced around spring tide.

Bedform preservation and set thickness

Maximum set heights of individual x-bedded units range from 0.2 to 1.5 m. From the still available record of numerous

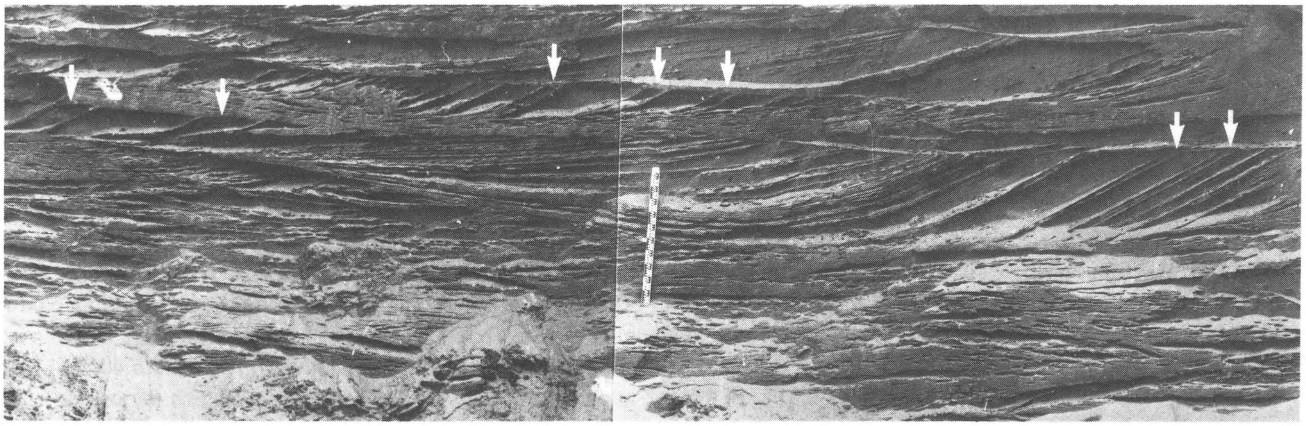

Fig. 7
Series of alternating thick and thin bundles of x-bedded sand (indicated by arrows) reflecting the diurnal inequality of the tide. Lenght of graduated stick is 1 m.

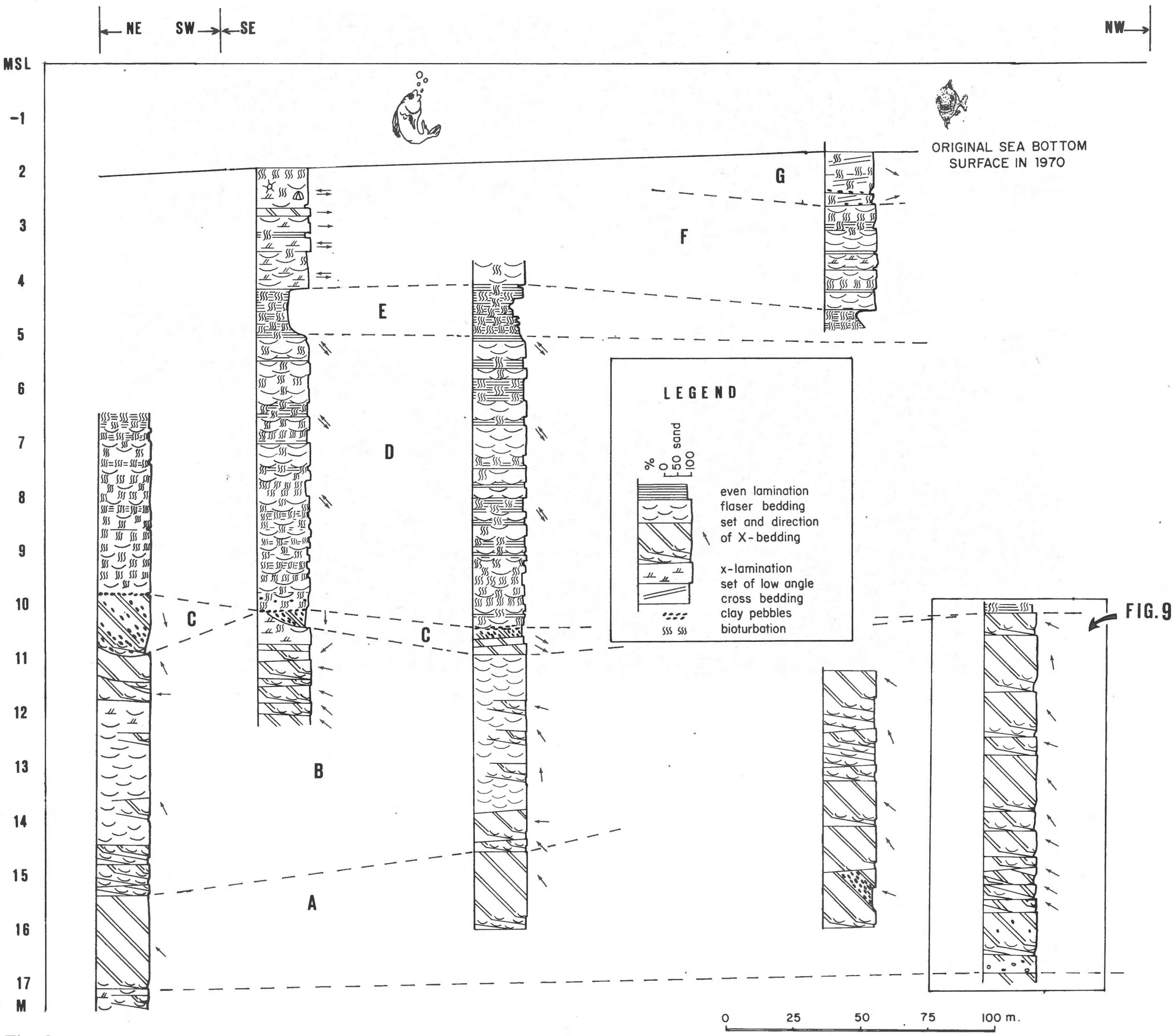

Fig. 8
General outline of the Schaar exposure.

soundings of the area, made in the period of rapid accumulation in the channel, a maximum ripple height of 1.5 m is deduced. The set heights measured in many places of the exposure point to an almost complete preservation of ripple front deposits, and therefore to an extremely high rate of sedimentation.

Unfortunately all sounding tracks run more or less perpendicularly to the direction of the channel axis and thus do not provide information on ripple spacing. However, this spacing can be estimated by comparing the rate of accumulation in the channel and the rate of migration of the set-producing bedforms:

In the time period between the sounding surveys of 1965 and 1966 – 357 days – the mean water depth of the area was reduced by 2.4 m (from approximately 9.0 to about 6.6 m, see Fig. 3). At the site of the exposure in this period 4 to 5 sets were preserved. An average migration rate of set-producing ripples in this interval of 12.8 m in a synodical month (29.53 days), or 155 m in the period between the soundings, can be deduced from the length of neap to neap bundle sequences. Assuming that in this year of rapid sedimentation all bypassing ripples at the site of the exposure have contributed to deposition, an average ripple spacing of 31 to 39 m is calculated. Based on numerous soundings of ripple fields in thalwegs of tidal channels in the SW Netherlands, it was found, that ripples with a height of more than 1 m indeed do have spacings between 15 and 50 m (TERWINDT, 1971). Even in the case of a minimum of 15 m, still more than 40% of the bypassing ripples would have contributed to deposition.

This assumption, however, implies an irregular pattern of alternating rapid sedimentation and erosion which does not fit in a process of gradual channel abandonment. This consideration, together with the fact that on the photograph at the bank ripples show spacings of generally over 25 m, strongly indicates that in this lower part of the sequence most, if not all, bypassing ripples are represented in preserved sets.

THE 'SCHAAR' EXPOSURE

This exposure is situated in the southwestern part of the 'Schaar' excavation in the mouth of the Oosterschelde (Fig. 1). A general impression of the whole outcrop may be obtained from Fig. 8. Seven lithostratigraphic units have been distinguished that are largely based on sedimentary structures (VAN DEN BERG ET AL, 1980). Here, attention is focussed on the lower two units (A en B).

Hydrographic background

Chronologically, the exposed deposits can be divided into two parts:

- from inspection of hydrographic charts, dating as far back as the beginning of the 19th Century, it follows that units A and B have been deposited at a depth which was not affected by tidal channels after the 18th Century.

It is established from the presence of juvenile specimens of *Mya Arenaria* (pers. comm. Dr. G. Spaink), a bivalve species imported by man from the Atlantic coast of North America at the end of the 16th Century (HESSLAND, 1946), that these deposits date from the 17th – 18th Century. This means, that they are formed in an environment similar to that of the present or at least that of the 19th Century Oosterschelde mouth.

- according to hydrographic charts, sediments down to a depth of 11 m below Mean Sea Level (units C – G) have been deposited after A.D. 1860. Most of these were formed in the second and third decade of the 20th Century and consist of rhythmic seasonal bedding produced in an abandoned channel (VAN DEN BERG, 1981b).

In addition it may be remarked, that the depths at which the deposits are exposed can be considered as depositional depths and – because of their relative youth – those depths do not need to be corrected for a relative rise of the sea level, as is the case with older Holocene deposits.

General description of the sequence of large-scale cross-bedding

At the base of the 'Schaar' pit a dragline straightened and planed in steps nearly vertical exposures of adjacent parts of the excavated wall. After cleaning and smoothing with a shovel and a trowel, photographs were taken of the walls and measurements were made. In this way an exposure of a 70 m long and almost 5.8 m high section of unit A could be studied in detail. Like the Philipsdam example, this exposure represents a longitudinal section (parallel to the main current direction). An overall view of set boundaries and pause planes, drawn after photographs is given in Fig. 9.

Unit A consists of generally NW to N (ebb) directed x-stratification. Lower set boundaries are planar to weakly cylindrical. The more or less straight foresets merge into well-developed bottomset layers. Sets are up to 2.5 m high. Foresets reveal the same features as the tidal bundles described from the Philipsdam exposure with the exception that slack water mud drapes are much better developed. They may be up to 3 mm thick. The thickest mud drapes enclose the thin bundles that were produced in the days around neap tide and reflect the relatively long slack water period at that time. In toe- and bottomsets both high and low water slack periods are generally represented in mud layer couplets.

The base of the unit is formed by a lag deposit with similar characteristics as the channel lag at the base of the outcrop in the Philipsdam pit. To the SE and in an upward direction, unit A passes gradually into unit B. The latter unit is characterised by mixed flaser bedding and ebb-oriented x-stratification. Flasers are formed on gently inclined slopes (predominantly at an angle of 5 to 10 degrees to the SW). Within the flaser beds solitary x-bedded sets occur which develop and disappear within short distances (see Fig. 10). The median grain size of both units varies between 150 and 210 microns.

Flood versus ebb current directions

Erosion of the steep lee-side of the megaripples (due to the subordinate flood current), is expressed in discontinuity planes between foreset strata. As might be expected most pronounced discontinuity planes coincide with thick bundles produced around spring tide. These erosional planes may contain a pattern of small-scale ripples generated by the subordinate tide. Such an occurrence was found in the two exposures which were studied, as well as in a number of previously described examples of recent and ancient tidal

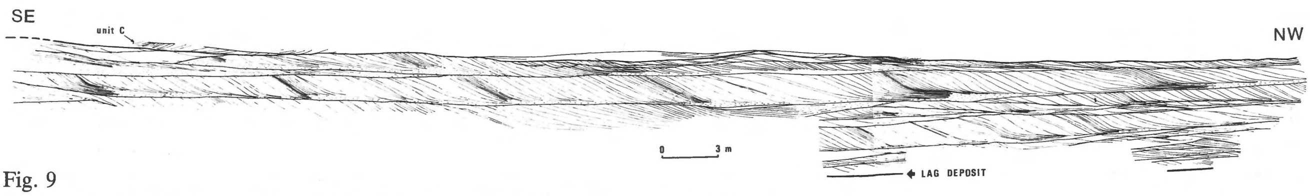

Fig. 9
Set boundaries and pause planes in the Schaar exposure. (For location see Fig. 8.)

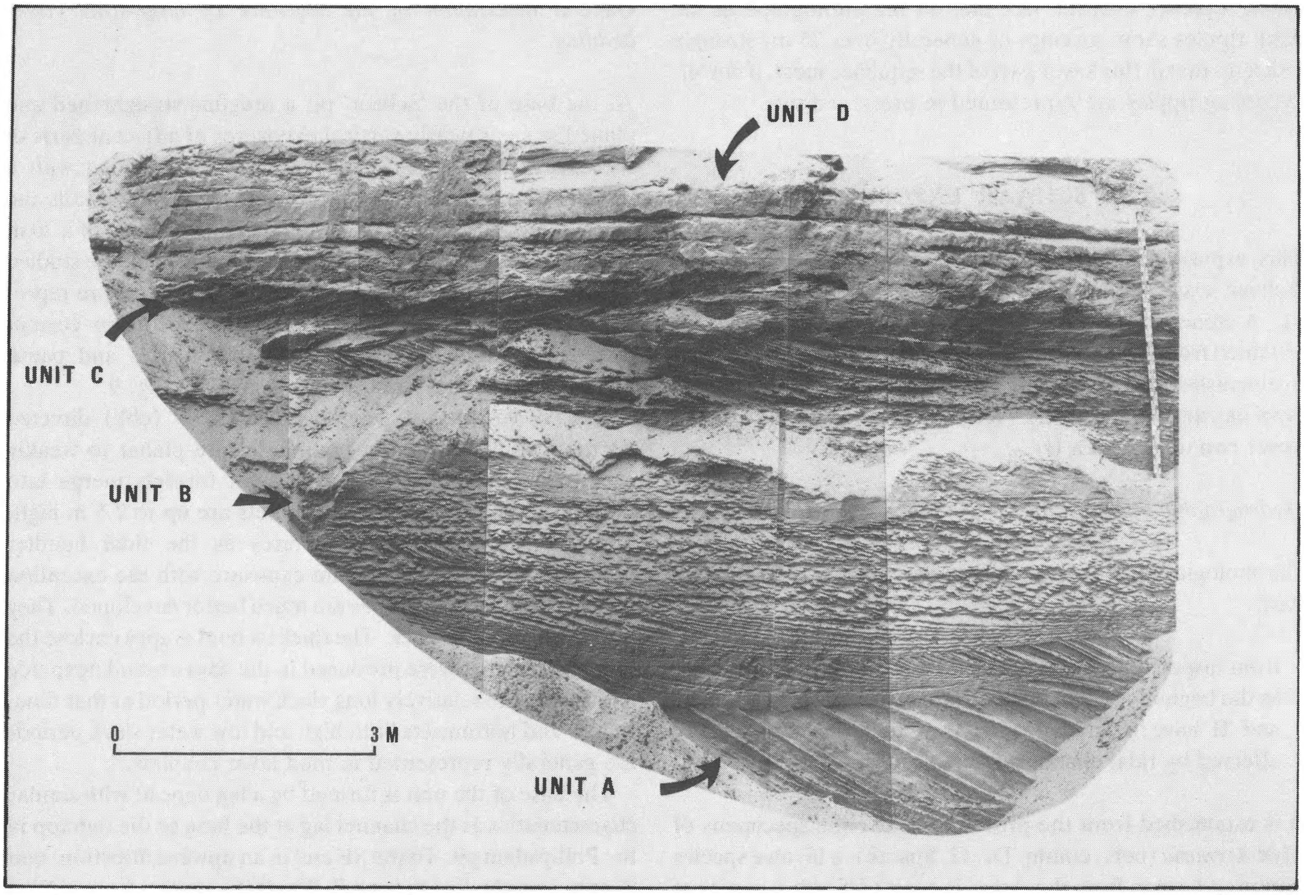

Fig. 10
The transition of unit A to unit B.

deposits. (TERWINDT, 1981; NIO ET AL, 1980; DE RAAF & BOERSMA, 1971; BOERSMA, 1969; ALLEN & NARAYAN, 1964, HOMEWOOD, 1981). In the sequence discussed here, the presence of well-developed slack water mud drapes overlying these ripples allowed an examination of the small scale ripple pattern, which indicated that the ripples have straight to sinuous crestlines. Ripple crest alignments and deduced migration directions could be measured easily by cutting back exposed ripple cross-sections with a trowel.

After numerous measurements it appeared that the average migration direction of these ripples is not completely opposite to the x-bed direction but shows a remarkable deviation to the left (Fig. 11). This is not necessarily an indication of not-oppositely directed tidal currents. One might also think of a consistent deviation between ripple lee slope azimuth and dominant current direction as a result of a lateral gradient in current velocity. Certainly, the feature points to a peculiar hydraulical and morphological situation which obviously continued during deposition of the whole sequence.

Bedform preservation and set height

In the 'Schaar' exposure the range of the maximum set heights is about the same as the one reported from the Philipsdam example. The fact, that at present ripple heights in the Oosterschelde rarely exceed 2 meters (TERWINDT, 1970) points to a comparable degree of preservation of ripples as was found in the Philipsdam pit. The presence of brinkpoint structures in

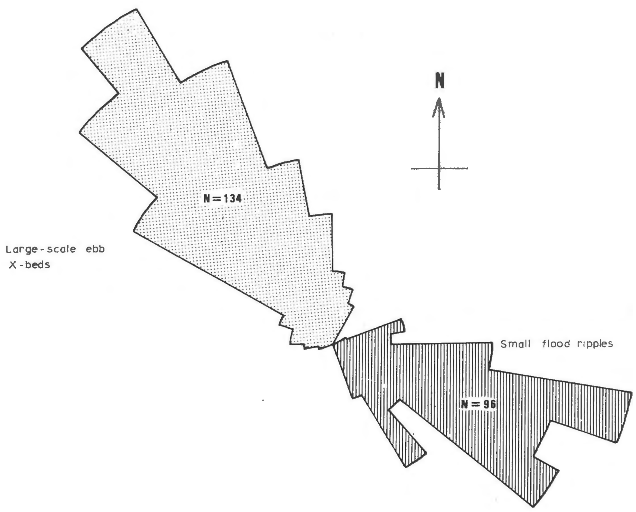

Fig. 11
Ebb x-bed azimuths and flood ripple migration directions.

the upper part of some of the thickest sets may further be mentioned as a significant indication of nearly complete preservation of ripple front deposits. A close-up of these structures is given in Fig. 12.

The depositional sequences of both the Schaar and the Philipsdam exposures have very much in common. Therefore it seems reasonable to base estimates of the rate of accumulation in this environment on the Philipsdam example. According to the length of the exposed neap to neap tide sequences, the average migration rate of the large scale bedforms was 278 m per year. If a preservation of all bypassing ripples and a minimal ripple spacing of 15 m is assumed, a maximum (vertical) accretion rate of 10.2 m in one year is calculated.

Depositional environment

The first reliable hydrographic chart covering the Oosterschelde area is the 'Carte réduite des côtes des Pays-Bas', made and published by the famous French cartographer Beautemps-Beaupré in 1817. Since then the area was surveyed repeatedly by the Dutch Hydrographic Service. From the available editions of the 19th and the beginning of the 20th Century, 6 maps have been selected and have been adjusted to a standard way of presentation (Fig. 13).

Although the discussed sequence was deposited before the first reliable map of the area was made, the series of charts provide an important indication of the probable depositional environment. The maps show a rapid change of a complex pattern of channels and shoals. The channels can be divided into ebb, flood and continuous channels, according to their topography (VAN VEEN, 1950).

Two major channels can be distinguished, separated by a broad shoal area intersected by a number of roughly NW-SE directed ebb and flood channels. The distribution of ebb and flood channels points to systematic temporal differences in water elevation between the northern and southern margin of the shoal area during the tidal cycle; all flood channels were connected with the northern major channel (Hammen), whereas all ebb channels originated from the southern major channel (Roompot). This means, that during flood the net transport of water was from the northern into the southern major channel. During ebb water flowed in an opposite direction. The tidal currents from the major channels were diverted into the smaller ebb and flood channels. As in river meander loops, this resulted in erosion of the outer bends of the channels, whereas deposition took place in the inner bends. This caused an eastward lateral shift of the flood channels which were connected with the northern major channel. The ebb channels on the contrary (which were connected with the southern major channel) migrated westward. The lateral migration was sometimes very fast: e.g. an ebb channel south of the location of the construction pit shifted 2 km to the west in the period from 1887 to 1922. From the history of the Oosterschelde entrance (DE BRUIN & WILDEROM, 1961; WILDEROM, 1964; VAN DEN BERG ET AL 1980) it can be deduced, that the 19th century morphodynamic system began to evolve in the 18th century. Since the northern rim of

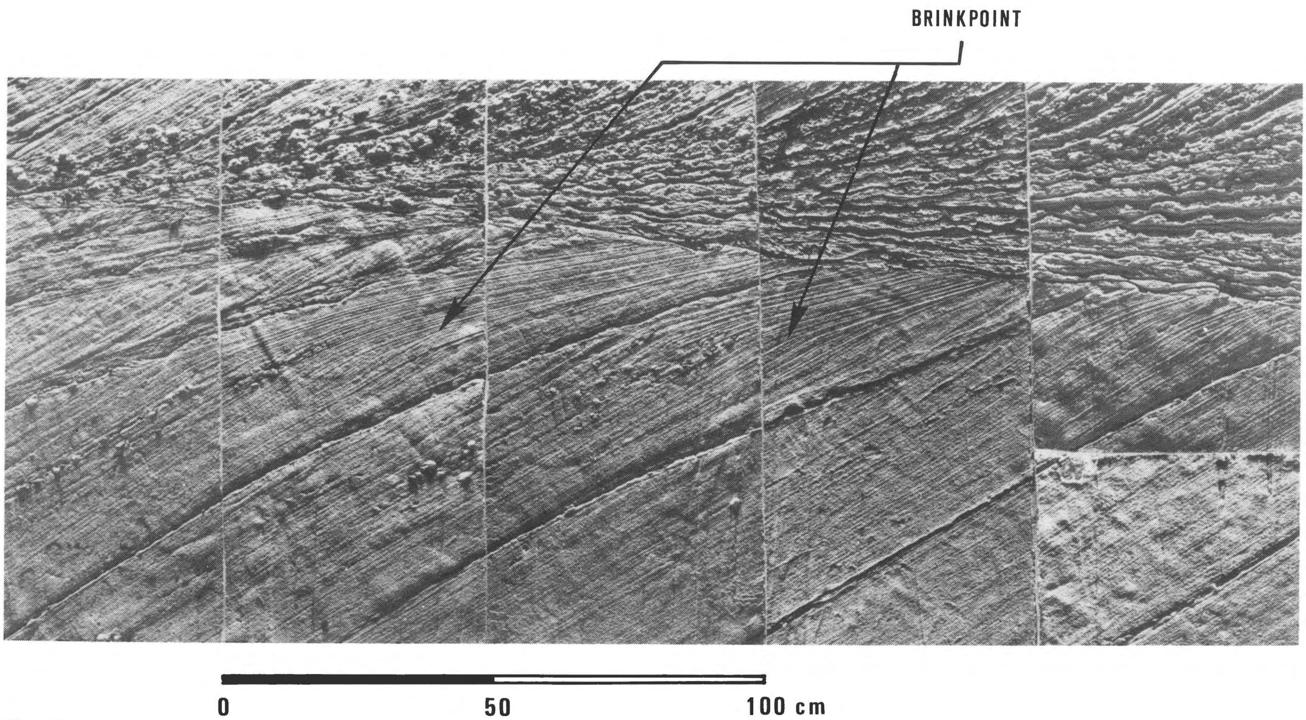

Fig. 12
Lacquer peels showing brinkpoints structures in the upper part of an x-bedded set.

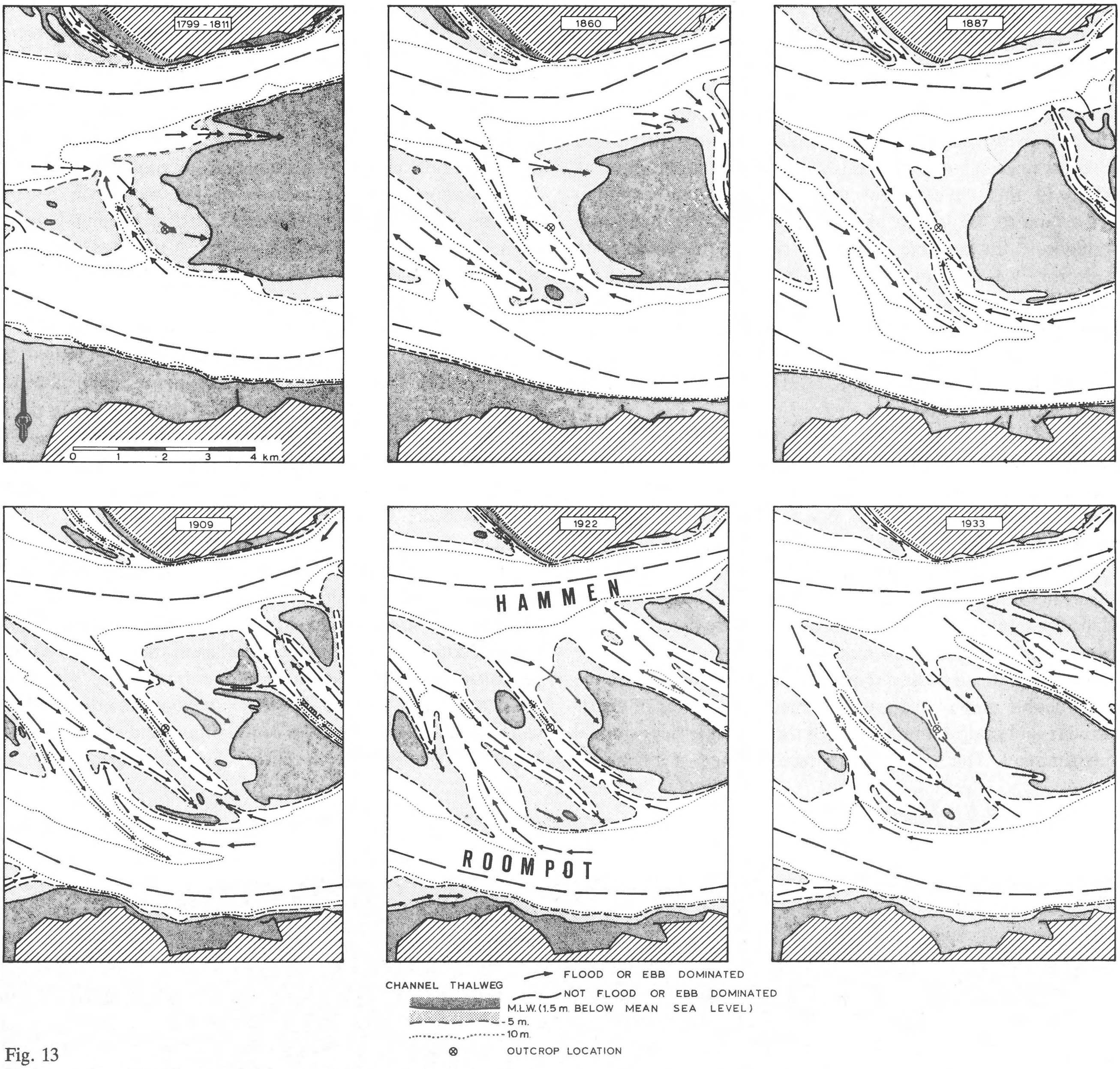

Fig. 13
Hydrography of the Oosterschelde mouth between 1800 and 1933.

the Roompot channel at that time was situated more to the north and closer to the pit, it is likely that one or more ebb channels migrated accross the location of the pit. The possibility that the sequence under discussion was produced at the passage of such a channel – for instance in an early stage of the ebb channel which was present near the location of the pit in the beginning of the 19th century – is supported by the following considerations:

– The 19th century ebb channels eroded to a maximum depth of 15-20 m; the channel lag at the base of the exposure was found at a similar depth of 16-17 m.
– The rapid shift of ebb channels involves rapid accretion on the inner banks. This is in agreement with the postulated high sedimentation rate of the x-bedded sequence.
– The gradual upward transition to the flaser beds of unit B could very well reflect a decrease in current intensity in connection with a lateral shift of an ebbe channel (OOMKENS & TERWINDT, 1960).
– The direction and angle of inclination of most of the flaser beds closely corresponds with slope characteristics of accretional banks of 19th century ebb channels.

CONCLUSIONS

The sequences studied in the Philipsdam and Schaar excavations have been built up rapidly in a channel which was dominated by one of the tidal currents. They represent respectively a stable channel which was abandoned by the tidal currents, and an actively migrating channel environment. The high rate of accumulation is manifested by large set heights in comparison with the amplitude of the original bedforms. These bedforms were straight to sinusoidal megaripples, with a maximum height of about 2 metres, and migrated in the direction of the dominant current at a speed of 5 to 15 metres in a neap to neap tide cycle. During this rapid accretion most or all of the dunes which passed by probably contributed to the sedimentary record.

High accretion areas make up only a small part of the Oosterschelde sea arm. They are generally confined to channel banks of rapidly migrating channel systems. The Philipsdam example may be considered an exception to this rule. Despite the rather scanty occurrence of recent high accretion areas in the environment, their fossil deposits should have a wide occurence in the subsurface: in the past two centuries a large portion of the shoal complexes of the Oosterschelde mouth and outer delta have been reworked by such dynamic channels down to a depth of 10 to 20 metres. Most deposits of these channels represent rapidly built-up accretional bank units, in which sequences like those described in this paper presumably have a great preservation potential.

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